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Critical raw materials: from dependency to open strategic autonomy?

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Introduction

'Cause we are living in a material world... [1]
Madonna
Material Girl, 1984

In March 2023, the European Commission proposed a Critical Raw Materials Act, the formal objective of which is to "ensure the EU's secure access to critical raw materials, while incentivising the development of sustainable supply sources" (EC, 2023a). Critical raw materials (CRMs) are deemed indispensable to fulfil Europe's climate and digital ambitions for 2030 and beyond, given the role that they play in a range of key, strategic areas, such as the clean energy sector, the electrification of the economy, and the production of semiconductor chips powering the latest digital technologies. Often lying at the very beginning of global value chains, they are vital inputs for many European industries. Reliable access to CRMs, at reasonable prices, is, however, far from a given for Europe. For many CRMs, the EU currently depends almost exclusively on imports, often from a limited number of suppliers, in particular China. Disruptions to the supply of essential goods during the COVID-19 pandemic and the energy crisis sparked by Russia's invasion of Ukraine have demonstrated the risks of the EU's structural supply dependencies.

The EU Critical Raw Materials Act should be seen in an international context of receding multilateralism, where geopolitical considerations are an increasingly important factor driving economic policymaking (Buysse and Essers, 2022). It sits squarely within the Commission's agenda of "open strategic autonomy", i.e. to develop the capacity to act autonomously when and where necessary and in cooperation with partners wherever possible (ESCB IRC, 2023). CRMs are clearly an area for Europe where greater resilience is warranted and, in this regard, an important aspect of the EU's policy initiatives is an accelerated diversification away from Chinese supplies, linked to a broader "de-risking" strategy vis-à-vis China (von der Leyen, 2023).

This article begins with an explanation of the term "critical raw materials" and why they are important (Section 1). We then highlight existing imbalances between demand and supply, and international competition for CRMs that are key to the green transition (Section 2). Next, we discuss the Critical Raw Materials Act in more detail, as well as related EU policy initiatives, the practical hurdles they face, and some potential solutions (Section 3). We then conclude with a number of key takeaways (Section 4).

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1 'Material world' is also the title of a recent book by Ed Conway (2023), in which he describes the world's past, present and future from the vantage point of six crucially important materials: sand, salt, iron, oil and gas, copper, and lithium. The latter two are typically considered critical raw materials (see Section 1).

1. What are critical raw materials and why do they matter?

1.1 Definitions and lists of CRMs

While there may be no universally accepted definition of "critical raw materials", many countries and regions maintain lists of primary materials that they deem to be of "critical" importance to their economies and societies. [2] Criticality assessments are typically informed by how significant certain materials are as inputs for the production of goods in key industries or for the functionality of modern technologies, as well as by concerns over the access to such materials. Therefore, CRM lists are bound to be subjective and location specific. Since the economic significance of and access to materials may change over time, owing to production, market, technological and geopolitical developments, CRM lists also tend to be dynamic (IRENA, 2023).

The European Commission has maintained a list of CRMs since 2011, which is updated every three years. The fifth and latest list was published in March 2023. [3] It contains 34 CRMs – 31 individual materials and three *groups* of materials (composed of ten heavy rare earth elements (HREEs), five light rare earth elements (LREEs), and five platinum group metals (PGMs)) – or 51 individual raw materials in total (EC, 2023b). [4] These CRMs were selected by screening an initial list of 87 candidate individual raw materials (see the annexed table). [5] To identify CRMs, the Commission checks the candidate materials against two main criteria, drawing on information pertaining to the preceding five years (see EC, 2017 for technical details). Firstly, an "economic importance" score is assigned to the material being assessed, determined according to its direct use in different EU manufacturing sectors and the value added of those sectors, and adjusted by a substitution index based on the technical performance and cost effectiveness of different substitute materials. Secondly, a "supply risk" score reflects the risk of a disruption to EU supplies of the material concerned. This is based on the concentration of both global suppliers and countries from which the EU is currently sourcing the material and considers the reliance on imports as well as the quality of governance and existing export restrictions in each supplier country. [6] The concentration measures are corrected according to the options available for substituting the material and for end-of-life recycling. Materials that reach or exceed the threshold values for economic importance and supply risk, as determined by the Commission, are classified as CRMs. As per the Commission's 2023 proposal for a Critical Raw Materials Act (see Section 3.1), materials that do not meet the thresholds but are considered "strategic raw materials" (SRMs), due to their high strategic relevance to the EU's green and digital transition and/or to its defence and aerospace sectors, are added to the CRM list. The relevance of materials for strategic technologies such as batteries, wind turbines, data storage and robotics is the subject of a separate, forward-looking assessment that considers the quantities of materials needed and the expected global demand for the technologies in question (EC, 2023a; JRC, 2023).

Figure 1 shows the outcome of the EU's 2023 CRM assessment. Materials such as the rare earth element (REE) groups are marked by extraordinary supply risks (due to China's near monopoly in REE processing, see Section 2.2), while tungsten and manganese stand out for their high economic importance for the EU (in the steel and toolmaking industries). Cobalt, magnesium and the PGM group score high on both dimensions. Copper and nickel do not meet the supply risk thresholds, given relatively well diversified sourcing and existent recycling options, but they are included as SRMs due to the sheer volume required in almost all strategic technologies.

2 IRENA and NUPI (forthcoming) identify 35 CRM lists by individual countries or regions.

3 This list was published as an appendix to the Commission's proposal for a Critical Raw Materials Act and may still be amended.

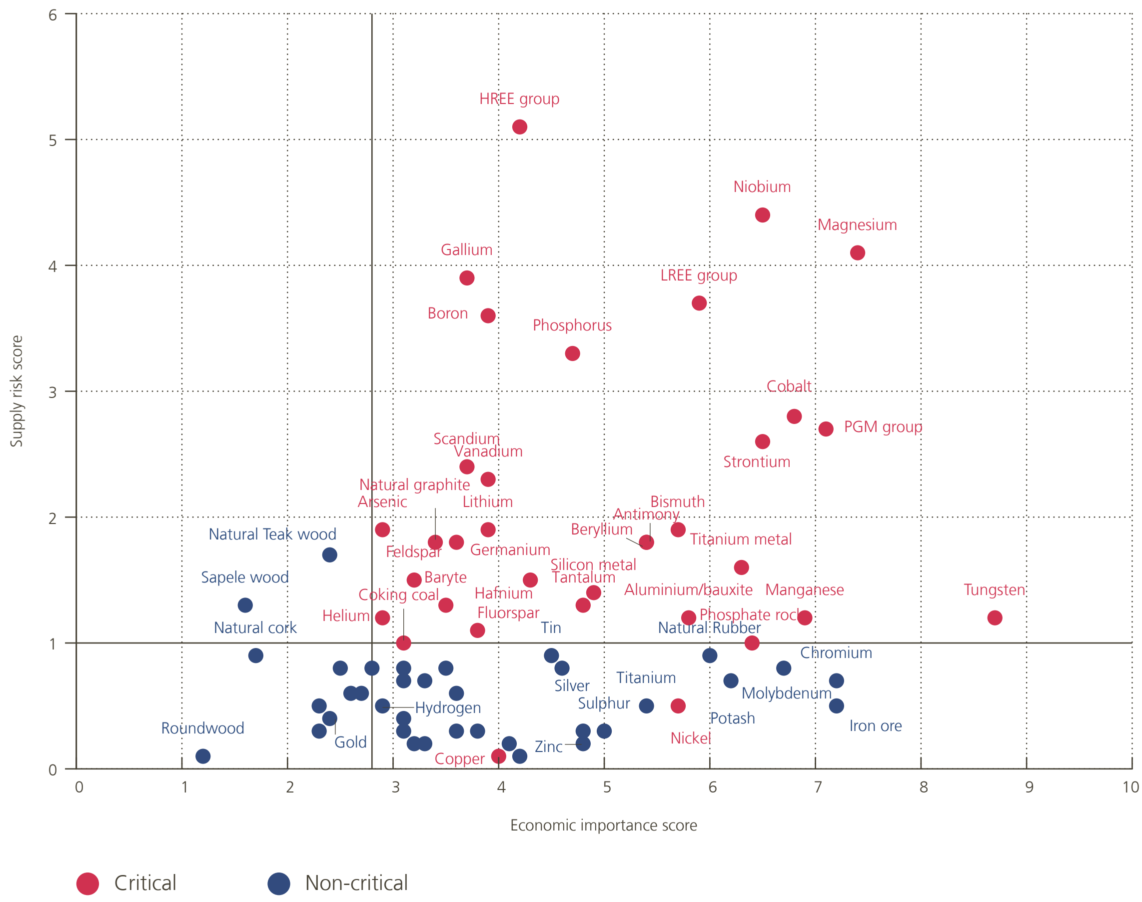
4 Technical and market information for each of these materials can be found in the factsheets provided by the SCRREEN (Solutions for CRitical Raw materials – a European Expert Network) project funded under the EU's Horizon 2020 research and innovation programme. See https://scrreen.eu/crms-2023.

5 The Commission's CRM list contained 14 CRMs in 2011, 20 in 2014, 27 in 2017, and 30 in 2020. The number of screened materials has also grown over time.

6 Where possible, supply risk is calculated at the extraction *and* processing stages and then measured at whichever stage represents the greatest bottleneck.

Figure 1

Results of the 2023 criticality assessment of raw materials for the EU [1]



Source: EC (2023b).

1 See the main text for an explanation of how the supply risk and economic importance scores are determined. The horizontal and vertical lines indicate the threshold values for the two scores (1 and 2.8, respectively).

In the United States, CRM assessments are performed by multiple government agencies. The US Geological Survey (USGS, a division of the US Department of the Interior) publishes a CRM list that is revised every three years. It uses a quantitative methodology that is somewhat similar to that of the Commission – i.e. an economic importance-cum-supply risk score that combines information on industries' value added, their commodity expenditures, commodity production concentration, US net import reliance, and partner countries' ability and willingness to supply the commodity. This is supplemented with an evaluation of potential "single points of failure", i.e. commodities with only a single domestic producer along their supply chain (see USGS, 2021 for more details). A separate analysis by the US Department of Energy (US DOE) again considers the supply risk of materials as well as their specific importance for the production, transmission, storage and conservation of energy, adopting a more global and forward-looking perspective. The combined USGS (2022) and US DOE (2023) CRM list contains 54 individual materials, and there is a large overlap with the EU list (see the annexed table). [7]

7 Exceptions include electrical steel and silicon carbide, which are engineered materials considered only by the US DOE (2023).

China has only had an official catalogue of CRMs/SRMs since 2016, which was developed as part of the 2016-2020 State Council's national plan for mineral resources and currently lists 17 (non-energy) minerals in addition to REEs (see the annexed table).[8] Unlike the US and the EU, China also labels gold, iron, potash and molybdenum as strategic. China's criticality/strategicness evaluation is based on various criteria, including the importance of a given material to its economic development and emerging industries, its national security and defence applications, and any risks to supply. In addition, China has defined a number of "advantageous strategic minerals", which it often has in abundance and for which it holds a competitive advantage or dominant position that could be leveraged to pursue strategic goals.[9] This suggests a way of thinking about CRMs that differs from that in the EU, US and most other countries (Andersson, 2020).

1.2 Relevance of CRMs

Almost by definition, CRMs are essential and often irreplaceable components for many modern industries: from the metallurgic, chemical, and medical sectors, to electronic and telecommunication equipment manufacturing and the automotive and defence sectors. Above all, "the energy transition is a materials transition" (JRC, 2023). In line with most of the CRM literature, this article will focus on those CRMs that are essential for a range of current-generation clean energy technologies and that have relatively large (potential) market sizes: copper (often used for electric wiring); cobalt, nickel and lithium (used in various types of batteries for electric vehicles (EVs)); and the REE group – in particular neodymium (used in the permanent magnets of EV motors and wind turbines).[10] Together, these CRMs are commonly referred to as "energy transition minerals" (IEA, 2021, 2023a). They feature on the criticality lists of the EU, the US, China and many other countries (see the annexed table). These CRMs are also of relevance to Belgium (see box).

Even though CRMs such as lithium and REEs are sometimes described as the "new oil and gas" (Breton, 2022), they are fundamentally different from fossil fuels in a number of ways (IRENA, 2023). First of all, the amounts of clean energy-linked CRMs extracted or traded are still several orders of magnitude smaller than those of fossil fuels. In 2022, some *10 million* tonnes of copper, lithium, graphite, cobalt, manganese, REEs, and PGMs were produced, compared to the extraction in 2021 of roughly *15 billion* tonnes of oil, natural gas and coal. Likewise, total export values in 2021 of raw copper (USD 91 billion), nickel (USD 4.2 billion), lithium (USD 1.5 billion) and cobalt (USD 118 million), let alone individual REEs, do not weigh up to those of crude petroleum (USD 951 billion) or natural gas (USD 335 billion). The CRM sector is set to grow rapidly over the coming years (see Section 2), but the aggregate volumes and values involved will remain smaller than those of fossil fuels today (IRENA, 2023).

Moreover, while both fossil fuels and CRMs imply external dependencies (for most countries) and other risks, the nature and dynamics of such dependencies and risks are very different. Even if CRM extraction and further processing is still limited and geographically concentrated – as we explain below – most CRMs, including lithium and even several "rare" earths, are in fact relatively abundant in the earth's crust, geologically widespread, and could be processed in many locations, were there to be investment in mining and refining capabilities. So in the medium to long term at least, when more mining and refining sites become operational, trade in CRMs should be less vulnerable to geopolitics than oil and gas (IRENA, 2023). The expected entry of new producers (sometimes with divergent geopolitical priorities), coupled with longer-term risks of substitution for some CRMs (through technological innovation), may make it very hard to form successful OPEC-style cartels (Hook et al., 2023). That notwithstanding, CRMs can be – and indeed have been – used as geopolitical leverage from time to time (see Section 2.3).[11]

8 China also classifies energy minerals, such as oil, (shale) gas, coal, and uranium, as SRMs.

9 REEs and tungsten are the most frequently cited examples of "advantageous strategic minerals" in the Chinese literature (Andersson, 2020).

10 This is not to say that niche CRMs, characterised by very specific uses and smaller volumes, can safely be ignored. For example, thulium and yttrium, among the rarest of the REEs, are used in military and surgical lasers. Rhodium, a precious metal that is far less abundant and more expensive than gold, is primarily used in catalytic converters that reduce harmful emissions from car exhausts.

11 The IMF (2023) finds that bilateral trade flows of CRMs are positively associated with trading partners' geopolitical alignment, measured as the similarity between countries' international military alliances.

Lastly, fossil fuels get consumed in the process of producing energy. A disruption in the supply of oil, gas or coal hence poses risks to energy security, with immediate but generally short-lived impacts on households and firms. Conversely, CRMs are used as components in more durable clean energy assets and installations, with multi-year/decade lifespans. Disruptions to CRM supplies are thereby less of an acute energy security risk but primarily a risk to the speed and cost of the energy transition, with potentially severe longer-term consequences (IRENA, 2023). In turn, once used, fossil fuels cannot be repurposed, which is not the case for most CRMs as recycling and reuse are possible (see Section 2.2).

Indirectly, CRMs are also of relevance to central banks. Access to CRMs will be an important factor in setting the pace and cost of the green transition of European and global economies (IEA, 2021, 2023a). An orderly green transition will contribute to price and financial stability over the longer term. In the shorter run, supply shocks to CRMs, which are typically found in the more upstream stages of value chains, may also have pass-through effects on the prices of a variety of goods. Model simulations by the IMF (2023) suggest that complete fragmentation of the markets for copper, cobalt, nickel and lithium – whereby trade in these CRMs between two opposing geopolitical blocs (US-Europe+ v China-Russia+) entirely ceases – would result in lower global investment in renewables and EVs than is required for a successful green transition. Such a scenario would also create large price increases and higher price volatility, complicating monetary policy (Alvarez et al., 2023).[12]

12 Bolhuis et al. (2023) show that failing to account for granular commodity production and trade linkages in modelling exercises can lead to a serious underestimation of the output losses associated with broader trade fragmentation.

BOX

Relevance of selected CRMs for Belgium *

Belgium has had a rich industrial mining past, but today local mining for CRMs is non-existent. That notwithstanding, substantial concentrations of lithium have been recently discovered in the underground water pumped by geothermal installations in the Antwerp and Limburg Kempen region (Michielsen, 2023). Moreover, *Global Sea Mineral Resources*, a subsidiary of the Belgian DEME Group specialised in dredging and marine engineering, is exploring the potential of deep-sea mining, whereby nodules containing copper, nickel, cobalt and other CRMs would be retrieved from the sea floor (The Economist, 2023a).

In international CRM value chains, Belgium is arguably best known for its leading materials technology and recycling company *Umicore*. Umicore imports raw copper, cobalt and nickel (next to many other CRMs), as well as their scrap and residual materials from all over the world, part of which is re-exported after refining or recycling. Besides its Belgian site in Olen, the company's battery materials division operates factories in Poland, Finland, South Korea and China, and plans a new facility in Ontario, Canada. *Aurubis* (of German origin) and *Jean Goldschmidt International* are other large recycling firms active in Belgium.

Refined copper is a crucial input for Belgian companies that manufacture electric cables for power grids, such as *Lamifil* and *Nexans*. Belgium‑based producers of steel and other metal alloys, including *ArcelorMittal* and *Aperam*, rely on imports of processed nickel. Belgium is also home to local desks of international trading companies, like *Glencore*, that deal in various metals. Belgian trade of lithium is much more limited and mostly related to the European distribution by foreign companies with a Belgian seat. Trading in REEs is minimal for Belgium.

In terms of manufactured products that incorporate CRMs, lithium batteries are an important Belgian import product. Rechargeable lithium‑ion batteries (also known as accumulators) are key components of the electric vehicles produced by foreign automotive companies with Belgian plants, notably *Audi* and *Volvo*, as well as for Belgian companies like *Van Hool* (a manufacturer of busses and touring cars) and *Norta* (e‑bikes). Lithium batteries are also used and/or distributed by companies in the electronic equipment and toolmaking sector.

Finally, Belgian institutions are very active in research and innovation with respect to CRMs. This encompasses most Belgian universities, research institutes such as *VITO* (Vlaamse Instelling voor Technologisch Onderzoek) and *Imec* (through IMOMEC, Institute for Materials Research in MicroElectronics), and private companies like *Umicore*, *Jean Goldschmidt International*, and *Solvay*, among many others. Belgian institutions cooperate among each other and with international partners, including in EU‑funded consortia and projects. Examples are LICORNE (setting up a European supply chain for lithium), ENICON (transformation of low‑grade nickel and cobalt into battery‑grade metals), RHINOCEROS and ACROBAT (recovering and recycling of battery materials), and CIRCUSOL (extending the life of batteries and solar PV modules).

* This is a qualitative and very partial overview, primarily informed by the Belgian international trade statistics, company websites and press articles.

2. Demand-supply imbalances and strategic competition for CRMs

2.1 Rapidly rising demand for CRMs

The deployment of clean energy technologies will have to accelerate rapidly if we are to meet the Paris Agreement goal of limiting the rise in global temperatures to 1.5 °C by the end of this century. According to the International Energy Agency (IEA), clean energy technologies encompass EVs and battery storage, electricity transmission and distribution grids, hydrogen, solar photovoltaics (PV), onshore and offshore wind, and other forms of low‑carbon power generation. As these technologies are very CRM‑intensive[13] during their deployment phase, the shift towards a clean energy environment is expected to drive an unprecedented increase in the demand for many CRMs over the coming years. However, as indicated in Table 1, the same CRMs also have applications

13 For example, a typical EV requires six times the mineral inputs of a conventional car, and an onshore wind farm requires nine times more mineral resources than a gas‑fired power plant (IEA, 2021).

in other strategically important sectors, such as the defense, aerospace and digital technology industries, which will further intensify the race to secure access to them. For example, (electric) traction motors – an essential component in EVs as well as in drones and robots – typically contain permanent magnets, produced using REEs. Permanent magnets are also used in wind turbines and in the hard disk drives essential to meet the ever-growing data storage needs of the digital economy. In addition, many electronic devices contain rechargeable batteries and semiconductors for which silicon is a key input, one that is also essential for solar PV systems.

Furthermore, the main technologies involved in the clean energy sector are also key contributors to other sectors, and vice versa. For instance, solar PV serves as an energy source for the ICT, defense and other energy-intensive industry sectors, while batteries contribute to the mobility, ICT and defense sectors, many of whose products require an uninterruptible power supply. In turn, the further integration of digital technologies across the economy is having an impact along the entire renewable energy value chain, from generation to transport, distribution, supply and consumption. Robotics and 3D printing are expected to increase productivity even further and optimise the performance of various processes along the renewable energy value chain (JRC, 2023).

Table 1

CRMs are essential inputs in various strategic technologies

	Green transition technologies					Other strategic technologies			
	Batteries	Fuel cells	Wind	Electric motors	Solar	Robotics	Drones	3D printing	Digital tech
Cobalt	✓	✓	✓			✓	✓	✓	✓
Copper	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lithium	✓	✓				✓	✓		
Nickel	✓	✓			✓	✓	✓	✓	
REEs		✓	✓	✓		✓	✓		✓

Source: JRC (2020).

The five key CRMs on which we focus in this article are all essential inputs for clean energy technologies, as well as having other applications (JRC, 2020, 2023; ETC, 2023).

- Cobalt is primarily used as a cathode material in rechargeable batteries for EVs (as well as in mobile phones and other electronic devices). However, thanks to innovations in battery technology, there is a strong possibility that future cobalt requirements could decrease: cathode chemistries are already shifting away from high-cobalt nickel-manganese-cobalt (NMC) batteries to low-cobalt NMC and lithium-iron-phosphate (LFP) batteries (IEA, 2023a). Cobalt's properties mean it is also heavily used to produce superalloys, which are used in 3D printing, hard disk drives, and the component parts of gas turbine engines.

- Copper is used across a wide range of technologies (it is a so-called cross-cutting mineral). It features in all clean energy technologies, with electricity grids and EVs serving as the two largest drivers of demand. There is also a large growth in demand for copper from non-energy sectors, driven by industrialisation and economic development in middle-income countries. Significantly, copper is already considered to be the most intensively traded industrial metal, and due to its extraordinary thermal and electrical conductivity, it is difficult to substitute – although aluminium and silver are sometimes used as alternatives for wiring.

- **Lithium** is the lightest solid element in the periodic table, and its low mass combined with its high electrochemical potential and high energy density mean it is present in almost all current battery technologies. As such, demand for lithium is almost entirely driven by demand for (EV) batteries, which rely on the movement of lithium ions to generate the free electrons needed to create an electrical current. There is some potential for sodium-ion batteries to mitigate demand for lithium but, currently, the former are only competitive alternatives for stationary storage systems or in the micro-mobility sector (IEA, 2023a).

- **Nickel** is also used in (typically low-cobalt) EV batteries, in its high-purity form. In addition, it is found in (alkaline) hydrogen electrolysers and as an alloy material in the steel used to produce wind turbines, electric motors, robotics and drones. In batteries, nickel faces competition from LFP chemistries. For steel products, it tends to be cheaper than potential substitutes like titanium or chromium.

- **(L)REEs** include minerals such as **neodymium**, which is a crucial element in the high-strength permanent magnets found inside wind turbine generators, EV motors, robotics and drones, as well as in hard disk drives used for data storage. Alternative magnets use either other LREEs, including praseodymium, or non-REE compositions such as ferrite magnets (which tend to be less performing).

The transformation of the clean energy sector has already emerged as a major driver of demand in CRM markets. From 2017 to 2022, it was the main factor behind a tripling in overall demand for lithium, a 70 % jump in demand for cobalt, and a 40 % rise in demand for nickel (IEA, 2023a). This trend is expected to accelerate as the energy transition progresses, with the pace varying depending on projected scenarios. The IEA [14] "Net Zero Emissions (NZE) by 2050" scenario is very ambitious and sets out a roadmap for the global energy sector to achieve net zero carbon dioxide (CO_2) emissions by 2050 (IEA, 2023b). The NZE scenario assumes the large-scale deployment of clean energy technologies and other emission reduction measures, but it also depends upon a high degree of global cooperation and collaboration. Advanced economies would take the lead and reach net zero by 2045, China by 2050, and other emerging market and developing economies after 2050. In addition, the NZE scenario requires a huge, policy-driven ramping up of clean energy capacity by 2030, which would reduce emissions by 35 % compared with the all-time high recorded in 2022. Scaling up investments in renewables, [15] improving energy efficiency, cutting methane emissions from fossil fuel supplies, and increasing electrification [16] with available technologies would deliver more than 80 % of the emissions reduction needed by 2030. The same technologies would propel the world economy towards NZE in 2050 if complemented by cutting-edge innovations, demand mitigation, the increased use of carbon capture, utilisation and storage (CCUS), hydrogen and bioenergy. By that time, the transformation of the electricity [17] and transport [18] sectors will be complete and progress towards net zero by heavy industry and the building sector will have greatly advanced. The rapid expansion of renewables, the rise of e-mobility and associated upgrades in infrastructure (electricity grids, charging stations) entail an explosion in demand for CRMs at the upstream end of the supply chain. With regard to the key minerals under consideration, total demand for lithium is forecast to be five and a half times larger by 2030 and ten times larger by 2050. Likewise, demand for cobalt, neodymium and nickel is expected to double in size by 2030 and to expand more moderately thereafter, as shown in the left-hand graph in Figure 2. The relative impact on copper demand will be smaller, increasing 40 % (50 %) in size by 2030 (2050), but this is mainly explained by its much bigger existing market share.

14 As part of its mandate to monitor developments in clean technologies, the IEA regularly publishes updates of the demand outlook for 35 CRMs under different scenarios. More recently, the EC has published its own foresight study, presenting a systematic and detailed analysis of complete supply chains (from raw and processed materials to components, assemblies, super-assemblies and systems) for 15 key technologies across five strategic sectors (renewable energy, electromobility, energy-intensive industry, digital, and aerospace/defense) (JRC, 2023). This included (for the first time) an outlook for materials demand until 2050 in the EU, in other economic regions, and across the entire world.

15 The share of electricity generation originating from renewable sources should rise from 30 % in 2022 to almost 60 % in 2030 under the NZE scenario. This requires a threefold rise in total renewables capacity, with a fivefold expansion of solar PV (IEA, 2023b).

16 The share of EVs in total car sales soars to 65 % by 2030 in the NZE scenario (IEA, 2023b).

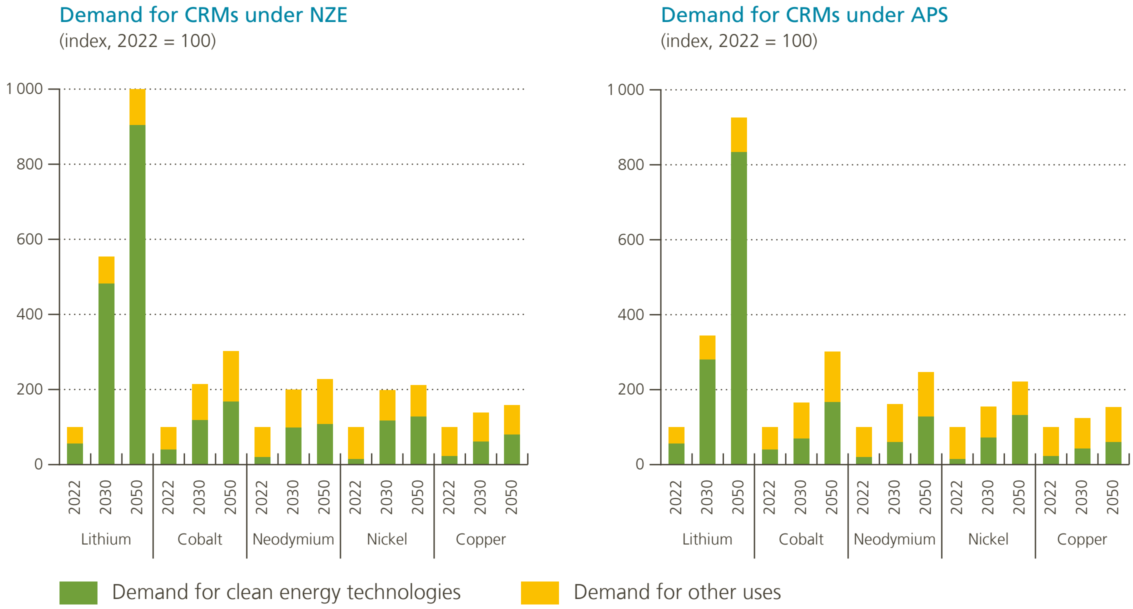
17 The share of renewables in global electricity generation should reach 90 % by 2050.This requires an eightfold rise in installed capacity compared to 2022 (IEA, 2023b).

18 After 2030, oil use in the transport sector decreases rapidly. Sales of transport equipment with an internal combustion engine will be completely phased out by 2050 (2035 for cars) and alternative fuels for ships and aircrafts will gradually replace fossil fuels.

The level of climate ambition and the exact trajectory of the transition strongly determine the pathways for CRM demand over time. The right-hand graph in Figure 2 presents the demand projections for CRMs under an alternative IEA scenario, the Announced Pledges Scenario (APS), which assumes that all announced long-term emission and energy objectives, including net zero commitments, will be met on time and in full, even where policies are not yet in place to deliver them. This scenario is characterised by inadequate policy ambition – all announced pledges taken together still fall short of reaching net zero emissions in the energy sector by 2050 – and gaps in policy implementation which imply less up-front expansion of clean energy technologies compared with the NZE scenario. This translates into more modest demand growth between 2022 and 2030 for all the CRMs focused on here. This dampening effect is particularly noticeable for lithium, for which demand is expected to grow "only" three and a half times by 2030, with some acceleration after 2030, meaning demand should still be ten times higher in 2050 compared to 2022. The increases in demand for cobalt, neodymium and nickel are also more drawn out over time, with volumes growing 1.5 to 1.6 times by 2030.

Figure 2

Clean energy technologies will be a major force driving demand growth for CRMs



Source: IEA.

Figure 2 illustrates that the demand outlook for CRMs is subject to substantial uncertainties, related to the pace at which clean energy technologies are deployed and the readiness of governments worldwide to move forward in a quick and coordinated manner. In a more geopolitically fractured world, the high degree of international coordination assumed by the NZE may be too optimistic (see Sections 2.3 and 3.2). In addition, even when national interests alone could arguably provide a strong incentive to accelerate climate mitigation efforts (Capital Economics, 2022), their implementation may be slowed down in a scenario in which geopolitical fragmentation leads to disruptions in CRM trade (Alvarez et al., 2023).

The possibility of disruptive innovation adds another layer of uncertainty to future demand for CRMs. For example, changes in EV battery chemistries over the past eight years or so have significantly reshaped demand for specific CRMs. LFP batteries have recently come to dominate the industry for EV batteries, partly displacing the earlier NMC types. Emerging battery technologies, such as sodium-ion batteries, have the potential to disrupt the EV battery market by replacing lithium and cobalt with less expensive and/or more abundant options, such as sodium. Alternative chemical compositions for battery anodes, replacing the graphite-based anodes that are currently dominant, are also under development. The battery market is likely to experience further shifts before eventually consolidating around a limited number of dominant materials and technologies (IRENA, 2023). Similarly, innovation in solar PV technology may prompt a shift away from silicon, while new techniques enabling the production of high-performing permanent magnets without neodymium or other REEs may gain popularity.

Several other factors are also likely to affect demand for CRMs, including the pace of change in terms of energy efficiency and consumer behaviour, exerting downward pressure on demand for energy products. These could include permanently lower room temperatures in homes and offices or a shift in consumer demand away from cars towards softer modes of mobility (e-bikes, public transport). Without such behavioural changes, demand for clean energy technologies will accelerate even more rapidly compared to the baseline. Demand pressures will further intensify as observed consumer preferences for large combustion engine cars are replicated in EV markets, where the average battery size of passenger EVs and the associated demand for necessary minerals are already being driven up.

2.2 Supply-side concentration and risks

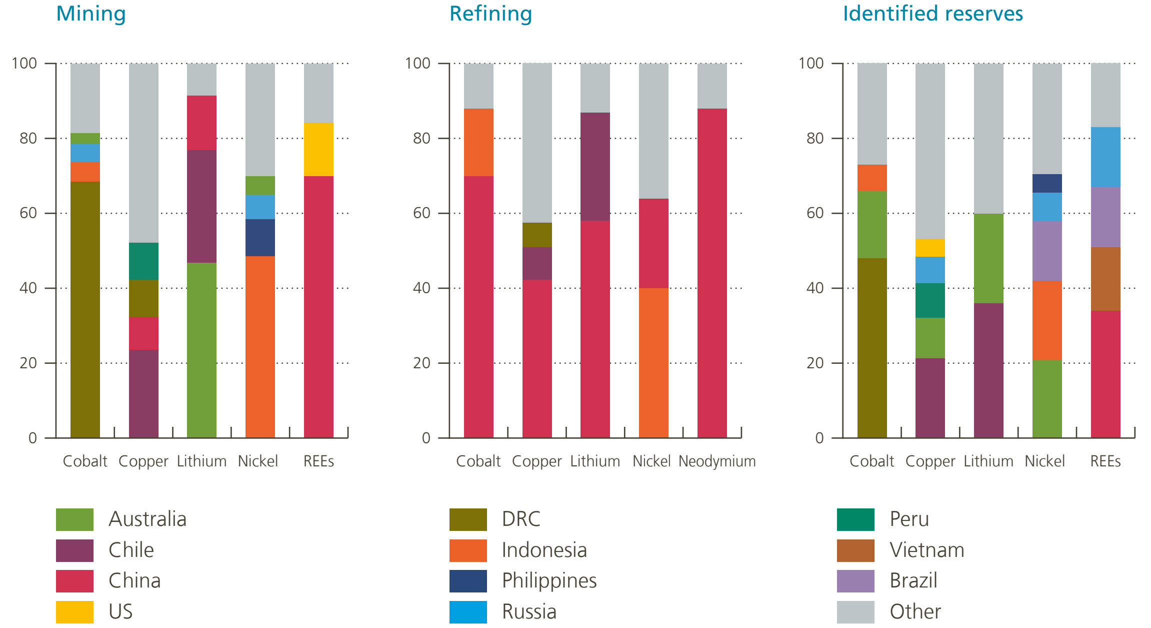
While copper is mined in several countries around the world, mining of the other CRMs discussed here is dominated by a few countries (see the left-hand graph in Figure 3). Nearly 70 % of all cobalt and REEs are mined in, respectively, the Democratic Republic of Congo (DRC) and China; 75 % of lithium is extracted in Australia and Chile; and about half of the global nickel supply is mined in Indonesia. This geographic concentration makes trade in CRMs indispensable and raises concerns that dominant countries may use their market position as leverage for other strategic priorities (see Section 2.3). It also makes CRM-dependent supply chains vulnerable to disruptions affecting producing countries, such as natural disasters, water stress, or social and political unrest. More specifically, about half of global copper and lithium production is concentrated in areas of high water stress; given that lithium mining requires substantial water resources, it could also trigger concomitant conflict (IEA, 2021). Nickel, cobalt and REEs, for their part, tend to be mined and processed in areas that are at greater risk of heavy rainfall and flooding (IRENA, 2023): in 2020, for example, a “once in a century” flood in the southwestern Chinese province of Sichuan shut down REE processing plants and damaged inventories. The race for minerals can contribute to or even exacerbate local armed conflict in multiple ways. In countries with weak governance and political instability, mineral extraction can be linked to local unrest, conflict and human rights abuses (Church and Crawford, 2018). For example, about 15 % of cobalt output in the DRC comes from artisanal mines, where labour and human rights abuses are rampant and unacceptable under due diligence regulations (Lazard, 2023). The proceeds from mining can also be exploited to sustain local conflicts, especially in areas with weak state-level authority and/or ethnic or religious tensions.

Beyond concerns over extraction, the fact that the refining of many CRMs is geographically concentrated in a single country, namely China, is even more worrisome, particularly against the backdrop of mounting tensions between the West and China (see the centre graph in Figure 3). China’s dominant position in the midstream supply chain operations for cobalt, lithium, copper, and REEs in particular, gives it a competitive edge in the manufacture of component parts such as battery anodes, cathodes and current collectors and, ultimately, in finished green-tech goods such as batteries and EVs. At the same time, it generates vulnerabilities in other countries’ clean-energy supply chains. The current situation is in part the outcome of decades-old decisions by Western firms to outsource mining and mineral processing, which often cause significant local environmental damage, to countries with lower environmental standards, China in particular (White, 2023). In addition, Chinese policies have long emphasised the importance of securing access to raw materials for the country’s own economic development (see Section 2.3). Recently announced investment plans do not suggest any significant changes in the concentration of refining operations over the coming years (IEA, 2023a).

Figure 3

Mining and refining of CRMs remains highly concentrated

(market share in %, 2022)



Sources: IRENA (2023), USGS (2023).

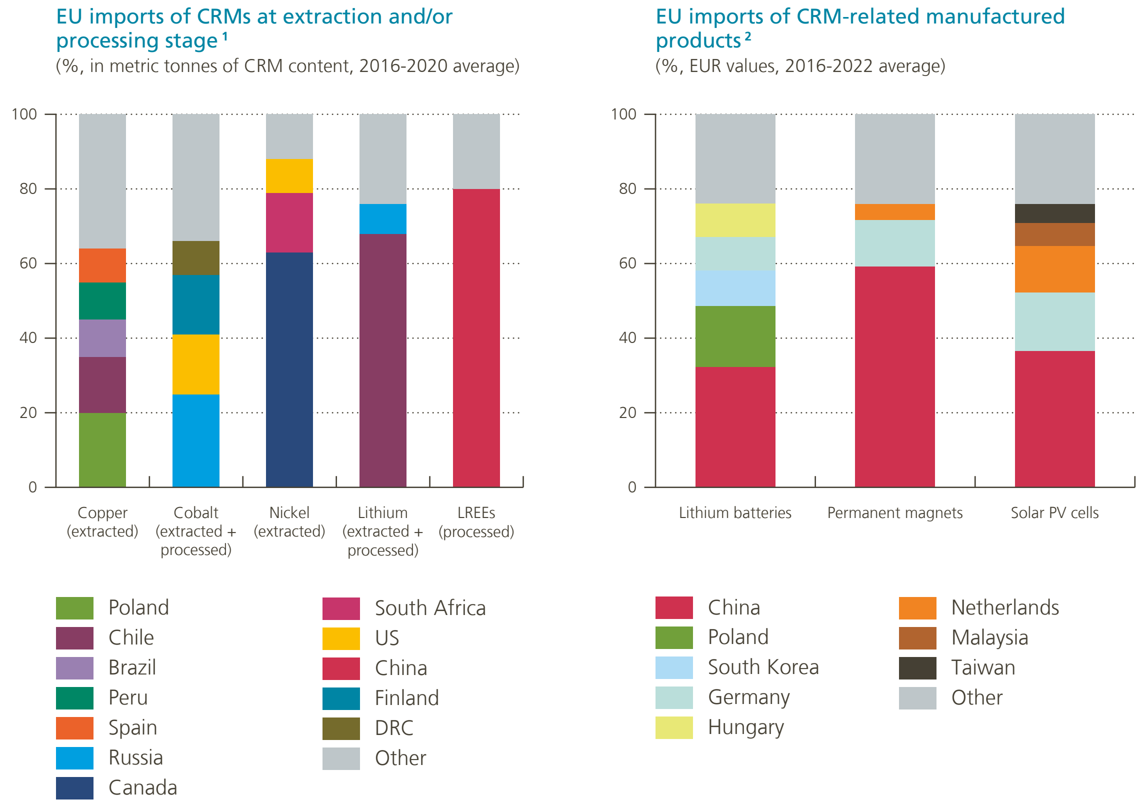
The US dominated the REE market until the late 1980s, at which time China emerged as a major player and gradually took control of the entire supply chain. The long-term strategic foresight[19] of the Chinese government, which created the right conditions to induce technology transfers from the West through joint ventures and to nurture a few large, highly competitive domestic firms greatly contributed to this outcome (Kefferpütz, 2010; Nakano, 2021). China currently accounts for 70 % of REE mining, 87 % of REE refining, and 92 % of permanent magnet production, while it holds only 34 % of known REE reserves. The risks associated with China's tight control over the REE value chain became clear in 2010 when China decreased its REE export quota by 37 % and banned exports to Japan for two months. This caused prices to spike amid the resultant supply disruption (IRENA, 2023). Until then, few countries with REE deposits had chosen to exploit them, as extraction was considered uneconomical (White, 2023). This changed in 2012, when the US resumed production at the Mounting Pass mine in California; however, due to environmental concerns, the extracted minerals were still shipped to China for further processing. To alleviate chokepoints in the upstream portion of the REE value chain, the US Pentagon has provided ample funding for the construction of new facilities for REE refining and the production of metals, alloys and magnets (Seligman, 2022). These facilities are scheduled to start operating in 2025. For its part, the EU has a facility to separate REEs for magnet production in Estonia, operated by Canada's Neo Performance Materials, and Belgian chemicals group Solvay has plans to start a similar production line at its site in La Rochelle, France (Financial Times, 2023). Europe's largest REE deposits were recently discovered in Kiruna, Swedish Lapland, and exploration is in its early stages.

19 China's recognition of the strategic value of minerals and their industrial applications dates back at least to the 7th National Five-Year Plan for Rare Earth Industry (1986–1990), which made it a priority to develop the research and production of advanced REE applications such as permanent magnets and lasers (Nakano, 2021).

The left-hand graph in Figure 4 quantifies the EU's direct import dependencies for the five key CRMs we consider, based on the latest available data collected as part of EU-funded research. EU imports of raw copper are relatively well diversified, partly thanks to intra-EU suppliers Poland and Spain. With respect to raw and processed cobalt, the EU's largest foreign dependency is vis-à-vis Russia, which accounted for about a quarter of total cobalt imports in 2016-2020. Canada dominated the raw nickel imports, and Chile the lithium imports of the EU. China accounted for no less than 80 % of the processed LREEs imported by the EU.[20]

Figure 4

Europe depends on a limited number of suppliers for CRMs and for key manufactured products incorporating CRMs



Sources: Eurostat, SCRREEN.

1 LREEs is the aggregate of lanthanum, neodymium, praseodymium and samarium (excluding cerium).

2 Based on a selection of six-digit Harmonised System codes following Rietveld et al. (2022). For solar PV cells, the shares are based on the 2016-2021 average.

More indirectly, the EU is exposed to CRMs that enter through the import of manufactured products. The value of those imports is multiple times greater than the value of directly imported CRMs (Le Mouel and Poitiers, 2023). As an example, the right-hand graph in Figure 4 shows the origins of imports of three manufactured goods that incorporate CRMs and are key for the green transition: lithium batteries, permanent magnets and solar PV cells. China is, by far, the most important source for each of those three products, particularly for permanent magnets that use LREEs.

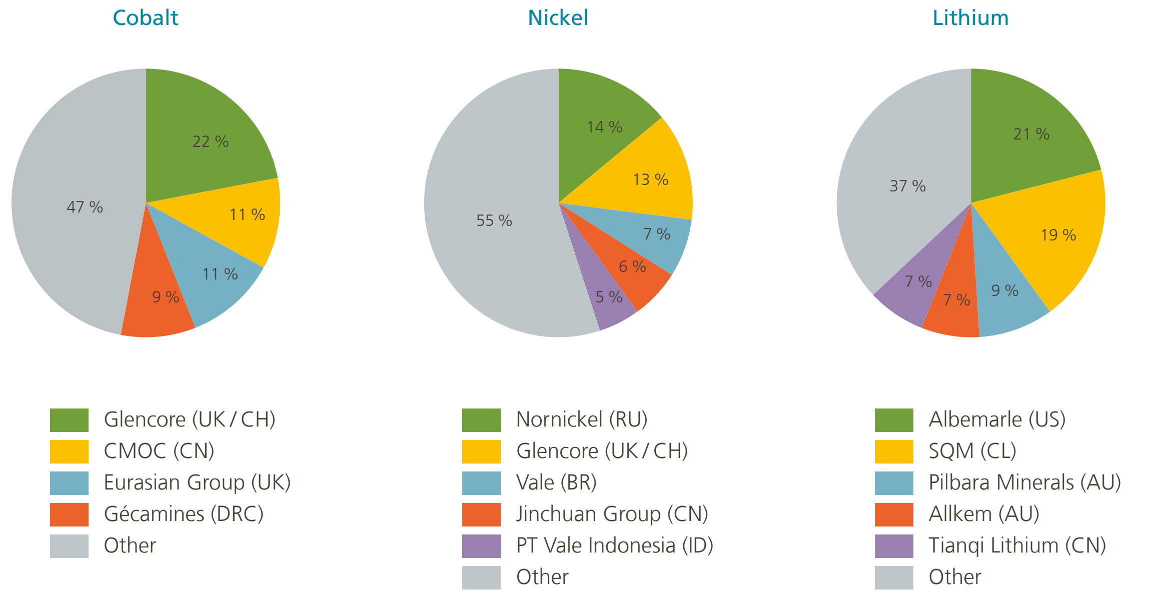
20 Beyond the five CRMs discussed here, China is also a highly dominant EU supplier for bismuth, gallium, magnesium and all HREEs (EC, 2023b; SCRREEN factsheets).

We can also look beyond geographical concentration to assess vulnerabilities in global supply chains involving CRMs by identifying the mining companies and their controlling shareholders. Due to the high capital-intensity of the mining industry, only a handful of large multinationals are typically active in the extraction of CRMs (Figure 5). These companies are often not incorporated in the countries in which their mining operations take place. For example, the DRC is the dominant country for cobalt production, but the leading producers are incorporated in the UK, Switzerland and China, with the Congolese mining company Gécamines only in fourth place, holding a market share of 9 % of global output.

Figure 5

A handful of large mining companies dominate the extraction of selected CRMs

(market share of output in %, 2021 ; country of incorporation between brackets)



Sources : IRENA (2023), Leruth et al. (2022).

The importance of China is once again visible when looking at where mining companies are incorporated : indeed, Chinese mining firms are involved in the extraction of every CRM discussed here. Using an index that measures the degree to which important shareholders can affect voting decisions, Leruth et al. (2022) show that thanks to an active policy of Chinese firms acquiring stakes[21] in firms in other countries, China controls some mining firms active in the extraction and processing of CRMs that are not incorporated in China. By contrast, the same study reveals that European control is mostly insignificant : Glencore is controlled by the South African Glasenberg family, while the Eurasian Group is controlled by the government of Kazakhstan.

The expected increase in CRM demand presents an opportunity to diversify future mining activities, given the wider global distribution of identified reserves[22] (right-hand graph in Figure 3). Brazil, Argentina, Vietnam and several African countries still have plenty of untapped reserves (USGS, 2023). There is also additional mining

21 Examples include Jinchuan's control of Metorex, a somewhat smaller company active in the extraction of cobalt and copper, and Chinalco's significant control of Rio Tinto, active in aluminium and copper mining. Tianqi Lithium is the second largest shareholder in SQM after the Pampa Group, which still holds a controlling stake (Leruth et al., 2022).

22 The USGS defines reserves as the portion of identified resources from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination.

potential on the European continent, albeit on a more limited scale. [23] The discovery earlier this year of vast lithium resources in the Indian Himalayas is significant and has already boosted India's ambitions to become a green industrial power. Nonetheless, it is still unclear how rapidly these resources could be turned into usable minerals and how they could benefit India's economy (Hendrix, 2023). In theory at least, currently known CRM resources appear to be adequate to satisfy rising demand from diversified locations.

A more serious concern is the time it takes to actually scale up CRM supplies. With only limited scope to expand output at existing mines, most of the increases in output required to keep up with rising demand will have to come from the development of greenfield mining projects. The IEA (2023b) estimates that to meet demand under the NZE scenario, 70 new average-sized mines will be needed by 2030 for lithium and nickel, 30 for cobalt, and a staggering 80 for copper. This presents a huge challenge, considering that the lead times for large new mining projects, from discovery to operation at full capacity, can be nearly 20 years (ETC, 2023). This timespan comprises the exploration and resource appraisal stages, the construction of the mine, and the ramping-up to full capacity, which take on average 12.5, 4.5 and 4 years, respectively. [24] It should be noted that exploration does not always result in a technically or economically feasible mining project. Moreover, feasible projects are often constrained by slow planning and permit delivery or can be delayed by local community concerns over environmental impacts, for example.

This relatively inelastic supply [25] in the short run contributes to the risk of demand-supply imbalances, which in turn drive the boom-bust cycles characteristic of many CRMs (Figure 6). Unlike traditional commodities such as oil, most CRMs are not widely traded on exchanges. Nickel, and even more so copper, are exceptions, with significant trading activity on the spot and futures markets, as both have a history of being used in a wider range of applications, such as electric wiring, construction and steelmaking. The increase in CRM prices during the COVID-19 pandemic can be partly explained by the shift in global demand from services to goods, in particular electronic equipment. In addition, supplies of raw materials crucially depend on international trade and transport, both of which were significantly disrupted during the pandemic (OECD, 2023). The subsequent economic recovery pushed commodity prices up across the board, often spreading to the prices of clean energy goods such as EV batteries and wind turbines. Supply disruptions from Russia's invasion of Ukraine, from February 2022 onwards, also contributed to CRM price volatility – with Russia a leading producer of top-grade nickel (IEA, 2023c). [26] The extreme rise in lithium [27] prices seen in 2022 was due to a severely undersupplied market faced with high demand. Lithium and other CRM prices declined in the first half of 2023 as a result of China's economic slowdown (which hit downstream demand) and destocking by battery component makers, as well as the entry of new supplies to the market (BMI, 2023).

23 Recent newcomers include Spain for cobalt, Sweden for lithium and REEs, the UK for lithium, Cyprus for copper, and Poland for nickel (IRENA, 2023).

24 Taken from IEA (2023c), lead time averages are based on the top 35 mining projects that came online between 2010 and 2019. See Manolo (2023) for similar estimates.

25 For example, Boer et al. (2021) estimate that a 10 % price rise increases the same-year output of copper by 3.5 %, nickel by 7.1 %, cobalt by 3.2 %, and lithium by 16.9 %. After twenty years, the same price shock raises the output of copper by 7.5 %, nickel by 13.0 %, cobalt by 8.6 %, and lithium by 25.5 %. The higher price elasticities for lithium can be explained by the much shorter lead times to open new production facilities, which can take up to seven years. This reflects with the different way of producing lithium: it is often extracted from mineral springs and brine, with salty water pumped from deep within the earth.

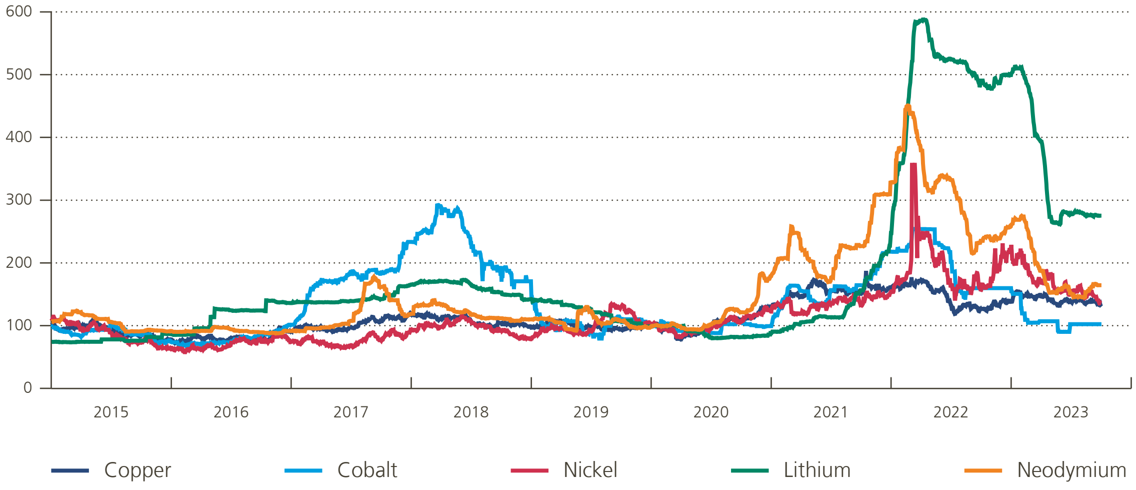
26 In March 2022, the price of nickel on the London Metal Exchange (LME) increased by more than 270% over the course of three trading days, due to a short squeeze, whereby large short positions around Chinese producer Tsingshan came under pressure. Trading in LME nickel contracts during Asian hours was suspended for more than a year.

27 The spot price of lithium is less relevant as the vast majority of lithium raw materials and chemicals are sold under bilateral long-term contracts between suppliers and end users, and the spot price is rarely used for large-scale negotiation or hedging (IEA, 2021).

Figure 6

CRM prices have been very volatile[1]

(USD per metric tonne ; index, January 2020 = 100)



Sources : Refinitiv, London Metal Exchange.

1 Prices for lithium and neodymium were originally quoted in RMB and have been converted to USD.

The price dynamics of cobalt and REEs are compounded by the fact that these minerals are by-products of other mined base metals : cobalt is typically a by-product of nickel and copper mining, while most REEs are by-products of iron ore mining. The production of these metals is therefore strongly influenced by the production of the base metals, which often generate more revenue. For example, investments in new cobalt projects are often linked more to market dynamics for copper than for cobalt. In other words, a higher cobalt price does not necessarily incentivise copper miners enough to produce more of it.

In the NZE scenario, the increase in demand is likely to be so fast that inflation-adjusted prices of copper, nickel, cobalt and lithium might remain at levels close to recent historical peaks up to 2040, although such price forecasts are subject to high uncertainty. This implies that the CRMs considered in this analysis are all potential bottlenecks for the energy transition (Boer et al., 2021). The price boom will induce a supply reaction, which is expected to reduce market tightness after 2030. High prospective prices and concerns about supply disruptions have prompted non-traditional players to make strategic investments in the extraction and processing of CRMs, with battery and EV producers increasingly pursuing vertical integration strategies. Following the example of their Chinese rivals, Volkswagen, Stellantis and Glencore teamed up in 2022 to purchase two private mines for battery CRMs in Brazil. General Motors invested USD 650 million in Lithium Americas, and Tesla plans to build a new lithium refinery in the United States. Chinese battery giant CATL won a tender to extract Bolivia’s largely untapped lithium reserves. Mining companies in turn are investing in innovative techniques that can extract more metals from low-grade ores. For example, miners in Indonesia are using so-called high-pressure acid leaching to turn low-grade nickel ores into material fit for EV batteries (The Economist, 2023b).

Secondary supply, namely from scrap and recycled materials, is a potential source that could contribute to reducing supply-side vulnerabilities by reducing the quantities of primary materials required. Recycling can also reduce the vulnerability of supply chains to disruptions if it is carried out close to demand centres (IEA, 2023c). Current end-of-life recycling rates vary greatly across materials, ranging from 60 % for copper and nickel to barely 1 % for lithium, graphite and neodymium. There is also the potential to increase secondary supplies once many of today’s clean energy technologies reach their end of life and when demand begins to flatten (ETC, 2023, Rizos et al., 2022). That being said, the retirement of clean energy technologies will not happen on a sufficiently large scale until the second half of the 2030s.

2.3 Major economies have devised CRM strategies

The unprecedented rise in (future) demand for CRMs, together with their relatively inelastic supply and the positions of dominant supplier countries and companies, have driven the issue of CRM supply chain security to the top of political agendas across the world. Some governments have expanded pre-existing CRM strategies to address the current challenges, while others have taken steps to develop them. The focus of such a strategy depends on whether a country is a net CRM exporter or importer. An additional concern in a world at risk of geopolitical fragmentation is China's ability to weaponise its dominant position in several CRM supply chains, which is shaping the strategic responses of other countries.

China's current dominant CRM position can be traced back to a tipping point in its economic development policies around the time of the 12th Five Year Plan (2011-2015). This plan highlighted seven strategic emerging industries to receive preferential support, including renewable energy and EVs (Meidan, 2020). This new direction was further elaborated on in the high-profile "Made in China (MIC) 2025" masterplan for the modernisation of the Chinese economy. Among the MIC 2025's main objectives is a determination to foster indigenous innovation and, insofar as possible, replace China's dependence on foreign core components, energy supplies and raw materials with domestic substitutes (Meidan, 2020; Buysse and Essers, 2019). China's resource policies have long been aligned with its industrial policies to achieve strategic national objectives. Hence, its focus has shifted from traditional industrial commodities to minerals identified as essential inputs for its strategic emerging industries.

The Chinese government has a long tradition of supporting the extraction of the CRMs the country has in abundance (including REEs, tungsten, silicon, natural graphite and lithium) by offering state-backed financing, promoting technological progress in mining, and sponsoring exploration. At the same time, it deploys industrial policies to push the domestic development of midstream and downstream sectors and has not shied away from the periodic use of export restrictions and duties to protect its infant industries. In October 2020, China passed an export-control law to restrict exports of controlled items (with no further specification), with the aim of protecting its interests and national security (Nakano, 2021). The Chinese government applied this new law in early June 2023 when it imposed licensing restrictions on exports of gallium and germanium (EIU, 2023). Both metals are used in digital technologies (including semiconductors) and in renewable energy industries. In October 2023 China also introduced export controls on graphite, another key (anode) material used in EV batteries. The measures were widely seen as retaliation against US restrictions on exports of sensitive chip technologies to China.

Where China lacks access to (domestic) resources, its government has pursued a "Going Out Strategy" since 2000 to secure the mineral supplies needed for its rapid industrialisation and urbanisation. Chinese firms are encouraged to take major positions in mineral supplies in other countries, mainly in Asia and Africa, assisted by a combination of state-directed investment and financing support and based on long-term strategic considerations. In addition, China's notably high tolerance for political and security risk and its ability to embed its firms in the development of local industries have not only enabled Chinese firms to gain footholds in complex natural resource markets but have also given them a competitive edge over their rivals (FP Analytics, 2019). For example, China's control over the cobalt supply chain is the result of Chinese acquisitions of mining operations in the DRC, facilitated by a minerals-for-infrastructure deal concluded between the governments of China and the DRC in 2007 (Gulley et al., 2019). As part of this deal, Chinese state-owned banks provided favourable infrastructure loans to the DRC government, purportedly in exchange for access to copper and cobalt mineral development rights. Other well-known cases of substantial Chinese overseas involvement in mining operations involve copper and cobalt in Zambia, lithium in Australia and South America, nickel in Indonesia,[28] and platinum in South Africa. Much of the extracted ores are shipped back to China for processing and refining. China's state-owned enterprises have also been able to take advantage of the country's low labour and energy costs and soft

28 Chinese investments in Indonesia are often touted as a model of Sino-Indonesian collaboration but they have also generated opposition at the local and national levels on numerous occasions, forcing the Chinese parties concerned to adapt to the rapidly shifting regulatory environment of their host country (Tritto, 2023).

budget constraints to build processing and refining capacities in China that far exceed the requirements of the domestic economy (Andrews-Speed, 2023). Since 2013, China's Belt and Road Initiative has facilitated Chinese foreign direct investment (FDI) related to CRMs by assigning the issue a high priority given the importance to the domestic development of strategic emerging industries.

A combination of deteriorating relations with China and rising demand for CRMs has led Western countries to take steps to reduce their reliance on China for these minerals. In 2010, US policymakers rekindled their interest in guaranteeing CRM supplies after China imposed an export embargo on REEs; the US Department of Energy duly issued its first Critical Materials Strategy at the end of that year. Alarmed about the US's continued heavy reliance on imports of CRMs, the Trump administration developed a Federal Strategy to Ensure Secure and Reliable Supply of Critical Minerals in 2019, which largely reflects the view that economic security equates to national security (Nakano, 2021). The strategy includes 24 policy goals under six major calls to action, alongside over 60 recommendations aimed at revitalising CRM production and processing operations in the US and alleviating vulnerabilities to supply disruptions. In addition to rebuilding domestic production, the strategy also acknowledges the importance of international cooperation.

With trade and technology tensions between the US and China showing no signs of abating, the security of CRM supply chains ranks highly on the agenda of the Biden administration and has led to a proliferation of initiatives. Shortly after his inauguration, President Biden mandated a review of vulnerabilities in domestic supply chains. In April 2022, he invoked the Defense Production Act to fund the mining, processing and recycling of lithium, nickel, cobalt, graphite and manganese in an effort to ensure sufficient mineral supplies for battery manufacturing (Castillo and Purdy, 2022). The landmark Inflation Reduction Act (IRA), which was signed into law in August 2022, contains many clean energy and green technology provisions, among which are generous tax credits and direct expenditure items linked to CRMs. More specifically, there are tax credits for manufacturers of clean technology products and components such as solar installations, wind turbines and batteries, and for producers of the associated CRMs – including high-grade polysilicon, aluminium, cobalt and graphite. The IRA also supports consumer purchases of EVs and hydrogen fuel cell vehicles, subject to conditions regarding the CRMs used in vehicle components. These include minimum thresholds for the share of CRMs extracted, processed or recycled in the US or sourced from countries with which the US has a free trade agreement. These thresholds are set to increase progressively from 40% to 80% by 2027 (Essers, 2023).

The governments of Australia and Canada – two industrialised countries rich in CRMs and close allies of the US – are similarly seeking to encourage investment in new mining and processing capacity by offering an enabling environment and financial support.[29] This is seen as necessary to meet rising CRM demand from their (friendly) trade partners. At the same time, these countries are also tightening up their scrutiny of foreign investments: in Australia, FDI in the mining sector is now subject to screening by the Foreign Investment Review Board, while the Canadian government has introduced a new national security review process for all FDI (UNCTAD, 2023). These policy decisions reflect concerns about national security, environmental sustainability, and local ownership of and control over natural resources.

Developing countries with abundant CRM endowments are pursuing a somewhat different policy direction from their developed-country counterparts, with strategies widely referred to under the broad banner of "resource nationalism". As the clean energy transition drives an unprecedented rise in demand for CRMs, these countries have a unique opportunity to transform their fortunes. Some countries are targeting the development of domestic capabilities either to process materials or use them in local manufacturing operations to raise the value added of their exports. This often involves state intervention, for example in the form of subsidies or restrictions on exports and foreign ownership, in order to support downstream domestic sectors. As discussed earlier, China has successfully applied such measures to onshore the global value chain for REEs. Following China's example, Indonesia introduced export bans on nickel in 2014, lowering domestic prices to the benefit of domestic

29 In 2021, the Australian government established the AUD 2 billion Critical Minerals Facility to support critical mineral projects with loans, loan guarantees, bonds and working capital support as a complement to commercial financing.

downstream users. Companies holding mining licenses were given a five-year grace period to set up local processing activities and Special Economic Zones were created to attract foreign capital for the development of downstream sectors (Tritto, 2023). The result is that Indonesia now has an extensive domestic smelting industry as well as battery plants and EV factories. This success has motivated the Indonesian government to extend this approach to other CRMs such as bauxite, the main aluminium ore (as of June 2023), and copper concentrate (from 2024). It has also inspired other countries to follow suit, with Zimbabwe and Namibia now banning exports of raw lithium (Hook et al., 2023). These practices could lead to increases in global market prices if exporters hold large market shares (OECD, 2023).

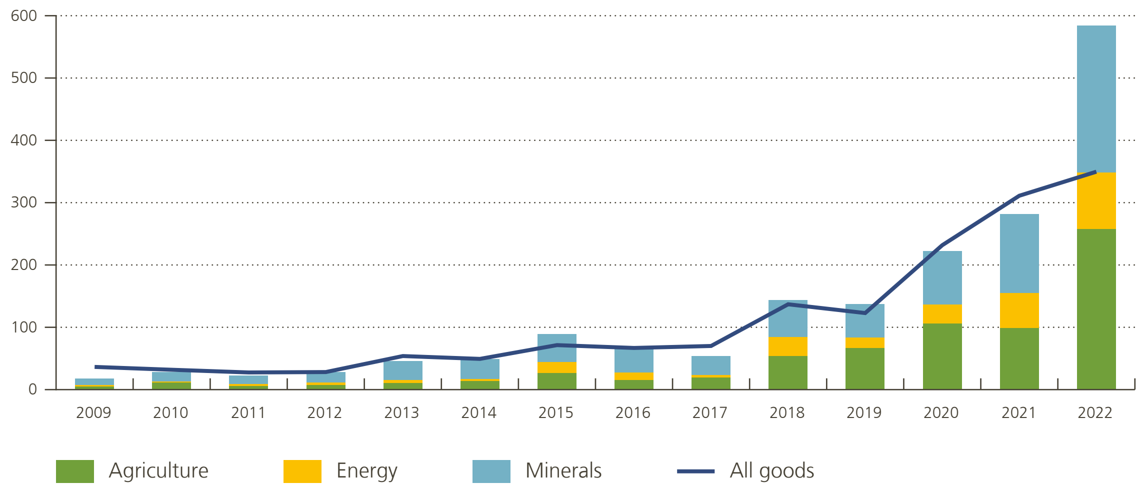
In addition to furthering the objective of supporting downstream industries, export restrictions in the form of export taxes are often used to raise tax revenue. This can be particularly attractive to countries that mainly depend on CRMs for their exports and/or have underdeveloped tax systems. Bolivia, Chile, Russia, South Africa, Namibia, Zambia, the DRC, Gabon, Senegal, Tunisia, China, India, Malaysia, and Lao PDR all levy taxes on the export of various CRMs (OECD, 2022). Royalties and taxes on the profits of mining companies are other sources of government revenue. The Philippines, Chile, and the DRC, for example, have recently introduced or raised such royalties (Lazard, 2023). These policy shifts occasionally have global implications: for example, supplies from the DRC's Tenke Fungurume copper and cobalt mine were brought to a standstill for several months in mid-2022 following a royalty payment dispute between the Chinese owner CMOC and its Congolese state-owned partner Gécamines. This disrupted 15 % of the global cobalt supply (White and Hook, 2023).

Export restrictions on CRMs are indeed becoming a growing concern. While not the only driving factor, developing countries' shifting CRM strategies have contributed to the rising number of new trade restrictions on commodities seen each year since 2018. This increase was initially fueled by US-China tensions and the COVID-19 pandemic; in 2022, Russia's invasion of Ukraine caused a further spike in new trade restrictions for commodities. In total, new trade restrictions on commodities in 2022 were about six times greater than the 2016-2019 average; in comparison, restrictions on overall trade increased by a factor of 3.5 (Figure 7).

Figure 7

Trade restrictions on CRMs have risen steadily since 2018 [1]

(number of new discriminatory trade restrictions by sector; index, 2016-2019 = 100)



Sources: Global Trade Alert, IMF (2023).

1 Policy interventions are adjusted for reporting lags. Liberalising interventions are excluded from the calculations.

The OECD, which has compiled an Inventory of Export Restrictions on Industrial Raw Materials covering the period 2009-2020, comes to a similar conclusion. Export restrictions take multiple forms, including export quotas, export taxes, obligatory minimum export prices, and licensing requirements, with taxes the most frequently used measure. The incidence of such restrictions grew more than fivefold over the period under consideration (OECD, 2023). In recent years, about 10 % of global CRM exports, in value terms, faced at least one export restriction. However, for several minerals, such as cobalt, precious metal ores and concentrates, tin, palladium and REEs, the share exceeded 30 % in 2020 (and 70 % in the case of cobalt). Almost one fifth of new restrictions between 2009 and 2020 were attributed to China (OECD, 2023).

Finally, some governments have also been tempted to retake control over their natural resource wealth through revisions of ownership and mining concessions. Chile's government announced its intention to nationalise lithium mining in April 2023, raising concerns among industry groups (Lazard, 2023). In April 2022, Mexico officially nationalised its lithium industry, giving the state exclusive rights over exploration, extraction and use (IRENA, 2023). In 2019 and 2021, the Zambian government took over the Copperbelt's largest copper mines at a high cost, a decision that the current government would like to reverse (Cotterill, 2023). Finally, China announced the establishment of the China Rare Earth Group in 2022, creating the world's largest producer of strategic REEs and reinforcing the central government's direct control (JRC, 2023). The above examples illustrate that private investment in CRM extraction is subject to considerable political risk, which could lead to a reduction in such investments.

3. An ambitious European CRM strategy: can it deliver?

3.1 The European Commission's CRM policy initiatives

Concerns about Europe's heavy dependence on external supplies of raw materials go back to at least the 1970s (Righetti and Rizos, 2023), but the Commission's first integrated CRM strategy, the Raw Material Initiative, saw the light of day only in 2008, in the wake of a huge commodity price boom and subsequent bust. The initiative had three key objectives: to ensure fair, undistorted access to raw materials from international markets; to foster a sustainable supply of raw materials from European sources; and to reduce European consumption of primary raw materials by increasing resource efficiency and recycling (EC, 2008). This eventually led to the Commission's first official list of CRMs (see Section 1) and the creation of a European innovation partnership (EIP) on raw materials, as well as an innovation community within the European Institute of Innovation and Technology (EIT), EIT RawMaterials, which brings together stakeholders from industry, public services, and academia for investment, research and education purposes.

Major supply chain disruptions and rising geopolitical tensions in recent years have focused policymakers' attention on resilience and have given a boost to Europe's CRM strategy. In September 2020, the Commission launched its Action Plan on CRMs, which is framed in terms of supporting the green and digital transitions (thereby complementing the European Green Deal and New Industrial Strategy) and contributing to the EU's open strategic autonomy (EC, 2020). The Action Plan outlined ten specific actions, the first of which was the establishment of a new, industry-driven European Raw Materials Alliance (ERMA), managed by EIT RawMaterials. ERMA was tasked with work along two main lines: firstly, holding value chain-specific consultations to identify and address specific CRM bottlenecks and, secondly, the development of financing strategies for selected CRM investment projects, including linking investors and investees under the Raw Materials Investment Platform. Its initial focus was on two value chains in particular: REE magnets and motors, on the one hand, and energy storage and conversion (including batteries and fuel cells), on the other. The Action Plan also included the promotion of CRM research under Horizon Europe and other programmes; the deployment of remote sensing for resource exploration through the EU's Copernicus Earth observation programme, to uncover new, potential CRM sites; the identification of CRM mining and processing projects that could be made operational by 2025; the mapping of recyclable EU CRM stocks and waste; the development of international partnerships on CRMs; and the promotion of codes of responsibility and sustainable financing criteria for CRM projects.

In September 2022, the annual State of the European Union address delivered by Commission President Ursula von der Leyen was heavily marked by Russia's invasion of Ukraine. In her speech, von der Leyen announced a European Critical Raw Materials Act that would prevent Europe from "falling into the same dependency as with oil and gas", with explicit reference to China's dominance in the global CRM processing business. The Commission's proposal for a Critical Raw Materials Act (CRMA) was spelled out in March 2023, when it was presented as part of the Green Deal Industrial Plan.[30] As of early November 2023, the CRMA was still subject to negotiations between the European Parliament and the Council.

The CRMA proposal sets (non-binding) EU-level capacity benchmarks for the extraction, processing and recycling of each SRM by 2030 – originally at minimum levels of 10 %, 40 % and 15 % of the EU's annual consumption, respectively (EC, 2023a).[31] In addition, the CRMA introduces a diversification benchmark: by 2030, no more than 65 % of the EU's annual consumption of each SRM, at any relevant stage of processing, should be sourced from a single non-EU country. This last benchmark has been dubbed the "China clause" for obvious reasons. In June 2023, the Council advised to increase the proposed targets for EU processing capacity to 50 % and for recycling to 20 % and to add aluminium (plus its primary ore bauxite) to the list of SRMs (see the annexed table). In September 2023, the European Parliament in turn specified that to reach the objective of raising processing capacity to 50 %, up to 20 % of the EU's new capacity might need to be developed in partner emerging markets or developing countries outside the EU. Moreover, the Parliament redefined the recycling target from a minimum percentage of domestic consumption to at least 45 % of each SRM contained in the EU's own waste, where feasible. The Commission was also asked to submit, at a later stage, a list of strategic *secondary* raw materials, such as ferrous scrap.

To achieve greater local extraction, processing and recycling capacity, the CRMA proposes a regulatory framework for the selection and implementation of "strategic projects" that meet criteria of public interest, feasibility and sustainability – to be determined by a new European Critical Raw Materials Board composed of member state and Commission representatives. Such projects would be eligible for streamlined member state-level procedures for the issuance of permits (which remains a national power), including a designated contact point and a maximum duration (initially set at 12 to 24 months, excluding environmental impact assessments and public consultations). Strategic projects would also benefit from support by the new board in gaining access to finance. In this respect, the European Parliament urged the Commission to consider the possibility of setting up a new EU-level fund devoted to SRMs, using revolving financial instruments or a reprioritisation of existing budget items under the EU's Multiannual Financial Framework. Furthermore, the CRMA asks member states to draw up national programmes for CRM exploration and for the shift to an increasingly circular economy for CRMs. It includes provisions for the enhanced monitoring of CRM supply chains and suggests looking into the coordination of strategic CRM stocks and joint EU purchasing.

Lastly, the draft CRMA has a short chapter on international engagement, which focuses on establishing "strategic partnerships" with third countries (i.e. commitments to increase cooperation via specific actions of mutual interest) that could contribute to increasing the security of the EU's CRM supplies while also respecting the rule of law, human and labour rights, local communities, and the environment. The chapter argues that,

30 The Green Deal Industrial Plan aims to provide a more supportive environment for Europe's clean energy industries. Alongside the CRMA, the Green Deal Industrial Plan encompasses the Net-Zero Industry Act and the Temporary Crisis and Transition Framework for state aid. The former sets a target for the domestic manufacturing capacity of net-zero technologies such as solar energy, wind energy and EV batteries to meet at least 40 % of the EU's annual deployment needs by 2030, while the latter provides extra flexibility for EU member state aid for the renewable energy roll-out. These initiatives can be seen, at least partly, as Europe's response to the clean energy provisions under the American Inflation Reduction Act (IRA) (Section 2.3). For more details, see Essers (2023) and the references therein.

31 See Section 1 for the distinction between CRMs and SRMs.

where possible, synergies should be sought with the Global Gateway, the EU's worldwide infrastructure investment programme and response to the Chinese Belt and Road Initiative. The Commission's communication around the CRMA also mentions setting up "a Critical Raw Materials Club for all like-minded countries willing to strengthen global supply chains". It is not yet clear what form such a Club would take.

Since the 2020 Action Plan was published, the EU has signed strategic partnership agreements on CRMs with Canada, Ukraine, Kazakhstan, Namibia, Argentina, and Chile. In July 2023, EU member states provided the Commission with a mandate to negotiate a CRM agreement with the US.[32] In parallel, the EU has concluded free trade agreements (FTAs) that include provisions on (critical) raw materials with New Zealand (awaiting ratification) and Chile (awaiting legal verification) and has been negotiating with Australia, India and Indonesia. Since June 2022, the EU (represented by the Commission) has also been a member of the Minerals Security Partnership (MSP), together with Finland, France, Germany, Italy, Sweden, and eight non-EU partners (Australia, Canada, India, Japan, Norway, South Korea, the UK and the US). Members of the MSP work to reinforce information sharing and promote overseas CRM mining, refining and recycling projects that meet high environmental, social and governance (ESG) standards.

3.2 Practical hurdles and potential ways forward

The previous section makes it clear that addressing the risks to CRM supply chains is now a firmly established priority for the EU. However, it remains debatable whether current and proposed policies will be sufficient to ensure steady, shock-proof access to CRMs for Europe.

The Commission's monitoring of Europe's CRM-related vulnerabilities, including the creation of its own lists of CRMs and SRMs based on indicators of economic importance, supply risks and demand projections for strategic technologies (see Section 1), has improved greatly in recent years. Data gathering efforts by the USGS, OECD and others have undoubtedly been helpful in this regard. That notwithstanding, there appears to be room for further improvement. Rietveld et al. (2022) find that the Commission's criticality assessment methodology is relatively robust to changes to the underlying data but could benefit from a wider scope, by including, for example, additional quantitative (sub)indicators such as price volatility, the geopolitical affinity between the EU and CRM suppliers, the size of known CRM reserves, and future (near-term) demand under differing scenarios.

Understanding the full extent of the EU's exposure to potential disruptions to CRM production (whether policy-induced or not) requires a comprehensive overview of the entire supply chain – from raw material extraction to the production of finished products and the recycling thereof (Le Mouel and Poitiers, 2023). Indeed, many CRMs enter the EU market embedded within intermediate or finished goods. The EU is also a strong net exporter of finished products, such as wind turbines, which use imported CRM-rich components. While the Commission already performs detailed qualitative assessments of selected supply chains (JRC, 2023), a broader, more systematic mapping of direct and indirect CRM dependencies (through the EU's trading partners) would be highly valuable to policymakers. This requires further (preferably internationally coordinated) efforts in constructing granular input-output databases (Rietveld et al., 2022).

Several experts believe it is insufficiently clear how the EU plans to achieve its very ambitious domestic CRM capacity targets. For one, there appear to be many practical obstacles to (re)building a European mining and refining business.[33]

32 One of the EU's main objectives for this CRM agreement is to obtain a status equivalent to US FTA partners for the purpose of the clean vehicle credit under the US IRA (see Section 2.3; Essers, 2023).

33 According to a senior EU diplomat quoted in the Financial Times (2023), "it is too late for Europe to completely shrug off its dependency on China for rare earths and other critical minerals".

First of all, even if recent discoveries in the Swedish Kiruna and elsewhere seem to suggest that European deposits of several CRMs have been underestimated and could theoretically meet a non-negligible share of EU demand, a reliable full-scale assessment of the European continent's geological potential is still largely missing (Righetti and Rizos, 2023). Deep-sea mining of nodules containing copper, nickel, cobalt and other CRMs could add to Europe's reserves but is still mostly experimental (The Economist, 2023a).

Aside from the availability of deposits, a core question for re-shoring CRM extraction and refining is to what extent, and within which timeframe, European mining potential can be realistically converted into actual production and further processing. As indicated before, mining projects tend to have long lead times and, in this respect, Europe is no exception. On the contrary, besides the issuance of permits and other bureaucratic procedures that the CRMA is trying to address, European mining projects have often been delayed, or even blocked altogether, by challenges on various social, health and environmental grounds (Mononen et al., 2020; Righetti and Rizos, 2023). Obviously, Europe's relatively high population density does not help efforts to advance mining operations. For example, lithium extraction in places such as Barroso, Portugal has faced protests from local communities and environmentalists who express concerns about the impact on traditional livelihoods and water management, among other issues. In Kiruna, the expansion of REE mining is said to risk further displacement of the indigenous Sámi people. Deep-sea mining faces opposition even from within the Commission, the European Parliament, and from several member states, due to concerns about marine ecosystems. Overcoming such opposition demands greater understanding of its root causes through engagement with local communities, as well as investing in clear communication, public mediation, and conflict resolution (Mononen et al., 2020).

The relative cost of CRM-related operations in Europe, compared with third countries, is another challenge to the development of domestic supply chains. European extraction of CRMs may only make sense, both politically and economically, if some of the further processing of those materials can also be done locally (in the near term). Re-shoring multiple segments of CRM supply chains requires access to a specialised skills base at every stage, which is not readily available in Europe, as well as large amounts of longer-term risk capital (Findeisen and Wernert, 2023). Building a European Capital Markets Union would facilitate the mobilisation of private capital. De-risking through public investment and guarantees is also likely to be needed. Whereas the deepening of domestic CRM supply chains is arguably a European public good, not all member states may be able to undertake the necessary investments. The location of new CRM mining and refining projects in Europe should be guided by where they can be executed in a cost-effective manner and where they would most contribute to a European supply chain, rather than by member states' financial and administrative capacities (Findeisen and Wernert, 2023). Hence, in the area of CRMs, it seems preferable to look for EU-level funding, rather than relying on relaxing state aid rules, for example. However, finding new money to support common EU goals has proven difficult in recent years. Europe's relatively high energy costs are another impediment to energy-intensive processes such as CRM mining, refining, and recycling.

The insistence of European institutions on shifting to a circular CRM economy and on end-of-life CRM recycling is laudable, both from an environmental perspective and as a potential alternative channel to gain access to raw inputs. Nevertheless, policymakers will need to be realistic about the significant differences in the technical and economic feasibility of recycling individual CRMs and the fact that the number of products containing CRMs that will reach their end-of-life in the near term will be small compared with total CRM demand (see Section 2.2). That being said, for some CRMs, the time horizon for scaling up EU recycling capacity to the point where it could provide a meaningful contribution may be shorter than for the expansion of mining production (Righetti and Rizos, 2023).[34]

34 In order to promote recycling and increase its feedstock, the European recycling industry, supported by environmentalists, has asked the European institutions to restrict exports of "black mass", i.e. shredded material from end-of-life batteries which is currently often shipped to Asia. This could be achieved by classifying black mass as hazardous waste (Simon, 2023).

Europe has also put a strong emphasis on fundamental innovation, which plays a key role in delivering alternative green and digital technologies that use fewer CRMs; however, developing the capacity to scale up and roll out individual technologies remains key to successfully navigating the green and digital transitions. This is an area where countries such as China appear to have a competitive edge.

In any case, it seems inconceivable that Europe will resort entirely to domestic sourcing of CRMs. Even if this were possible, it would make European CRM supply highly susceptible to local shocks and therefore less resilient overall (Rietveld et al., 2022). Any successful CRM strategy will have to be international.[35]

Unfortunately, the CRMA proposal focuses on domestic regulation and is relatively vague on how to address the international dimension of Europe's CRM vulnerabilities (Le Mouel and Poitiers, 2023). Furthermore, there is some tension between the willingness to remain open and cooperative – which EU and national officials have expressed on many occasions – and the CRMA's import-substituting targets (Packroff, 2023). The European Parliament's amendment to the effect that part of the EU's new processing capacity may be developed under strategic partnerships with foreign countries, as long as projects respect international standards and conventions on the environment and human rights, is a positive step. Friend-shoring to like-minded partner countries has an advantage over re-shoring in that it allows for better international specialisation, in line with respective comparative advantages. A drawback is that geopolitical alliances may be issue-dependent and can shift over time (Buysse and Essers, 2022; Rietveld et al., 2022).

It remains to be seen how the Commission will wield the various tools for international engagement on CRMs at its disposal. FTAs, such as that negotiated with Chile, constitute a comprehensive and relatively watertight instrument. They not only contribute to creating a level playing field for EU firms seeking to invest in CRM projects abroad (and vice versa) but also provide common ground on environmental and social issues and a means for dispute resolution. However, their comprehensive nature and rigid structure (dictated by WTO rules) make FTAs a cumbersome and time-consuming policy option to gain better access to a particular CRM from a specific partner. In addition, FTAs may provide limited incentives to diversify CRM imports. The EU already applies very low tariffs on CRMs, leaving little room to offer partner countries further tariff reductions (Rietveld et al., 2022; Le Mouel and Poitiers, 2023). Bilateral CRM-only strategic partnership agreements provide more flexibility than full-scale FTAs to work together towards removing specific supply chain frictions but tend to be less binding. For example, a 2012 partnership on REEs with Greenland did not result in significant new supplies (Findeisen and Wernert, 2023).

Diversification of CRM supplies and related products is arguably best served by coordinated investments. Developing countries may perceive European investments in their commodity sectors as an encroachment on their sovereignty over natural resources, perhaps even as a form of wealth extraction reminiscent of colonialism (Crochet and Zhou, 2023). The EU could step up its development assistance for infrastructure projects through the Global Gateway initiative, in order to support the development of domestic mining and refining industries in CRM-rich countries, and create local value-added, with due attention paid to environmental and social criteria. Increased overseas investment and aid would help not only to diversify the supply of CRMs directly imported by EU industry, but also create deeper and more competitive markets for foreign companies that supply intermediate goods to EU industries (Rietveld et al., 2022). Such an approach would likely require additional financial firepower for the Global Gateway. The CRMA proposal does not specify where this money should come from. Like-minded partner countries, which are on similar decarbonisation paths, should attempt to coordinate and share the burden of investing in global CRM supply chains, with the ultimate goal of creating liquid and diversified world markets for CRMs where these do not yet exist (Le Mouel and Poitiers, 2023).

35 The need for strengthened international collaboration was acknowledged in the G7's April 2023 Five-Point Plan for Critical Minerals Security and at the first IEA Critical Minerals and Clean Energy Summit in September 2023, which was attended by representatives of government, business and civil society from nearly 50 countries.

Coordinated investment is not the only form international cooperation on CRMs can take. The idea of a Critical Raw Materials Club, raised by the Commission, could be developed into a multilateral arrangement through which member countries commit to supporting each other were CRM supplies to be disrupted (Findeisen and Wernert, 2023). The design, monitoring and enforcement of transparency, environmental and social standards for CRM mining and refining is another natural area for cooperation. The EU seems to be well placed to lead international efforts here, given the Commission's ongoing work on corporate due diligence rules.[36] In addition, the existing patchwork of bilateral and plurilateral initiatives on CRMs, which stretches far beyond the arrangements described in this article, could benefit from greater coherence and consolidation (IRENA, 2023). Ideally, partnerships would extend beyond just CRMs to global supply chains of green technologies more broadly, involving different advanced economy and developing country members that are now overly dependent on China. Each member would contribute in line with its comparative advantage, be it in CRM extraction, refining, green tech manufacturing or even innovation. The aim of such green tech partnerships would be to supplement, rather than to replace, the China-dominated supply chains, since both may be needed for global decarbonisation efforts, including in China itself (Garcia-Herrero et al., 2023).

Of course, the EU is not rendered immune to intensifying competition over access to CRMs by cooperation commitments. The proliferation of (green and other) industrial policy strategies in major CRM-seeking economies puts them inherently in competition with one another and will remain a source of tension (Crochet and Zhou, 2023). Even like-mindedness does not prevent conflicts, as exhibited by frequent trade skirmishes among G7 countries (Rietveld et al., 2022). The EU will have to continue to rely on trade defence instruments such as anti-dumping and anti-subsidy duties to push back against unfair, WTO-inconsistent practices in the trade in CRMs or related products. Moreover, in the past the EU has brought several WTO cases against China for the country's export restrictions on CRMs (including bauxite, cobalt, copper, magnesium, tungsten and REEs) (Buysse and Essers, 2019). While settling these cases took time, due in part to appeals by China, the WTO proceedings were ultimately successful and, until very recently, appeared to have disincentivised China from reimposing such restrictions. In 2019, the EU also challenged Indonesia's export restrictions and performance requirements for nickel. The WTO panel sided with the EU, but Indonesia appealed the panel's decision into the void (meaning the dispute remains pending and Indonesia does not yet need to implement the decision), as the WTO's Appellate Body continues to be non-operational (Crochet and Zhou, 2023). Resolving the Appellate Body crisis, or at least expanding country membership under a temporary alternative, the Multiparty Interim Appeal Arbitration Arrangement, would avoid such deadlocks in the future.[37]

4. Conclusion

Like many other countries and regions, the EU maintains lists of raw materials considered critical or strategic (CRMs or SRMs) based on their economic importance to European industries, their relevance to the green and digital transitions, and their sensitivity to supply risks. In this article, we have focused on copper, cobalt, nickel, lithium and rare earths, all of which are all essential inputs to clean energy technologies – ranging from EV batteries and motors, to wind turbines and electric wiring. Demand for these and other CRMs is projected to grow rapidly, although forecasts of global needs are subject to many uncertainties. On the supply side, the extraction of CRMs is often dominated by a few countries and/or a few large mining companies. The refining of many CRMs is, in turn, even more intensely concentrated and often dominated by a single country, namely China. In the short run at least, CRM supplies are deemed relatively inelastic, contributing to high price volatility.

36 In February 2022, the Commission proposed the Corporate Sustainability Due Diligence Directive (CSDDD) (EC, 2022). The CSDDD, which is now being negotiated in the European Parliament and the Council, would require large EU companies and businesses operating in the EU to identify, prevent and mitigate adverse impacts on human rights and the environment along their supply chains.

37 For a short primer on the WTO Appellate Body crisis, see Titievskaia (2021).

The Commission's recent proposal for a Critical Raw Materials Act (CRMA) seeks to ensure secure and affordable access to CRMs for Europe. Increased attention to CRM access seems overdue in an environment characterised by strategic competition for resources, where all major players have devised their own strategies. The CRMA sets EU-level capacity benchmarks for the extraction, processing and recycling of CRMs by 2030 – goals Europe intends to meet through the selection of strategic projects for which permit issuance procedures are streamlined and financing facilitated. Meanwhile, the Commission has stepped up its efforts in terms of CRM monitoring, exploration and innovation research. There is certainly room for improvement in each of these areas, for example by developing a more granular understanding of indirect dependencies through products embedding CRMs and through foreign countries and companies, beyond the first tier of trade partners.

The overall feasibility and ultimate effectiveness of Europe's ambitious CRM-related policies remain unclear. Re-shoring (large parts of) global CRM extraction and processing to Europe would be extremely challenging: this would take a substantial amount of time and is bound to be very costly, even if large CRM deposits were to continue being discovered on the European continent. Europe may not be able to afford the patience and funds required. In addition, in building domestic capacity, there is a risk of large resources being wasted if, in the meantime, innovation reduces the need for particular CRMs.

Hence, any successful European CRM strategy must have an international dimension. In line with the open strategic autonomy mantra, it could be argued that the EU needs to remain open and cooperative without being naïve. This is where the Commission and other institutions may wish to develop a clearer approach. The EU could further specify how it intends to use the various instruments at its disposal to achieve international engagement on CRMs. Strategic partnership agreements with CRM producers will need to be backed by substantial amounts of financial support, channelled to infrastructure projects through the Global Gateway and/or other initiatives. Moreover, the EU will have to be sensitive to the domestic ambitions of producer countries, in terms, for example, of boosting local value added. Wherever possible, synergies should be sought with like-minded countries (including other net CRM importers) in shouldering the financial burden of investing in global CRM supply chains and in setting common transparency, environmental and social standards for CRM businesses. For the medium to longer term, it makes sense to conclude more comprehensive bilateral free trade agreements, which include chapters on CRMs, and to restore the WTO's multilateral dispute settlement architecture, since new CRM-related trade conflicts are likely to emerge.

Annex

List of raw materials screened under the EU’s 2023 criticality assessment and comparison with similar US and Chinese lists

Individual materials		
Aggregates	**Helium**	Potash
Aluminium/Bauxite	Hydrogen	Rhenium
Antimony	Indium	**Scandium**
Arsenic	Iron Ore	Selenium
Baryte	Krypton	Sulphur
Bentonite	Lead	Silica sand
Beryllium	Limestone	***Silicon metal***
Bismuth	Gold	Silver
Boron	Gypsum	**Strontium**
Cadmium	***Lithium***	Talc
Chromium	Magnesite	**Tantalum**
Kaolin clay	***Magnesium***	Tellurium
Cobalt	***Manganese***	Tin
Coking coal	Molybdenum	Titanium
Copper	***Natural graphite***	***Titanium metal***
Diatomite	Neon	***Tungsten***
Feldspar	***Nickel***	**Vanadium**
Fluorspar	**Niobium**	Xenon
Gallium	Perlite	Zinc
Germanium	**Phosphorus**	Zirconium
Hafnium	**Phosphate rock**	
Platinum group metals (PGMs)		
Iridium	***Platinum***	***Ruthenium***
Palladium	***Rhodium***	
Rare earth elements (REEs)		
Light rare earth elements (LREEs)	Heavy rare earth elements (HREEs)	
Cerium	***Dysprosium***	**Lutetium**
Lanthanum	**Erbium**	***Terbium***
Neodymium	**Europium**	**Thulium**
Praseodymium	***Gadolinium***	**Ytterbium**
Samarium	**Holmium**	**Yttrium**
Biotic materials		
Natural rubber	Natural cork	Roundwood
Sapele wood	Natural Teak wood	
Other materials not screened by the EU		
Cesium	Rubidium	Silicon carbide
Electrical steel		

Bold	Listed as a critical raw material by the EU in 2023
Italic	Listed as a strategic raw material by the EU in 2023
	Listed as a critical material by the US in 2022/2023
	Listed as a strategic mineral by China in 2016
	Listed by the US and China

Sources: Table drawn up by the authors based on EC (2023a, 2023b), USGS (2022), US DOE (2023), IRENA (2023) and IEA.

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Conventional signs

%	per cent
EUR	euro
et al.	*et alia* (and others)
i.e.	*id est* (that is)
RMB	Chinese renminbi
USD	American dollar
v	versus

List of abbreviations

Countries or regions

EU	European Union
CH	Switzerland
UK	United Kingdom
US	United States
AU	Australia
BR	Brazil
CN	China
CL	Chile
DRC	Democratic Republic of Congo
ID	Indonesia
RU	Russia

Abbreviations

APS	Announced pledges scenario
BMI	Benchmark Mineral Intelligence
CRM	Critical raw material
CRMA	Critical Raw Materials Act
CSDDD	Corporate Sustainability Due Diligence Directive
EC	European Commission
ESCB IRC	International Relations Committee of the European System of Central Banks
EIP	European innovation partnership
EIT	European Institute of Innovation and Technology
EIU	Economist Intelligence Unit
ETC	Energy Transitions Committee
EV	Electric vehicle
FDI	Foreign direct investment
FTA	Free trade agreement
IEA	International Energy Agency
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
IRA	Inflation Reduction Act
JRC	Joint Research Centre (of the European Commission)
LFP	Lithium-iron-phosphate
LME	London Metal Exchange
MIC	Made in China
MSP	Minerals Security Platform

NMC	Nickel-manganese-cobalt
NUPE	Norwegian Institute of International Affairs
NZE	Net-zero emissions
OECD	Organisation for Economic Co-operation and Development
PGM	Platinum group metal
PV	Photovoltaics
(L/H)REE	(Light/heavy) rare earth element
SRM	Strategic raw material
UNCTAD	United Nations Conference on Trade and Development
USGS	United States Geological Survey
US DOE	Unites States Department of Energy
WTO	World Trade Organisation

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