REDUCING SUPPLY RISKS FOR CRITICAL RAW MATERIALS

Evidence and policy options

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SUMMARY

The uptake of strategic green and digital technologies will massively increase demand for critical raw materials (CRMs) over the coming years. CRM supply chains, however, are now heavily concentrated in a limited number of countries, with China holding significant market power. In the EU, this has raised legitimate concerns about its excessive exposure to CRM supply risks – all the more justified amid mounting geopolitical tensions. As a growing number of countries are coming to acknowledge these risks and adopt CRM strategies, the Critical Raw Materials Act was the EU's response to these concerns.

As the EU consolidates its CRM strategy, several realistic policy options emerge. Domestically, there is potential to produce both primary and secondary CRMs at scale, yet significant time and resources will be required to turn this potential into large-scale production. Mining operations still face a host of challenges, including lengthy permitting processes and public opposition, as well as a possible lack of specialised workforce and difficulty in attracting private capital. Overall, the absence of a comprehensive mapping of EU resources leaves a substantial degree of uncertainty as to the underground potential of the continent.

Given the intrinsic limitations of domestic sourcing, the EU will need to consider a broader policy toolkit, especially in the short term. Material substitution and resource efficiency might play non-negligible roles, provided continued research and innovation efforts support the market uptake of alternative solutions. On the international front, both trade policy and international cooperation hold significant prospects for mitigating CRM supply risks. For the former, this entails lowering tariff and non-tariff barriers to CRM trade. For the latter, it means engaging in business-oriented strategic partnerships to channel know-how and capital into extra-EU production capacity. Multilateral fora such as the Minerals Security Partnership and the Critical Raw Materials Clubs promise to play an important role in coordinating global efforts. If properly managed, stockpiling CRMs can also help shield against short-term supply or price shocks.

Building upon existing evidence and expert inputs, this CEPS In-Depth Analysis provides an overview of EU CRM supply risks and the options available for securing access to these resources.

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1. INTRODUCTION

Critical raw materials (CRMs) are climbing up policy agendas worldwide. As vital constituents of a number of modern day technologies, these resources are strategically important to support the decarbonisation and digitalisation of the global economy. Against highly concentrated production and an expected sharp increase in demand, a growing number of countries are recognising the vulnerability of global CRM supply chains, and are adopting strategies and policies to offset supply risks (IEA, 2023; IRENA; 2023). This mushrooming of CRM policies, coupled with mounting geopolitical fragmentation and renewed interest in developing homegrown industrial manufacturing capacity, will likely increase competition for access to these resources and put further pressure on already tight CRM markets.

The EU is certainly not immune to this trend. If anything, its long-standing position as a large net importer of CRMs has made it well aware of CRM supply risks, and dedicated strategies and policy initiatives have been adopted since at least the late 2000s. Still, the Covid-19 crisis and the Russian invasion of Ukraine have recently sparked new impetus in investigating the possibilities of securing access to these materials, particularly within domestic borders (Righetti & Rizos, 2023). Newly emerging concerns about the EU's ability to supply CRMs to domestic industries have hence translated into political action and a major revision of the EU policy framework on raw materials: the Critical Raw Materials Act (European Commission, 2023a).

Building upon existing initiatives on CRMs and tabled as part of a broader strategy to enhance EU industrial competitiveness[1], the Act puts forward significant additions to the EU's policy framework on CRMs. The actions it includes aim at reducing CRM supply risks through several means – from expanding domestic mining capacity to forging new strategic partnerships with resource-rich countries. The regulation itself largely focuses on setting the enabling conditions for exploiting EU domestic primary and secondary sourcing options, with notable new provisions on permitting, exploration, monitoring, stockpiling and recyclability, among others. Alongside the regulation, an accompanying Communication (European Commission, 2023b) outlines the broader CRM strategy, including non-regulatory measures on investment, standardisation, skills and trade diversification.

This CEPS In-Depth Analysis provides an overview of existing evidence on EU CRM supply risks and the options for securing access to these resources. Section 2 starts by describing the main technological applications of CRMs and chief bottlenecks along their value chain. Section 3 proceeds by exploring the extent to which the EU exploits its own primary and secondary resources, with a subsection (3.2) assessing the factors that may prevent an expansion of mining operations in the EU. Section 4 explores other options for addressing CRM supply risks

[1] The EU's Critical Raw Materials Act was presented as one of the pillars of a broader plan, the EU Green Deal Industrial Plan, aimed at enhancing the competitiveness of the EU's net-zero industry (European Commission, 2023c).

beyond the expansion of domestic production, namely substitution, resource efficiency, trade policy, international cooperation and stockpiling. Section 5 concludes with some reflections.

2. CRITICAL RAW MATERIALS AND STRATEGIC TECHNOLOGIES

The EU defines critical raw materials as materials of high economic importance and high supply risks[2] (European Commission, 2023d). While they have long been employed for a wide range of applications, access to CRM has become especially important for a specific group of technologies, defined by the European Commission's Joint Research Centre (Carrara et al., 2023) as 'strategic' due to their crucial role in supporting the EU green and digital transitions. First, these include green technologies used for renewable energy production as well as for the decarbonisation of the broader energy system, notably in transport (for instance, electric vehicles (EVs), heating (e.g. heat pumps) and industry (e.g. electrolysers)). In the digital space, they also comprise information and communication technologies such as data transmission networks, data storage and servers, as well as everyday electronic devices like smartphones and tablets. In light of their increasing importance in EU's agenda (European Commission, 2022), space and defence technologies also fall within this domain.

The rapid and large-scale deployment of strategic technologies is set to drive a significant increase of CRM consumption. The EU's Joint Research Centre expects that the expansion of EU battery manufacturing capacity alone will lead lithium consumption to increase from 9 to 12 times by 2030, and up to almost 21 times by 2050. As another example, the EU's demand of platinum – used for example in electrolysers, fuel cells and data transmission networks – is expected to increase from less than 1 tonne to 2-3 tonnes in 2030 and further to 10-20 tonnes in 2050. In addition, the EU's consumption of dysprosium, a key ingredient of the permanent magnets used within EV motors and wind turbine generators, is projected to increase from 2 to 6 times by the end of the decade, and up to 7 times by 2050 (Carrara et al., 2023). Notably, since not all of the 34 CRMs will be equally relevant for these technologies, the European Commission (2023d) recently identified a subset of 16 CRMs – the strategic raw materials (SRMs)[3] – bound to experience the largest increase in demand (see Table 1) and for which actions should therefore be prioritised.

[2] Established for the first time in 2008 with the Raw Materials Initiative, the list of CRMs has since been updated every 3 years. The criticality classification depends on demand (economic importance) and supply (likelihood of and vulnerability to disruption) factors, and is therefore dynamic and context dependent (Månberger, 2023). The latest list, published in 2023, includes 34 materials (European Commission, 2023d).

[3] In the European Commission's proposal for a Critical Raw Materials Act, the list of SRMs includes bismuth, boron (metallurgy grade), cobalt, copper, gallium, germanium, lithium (battery grade), magnesium metal, manganese (battery grade), natural graphite (battery grade), nickel (battery grade), platinum group metals, rare earth elements for magnets, silicon metal, titanium metal and tungsten. In the provisional agreement of the text, the list includes aluminium as well.

Against this backdrop, ensuring secure and reliable access to CRMs (and to SRMs in particular) will be key for the EU to sustain its manufacturing capacity of strategic technologies. Yet global CRM supply chains are today heavily concentrated in a small number of countries, and the EU largely relies on imports to meet its raw material requirements – especially from China. The country holds a dominant position in the supply of several CRMs, including heavy rare earth elements[4] (HREEs) (100 % of global supply), magnesium (91 %) and silicon metal (79 %), among others (European Commission, 2023d). For other CRMs, global production is concentrated elsewhere; in the case of cobalt, for instance, 60 % of global production is located in the Democratic Republic of the Congo. However, China often holds a significant stake in mining companies in these regions as well (Leruth et al., 2022). The high degree of market concentration gives the country substantial leeway to influence the price and availability of these materials.

This quasi-monopolistic market structure has led to the situation depicted in Table 1, where for the majority of CRMs the EU is entirely (or almost entirely) import-dependent, in most cases from only one or very few suppliers. For instance, the EU sources 100 % of the rare earth elements used for magnet manufacturing and 97 % of its magnesium supply from China, as well as 99 % of its boron supply from Türkiye and 79 % of its lithium supply from Chile (European Commission, 2023d). With rapidly increasing global demand – hence competition for these resources – and intensifying geopolitical rivalries, the combination of high market concentration and high import dependency for raw materials exposes the EU to significant CRM supply risks.

[4] Dysprosium, erbium europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium and yttrium.

Table 1. Main EU suppliers, import reliance and strategic applications of strategic raw materials

SRMs	Main EU supplier (share) E	Main EU supplier (share) P	Import reliance E	Import reliance P	Li-ion batteries	Wind turbines	Solar PV	Electrolysers	Fuel cells	Traction motors	H2-DRI	Heat pumps	Data transmission networks	Data storage and servers	Smartphones, tablets, laptops	Additive manufacturing	Robotics	Drones	Space applications
Aluminium/ bauxite	Guinea (62 %)	Russia (19 %)	89 %	58 %	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bismuth	-	China (65 %)	-	71 %									✓	✓	✓				✓
Boron	Türkiye (99 %)	-	100 %	70 %		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓
Cobalt	Russia (70 %)*	Finland (62 %)	81 %	1 %	✓			✓	✓				✓		✓	✓	✓	✓	✓
Copper	Poland (19 %)	Germany (17 %)	48 %	17 %	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Gallium	-	China (69 %)	-	98 %			✓						✓	✓	✓		✓	✓	✓
Germanium	-	China (45 %)	-	42 %			✓						✓	✓	✓				✓
Lithium	-	Chile (79 %)	81 %	100 %	✓								✓		✓		✓	✓	✓
Magnesium	Slovakia (31 %)**	China (97 %)	-	100 %				✓						✓	✓	✓	✓	✓	✓
Manganese	S. Africa (41 %)	Norway (21 %	96 %	66 %	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Natural graphite	China (40 %)	-	99 %	-	✓			✓	✓		✓		✓		✓		✓	✓	
Nickel	Finland (38 %)	Russia (29 %)	31 %	75 %	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
PGM	-	-	-	100 %				✓	✓				✓	✓	✓		✓	✓	✓
HREEs	Japan (55 %)	China (100 %)	100 %	100 %		✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓
LREEs	-	China (85 %)	80 %	100 %		✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓
Silicon metal	France (20 %)***	Norway (34 %)	-	64 %		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Titanium metal	Zambia (23 %)****	-	-	100 %											✓	✓	✓	✓	✓
Tungsten	Finland (34 %)	China (31 %)	21 %	80 %				✓							✓	✓		✓	✓

Notes: E = extraction stage; P = processing stage; IR (import reliance) = (import – export) / (domestic production + import – export); H2-DRI = hydrogen direct reduced iron and electric arc furnaces; space applications include space launchers and satellites; PGMs (platinum group metals) include ruthenium, rhodium, palladium, iridium and platinum; LREE (light rare earth elements) comprise lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium and gadolinium; HREE include terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium; Only REEs used for the magnet production (i.e. neodymium, praseodymium, terbium, dysprosium, gadolinium, samarium and cerium) are classified as SRMs.

* European Central Bank (2023)

** Refers to magnesite extraction

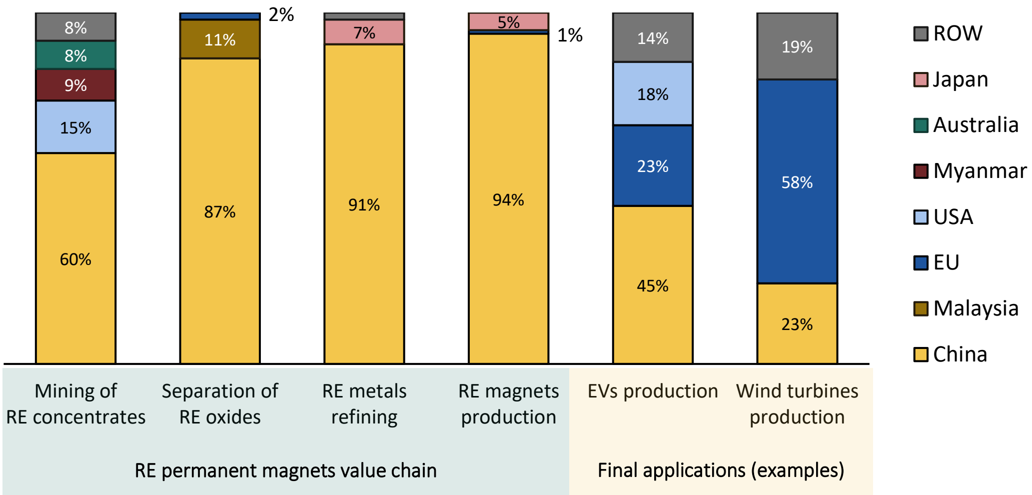
*** Refers to silica sand extraction

**** Refers to titanium ores

Sources: European Commission (2023d), Carrara et al. (2023) and European Central Bank (2023).

Although risk exposure is notoriously strong upstream, it is important to note that there are dependencies throughout the whole CRM value chain, up to the level of strategic technologies themselves. In fact, the EU's marginal presence in upstream segments (i.e. materials extraction and separation) often extends to downstream – including at the refining or manufacturing stage. Rare earth permanent magnets, for instance, are almost entirely sourced from China, which controls about 94 % of the global market and a similar share of the proceeding value chain steps (see Figure 1) (Rizos et al., 2022). Similarly, solar photovoltaic (PV) panels are primarily sourced from China, which dominates 89 % of global supply (Rietveld et al., 2022). As a result, EU inflows of CRMs are primarily – in both volume and value – in the form of components or finite products embedding these materials, rather than actual raw materials (Rietveld et al., 2022).

Figure 1. Geographical concentration of the value chain of rare earth permanent magnets



Source: Rizos et al. (2022).

This situation highlights the need to strengthen the entire value chains of these technologies, beyond the upstream sourcing of CRMs. Building up rare earth production, for instance, would largely fall short of solving EU supply uncertainties if such materials were then to be shipped outside the EU to be further processed into rare earth metals and permanent magnets, due to a lack of domestic refining or manufacturing capacity. The EU's CRM strategy should hence only be a part of a more comprehensive and coherent plan to address vulnerabilities and enhance resilience along the whole value chain, from the sourcing of raw materials to the manufacturing of strategic technologies[5]. Still, as the raw materials step was identified as the most vulnerable across all the value chains of strategic technologies (Carrara et al., 2023), action on this front should be prioritised.

[5] As part of the EU Green Deal Industrial Plan, the EU indeed tabled a net zero industry act (European Commission, 2023e) to scale up the domestic manufacturing of clean technologies and reach 40 % of EU deployment needs by 2030. In a similar vein, the Chips Act aims at reaching a 20 % share of the global market in semiconductor production.

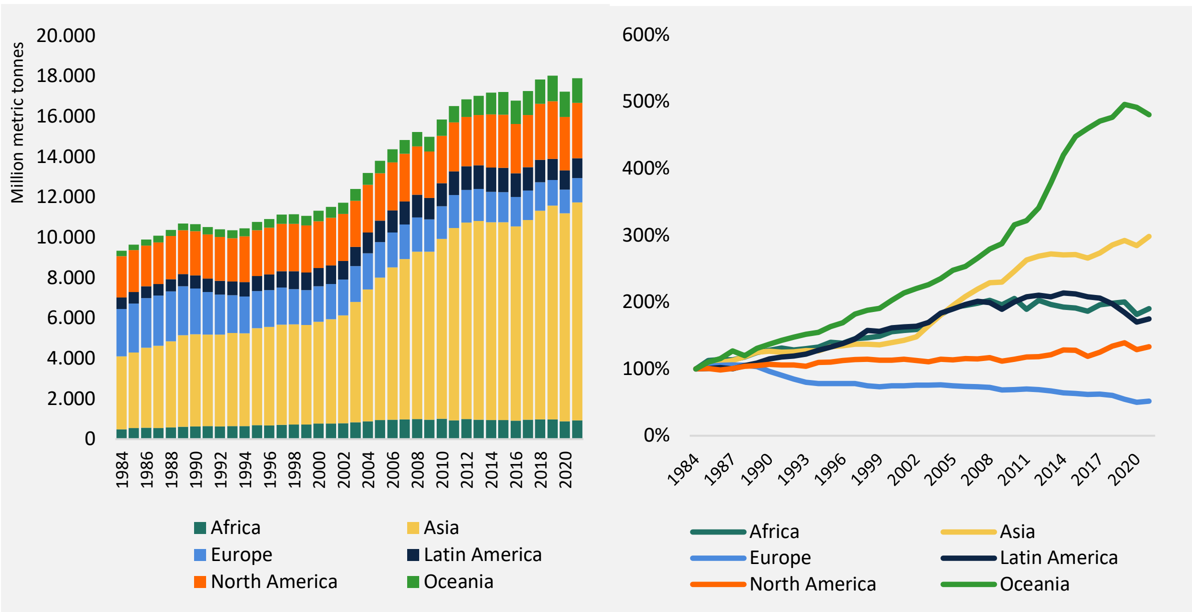
3. TO WHAT EXTENT CAN THE EU EXPLOIT ITS OWN RESOURCES?

Leveraging unexploited domestic resources would naturally be the first option for mitigating CRM supply chain risks. These can either take the form of primary (i.e. underground) or secondary (i.e. recyclable) materials.

3.1 THE EU'S DOMESTIC MINING POTENTIAL

Europe has been one of the most productive mining regions until the early 1990s, when its mining output started to decrease (Figure 2, left). This has partly been the result of a structural shift towards economic activities of higher added value (services) (Herrendorf et al., 2014), but also of societal and environmental concerns typically linked to mining activities (Mononen et al., 2022). Meanwhile, as the EU and other Western economies have been gradually outsourcing mineral production, other countries – notably China – have been consolidating their leading position in this sector, particularly since the early 2000s (Nakano, 2021). In all, Chinese mineral production has indeed more than doubled over the last 20 years, and currently accounts for over 60 % of the world total. While considerable geological endowments have helped China in establishing its primary role in raw material supply chains, high internal demand and strong political commitment to support the mining industry have been major drivers of this trend (Kalantzakos, 2020).

Figure 2. Historical evolution of world mineral production in absolute and relative terms, by continent

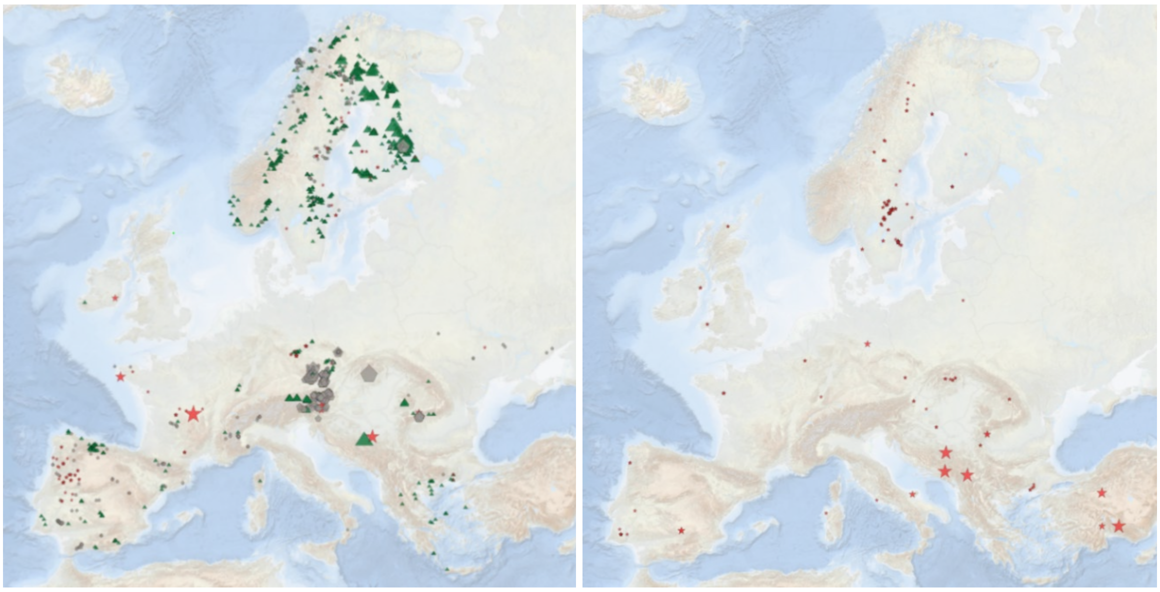


Note: Bauxite (used for aluminium production) is not included.
Source: World Mining Data (2023).

But even though Europe's mining activity has been decreasing for decades, the continent is not lacking indigenous resources. Recent assessments and discoveries have shown that European mining potential is still largely unexploited. This is particularly the case for battery raw materials, i.e. those employed in the manufacturing of li-ion batteries (i.e. cobalt, copper, lithium, manganese and natural graphite). As for lithium, Portugal holds some of the largest reserves worldwide, and it is already ranked seventh globally in terms of lithium mine production (USGS, 2023). France could also benefit from substantial lithium endowments: in late 2022, a major mining project was announced, with a target to produce up to 34 000 tonnes of lithium over 25 years in the Allier region (Vif, 2022). Overall, European lithium resources are estimated to account for about 6.5 % of the world total, with substantial mineral endowments having also been identified in Germany, Czechia, Serbia, Spain, Finland and Austria (USGS, 2023). According to estimates by Transport & Environment (2023a), based on current and planned extractive projects, Europe could secure about 30 % of its 2030 lithium demand via domestic mining, or up to 52 % if projects currently facing public opposition were to become operational.

European cobalt resources also appear promising. Finland in particular offers interesting prospects for cobalt mining production (Figure 3), though deposits that might be exploitable have also been identified in the Balkans and in central and northern Europe (Horn et al., 2021). The expansion of cobalt mining output could leverage current cobalt refining capacity in Europe, second only to China (Finland and Belgium account for 11 % and 5 % of world cobalt processing, respectively (European Commission, 2023d)). Besides battery raw materials, one other interesting group of materials for which Europe shows promise is rare earth elements. Considerable deposits have in fact been identified in Sweden, Norway, Finland and in the Balkans region, with enough resources to potentially serve a significant portion of EU demand (Goodenough et al., 2016). The recent discovery of a deposit in Kiruna (Sweden), currently the largest known European deposit of rare earth elements, seems to confirm this potential (LKAB, 2023).

Figure 3. Mineral occurrences of battery raw materials (left) and rare earth elements (right)



Note: Battery raw materials include lithium (red stars) cobalt (green triangles) and natural graphite (grey pentagons).
Source: EGDI (2023).

If several assessments and recent discoveries seem to indicate that the EU has considerable reserves of (at least some) CRMs, it should be noted, however, that information remains, on the whole, rather scattered. A comprehensive assessment of the level of EU domestic resources is indeed still lacking. While technological and geological constraints have made such an assessment a complex task, this is primarily due to the EU neglecting exploration efforts over recent years (Righetti and Rizos, 2023). Further, the absence of a unique EU system to coordinate and support exploration programmes at the national level has limited the efficacy of existing, isolated initiatives. Previous data collection efforts in the context of EU-funded projects[6] as well as the recently established Geological Service for Europe may provide the basis for developing such a centralised EU platform, including for identifying the potential of CRM recovery from abandoned mine wastes[7]. Even so, it may take substantial time and financial resources for Member States to develop the required capacities to comprehensively map the CRM extractive potential within their territories.

3.2 CHALLENGES FOR INCREASING THE EU'S MINING CAPACITY

Provided that mining potential exists in Europe, several challenges remain to be addressed for the EU to exploit its own mineral endowments. Notably, four prime obstacles were identified: long lead times, low public acceptance, a lack of specialised skills and difficulty in attracting investment[8].

The first key issue that emerged from interviews is the long lead time of mining projects. According to interviewed experts, it typically takes between 10 to 15 years to open new mines in the EU. This alone would preclude any significant contribution of additional mining output to cover EU demand until the early 2030s, i.e. during the period when CRM demand is set to increase the most. Complex procedural requirements – including e.g. exploration and feasibility studies – as well as laborious regulatory environments contribute to causing such delays (Manalo, 2023). Experience from different EU Member States has indeed shown that the permitting processes entail a complex array of steps that need to be taken to comply with varied requirements often coming from different levels of authority. As such, estimating the time when a mine can provide outputs is hard, which in turn increases the investment risk (Söderholm et al., 2015).

A second major hurdle lies in the strong public opposition to mining projects, which often further delays – or blocks altogether – the opening of new mines in the EU. One case in point is the controversy over expansion of the mine in Covas de Barroso, a village in the Portuguese northern territories with possibly the largest European lithium reserve. In some cases, public

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[6] See, for example, Mineral Intelligence for Europe (Mintell4EU) project, which aimed to develop a knowledge management system for primary and secondary raw materials.

[7] There have been various EU-funded projects focused on the recovery of CRMs from mine waste – see, for instance, RAWMINA and NEMO.

[8] Information for this section has been collected via both desk research and interviews with experts. Four in-person and online interviews with experts from industry and academia were conducted between January and April 2023.

opposition is motivated by concerns about the lack of involvement and engagement of local communities throughout the mine development process. One such example is the Sami lands in Sweden, where there have been controversies over engagement of the indigenous populations and assessments of impacts in the region (Larsen et al., 2022; Lawrence & Larsen, 2017). Such cases contribute to a negative public perception of the mining sector. As noted by one interviewed expert, increasing public knowledge about the material requirements of green and digital technologies and the impacts of extracting these outside the EU would benefit the perception of mining in the EU. The absence of a single coherent framework on 'sustainable mining' further contributes to the conundrum (Borowczyk et al., 2023).

A possible shortage of skills is yet another important issue reported by experts. Mining operations require highly specialised profiles (e.g. mining engineers), yet due to the shrinking of European mining output over the last few years the EU now faces the risk of lacking these profiles. A recent report by the European Labour Authority (2023) identified mining among the sectors for which the northern regions of Finland, Sweden and Norway face shortages. According to Abenov et al. (2023), attracting young talent to high-skilled professions such as mining engineering is an increasingly tall order for governments. The perception that mining jobs can be physically challenging or that proper infrastructure (including hospitals and schools) is unavailable in remote areas have traditionally contributed to the unattractiveness of mining jobs. More recently, other factors such as competition for high-skilled jobs with other sectors (e.g. digital) has further weighed on the mining sector.

The unattractiveness of the mining sector for private investors is another significant bottleneck preventing the take-off of mining operations in the EU. Beyond the structural impediments described above, the uncertain and unappealing economics of these operations is a major reason behind investors' lack of confidence in the sector. Indeed, the gradual depletion of high-grade deposits risks making the extraction of material less and less profitable at some sites (i.e. increasing the costs required to access the same volume of material)[9] (Bardi et al., 2016). Together with the volatile prices of these resources (Renner & Wellmer, 2020) this increases uncertainties over future returns. Further, high EU energy prices complicate the business case around energy-intensive sectors such as mining and refining in Europe, particularly compared with other world regions like Asia or North America.

Added to this, the opaque and unpredictable nature of commodity trades may dampen investor confidence. Indeed, although there are several commodity exchanges in the EU[10], CRMs are still largely traded over-the-counter (i.e. as part of direct transactions between private counterparts) (Krol-Sinclair, 2023), which undermines transaction transparency. Further, the small size of recognised exchanges and their illiquid nature make them unable to predict – and

[9] This challenge might be offset by advancements in mining technologies, for which the EU is among global leaders.

[10] Three main stock exchanges for metals currently exist in Europe: the London Metal Exchange, the London Bullion Market Association and the Paris Stock Exchange (Hache & Jeannin, 2023).

therefore highly vulnerable to – supply side shocks or speculative activities, as happened with the nickel crisis in March 2022[11] (IEA, 2023; Krol-Sinclair, 2023).

Finally, some interviewed experts noted that even when the initial investment is secured, it is hard to continue attracting financial resources during the 'valley of death', i.e. the period of time before actual mining production. Also due to the extensive permitting processes highlighted above, this phase tends to be particularly long for the sector, which disincentives investors. The uncertainties surrounding the legal environment for mining in Europe and its future development also make the mining business case unattractive for investors, according to the experts.

3.3 THE EU'S DOMESTIC RECYCLING POTENTIAL

Along with the increase in domestic mining output, recycling also holds potential for contributing to the future EU supply of CRMs and mitigating supply risks. Where feasible, recycling should be prioritised over primary resource extraction, as it reduces the social and environmental impacts associated with mining activities. European recycling chains are already mature for several widely and long-used base metals, such as aluminium, copper or nickel. Thanks to favourable physical properties, well-established collection systems and somewhat saturated markets, the contribution of recycling towards the overall supply of these materials – the end-of-life recycling input rate (EoL RIR) – is already fairly high (see Figure 4)[12]. Overall, according to Eurometaux (2019) about half of EU base metal production is today covered via recycling.

As shown in the figure below, however, for the majority of CRMs the input from recycling is currently either very low or virtually non-existent. These low rates can be attributed to the collection and recycling pathways of CRM-containing products being significantly more complex than, for example, pure aluminium or copper waste streams. This, in turn, generates a number of product-specific barriers of an economic nature (e.g. high labour intensity, hence high recycling costs), in the supply chain (e.g. inefficient collection and sorting systems) of a regulatory nature (e.g. limitations in the cross-border transport of hazardous waste) or a technical nature (e.g. complex product disassembly)[13]. On top of this, the limited available information regarding volumes and types of CRMs already available 'in-stock' as well as in future EoL streams creates uncertainty and further hinders the establishment of markets for recycled materials. For many of the products mentioned in Section 2, therefore, efficient recycling chains have yet to form in the EU.

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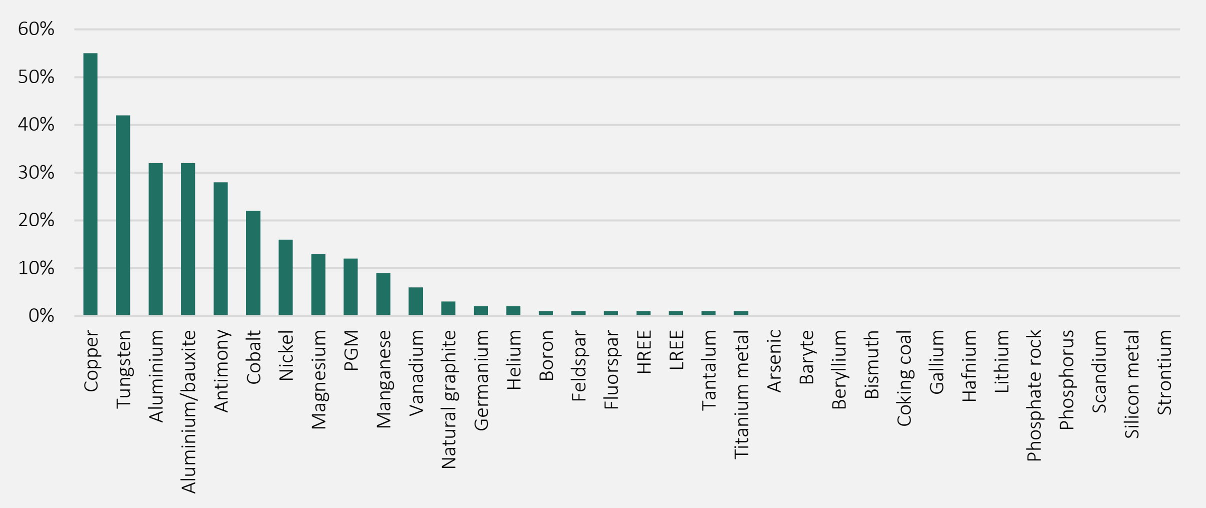
[11] On 8 March 2022, nickel trades at the London Metal Exchange had to be suspended for the first time in history due to extreme price volatility, after a record 250 % price increase in a single day.

[12] This condition of a saturated market does not apply to nickel, whose consumption is increasing for li-ion battery manufacturing. This is why the EoL RIR of nickel material is significantly lower than that for materials with comparable EoL RIR.

[13] For comprehensive overviews of the barriers hindering the establishment of recycling practices for rare earth magnets and electrical and electronic equipment, see Rizos et al. (2022) and Rizos & Bryhn (2022), respectively.

Figure 4. End-of-life recycling input rate of critical raw materials in the EU



Source: European Commission (2023d).

Despite the bottlenecks described above, recycling technologies for CRM-containing products have greatly advanced in recent years and offer good prospects for rapid commercialisation and scaling up. Good cases in point are the recycling processes of li-ion batteries and rare earth permanent magnets. Based on planned projects, Bünting et al. (2023) expect the EU battery recycling capacity to expand to the point that all EU-disposed batteries – and possibly imported volumes as well – could be recycled by the end of the decade. For permanent magnets, recycling capacity will likely take more time to develop at a similar scale, but recycling technologies are reaching maturity and recycling plants are now being planned in France and Belgium (Gauß et al., 2021). Although at different stages of maturity, therefore, recycling processes for CRMs exist and hold potential to rapidly upscale in the coming years.

But even if highly efficient recycling chains were to be achieved in a relatively short time, the recycling of low-carbon technologies could not be expected provide substantial inputs for their manufacturing in the short term. This is due to the dynamics of demand and EoL supplies of these products: while for most of these technologies the market is now rapidly expanding, few of these applications will have reached the EoL stage in the coming years, due to their relatively long lifetime (e.g. between 10 to 12 years for EVs, but up to 30 for wind turbines and 40 for solar panels). As such, the mismatch between recyclable CRMs and those in demand will be substantial for a few years, and only diminish once markets are saturated. For most of these products, this will only happen towards the early 2030s or later. For example, in a closed-loop recycling scenario[14], Rizos and Righetti (2022) estimate that a highly efficient system for EV battery recycling could provide up to 21 % of the lithium, 14 % of the nickel and 18 % of the cobalt required for EV battery manufacturing by 2030, but 10 years later these figures are expected to more than double (52 % for lithium, 49 % for nickel and 58 % for cobalt).

[14] Closed-loop recycling refers to the recycling process in which materials from disposed applications are upgraded within the same application category (e.g. from spent to new batteries).

While closed-loop recycling opportunities for low-carbon technologies will be limited in the short term, untapped potential for CRM recycling might exist in other available waste streams, such as waste electrical and electronic equipment (WEEE) or disposed (conventional) vehicles. Harvesting materials from such EoL applications could represent a significant source of secondary CRMs, as large stocks of these applications are already available in the economy. Still, most of them are not yet properly collected or recycled in the EU. For instance, only 46 % of WEEE is collected in the EU (Eurostat, 2023), and only between 12 % and 15 % of mobile phones are properly recycled (Rizos et al., 2019). As for EoL vehicles, Mehlhart et al. (2017) indicate that only about a third of them are currently collected for recycling in the EU.

4. WHAT OTHER POLICY OPTIONS?

In light of the inherent limitations in the domestic sourcing of CRMs, the EU is called upon to leverage a larger toolkit of policy options, especially in the short term. Here, we explore the potential and limitations of substitution and resource efficiency, trade policy, international cooperation and stockpiling.

4.1 SUBSTITUTION AND RESOURCE EFFICIENCY

Shifting CRM consumption patterns could help tackle CRM supply risks by reducing CRM demand. In practice, this could imply

a) substitution at the material level – ideally, from critical to non- (or less) critical ones;
b) substitution at the technology or component level, i.e. from CRM-containing ones to others employing no (or less) CRMs; or
c) reduction in the amount of CRMs employed within certain technologies or components, i.e. an increase in resource efficiency.

Crucially, in all these instances technology performance and cost considerations become key.

At the material level, substitution options already exist or are being explored for several strategic technologies. Batteries are a dynamic technology in this domain. Supply concerns and market dynamics are in fact already driving a shift in battery chemistries, with cobalt-rich lithium-ion batteries being gradually substituted by either (cheaper) nickel-rich ones[15] or by cobalt and nickel-free batteries, such as lithium iron phosphate (LFP) batteries (Transport & Environment, 2021). In light of possible lithium shortages or price spikes, lithium-free chemistries such as sodium-based ones are also expected to be increasingly deployed in the medium to long term[16]. While lower performance compared with traditional li-ion batteries might initially limit the scope of application of these alternatives (e.g. to the lowest-performing

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[15] The nickel supply risk is significantly lower than that of cobalt. In fact, prior to the 2023 CRM list update, nickel was not considered a CRM. Therefore, while the shift towards nickel-rich ones is primarily driven by cost factors, such a shift would also make sense from a broader security-of-supply perspective.

[16] According to Bloomberg NEF estimates, the uptake in sodium-ion batteries could help reduce global lithium demand by up to 37 % by 2035 (Burton, 2023).

range of EVs or stationary energy storage systems), rapid battery-technology innovations are expected to lead to CRM-free chemistries suitable for a larger battery market share (IEA, 2023; Armand et al., 2023).

For some strategic technologies, CRM-free substitutes might not yet be commercially available, or only at the expense of significant quality losses. For instance, rare earth-free magnets – notably the 'ferrites' – have long been employed for some end uses like home appliances, because of their lower costs compared with market alternatives. However, due to significantly lower strength and resistance compared with rare earth-based magnets, they are unlikely to be used for, e.g. high-performing motors of EVs or wind turbine generators (Kalvig, 2022)[17]. Magnets of comparable quality, lower CRM content and possibly lower environmental impacts – such as iron nitride magnets (Wang, 2020) – are emerging as potential substitutes, yet research in this domain is still ongoing. Similarly, in the fuel cell domain, iron-nitrogen-carbon catalysts are being explored as substitutes for platinum-based ones[18] but it remains uncertain whether performance is yet comparable (Sgarbi et al., 2022).

Whenever substitution would either not be technically or economically viable at the material level, a change in the type of technology employed could be considered instead. For instance, while today the vast majority of EVs use (rare earth-based) permanent magnet motors, permanent magnets-free models such as induction motors are now being re-evaluated by car manufacturers (Onstad, 2021). A similar situation applies to wind turbines, where traditional permanent magnet-based generators could be substituted by either multipolar synchronous generators (i.e. with no permanent magnets) or hybrid drive generators (i.e. employing smaller permanent magnets) (Alves Dias at al., 2020). In theory, technology substitution options could also arise further down the value chain. In these cases, however, a broader and more complex set of factors (including environmental conditions, infrastructure availability or regulatory environment) would need to be considered to assess the efficacy and feasibility of the substitution.

Crucially, when assessing substitution options the broader impact in terms of materials consumption at system level should be properly accounted for. Indeed, substitution of CRMs will inevitably entail increasing pressure on other non- (or less critical) materials, which might eventually become (more) critical as a result. Shifting from permanent magnet-based motors to induction motors, for instance, would reduce rare earth demand at the expense of a substantial increase in copper and aluminium consumption (IEA, 2021). Increasing the share of LFP batteries would lead to a significant reduction of nickel and cobalt use but increase the consumption of phosphates, which are crucial also for fertiliser production (Carrara et al.,

[17] In an effort to reduce environmental and supply risks, Tesla has recently announced its intention to replace rare earths with ferrites in its next generation of EVs, despite acknowledging their significantly lower performance.

[18] Platinum is a CRM belonging to the group of platinum group metals (PGM). Platinum in catalysts could also be partially or entirely substituted with the cheaper palladium, which is yet another CRM among the PGMs group.

2023). A good understanding of these trade-offs is hence key to inform and implement effective substitution strategies.

Higher material efficiency – that is, lower CRM use per technology unit – could help reduce overall CRM demand, while avoiding possible conflicts among alternative material uses. Similar to material substitution, reduced CRM intensity in products has already been partly driven by the price and market dynamics of these resources. Within the magnets domain, high prices and constrained supply of dysprosium – the rare earth element used to increase a magnet's resistance to demagnetisation at high temperatures – have led magnet manufacturers to greatly optimise its use over time (Pavel et al., 2017). Likewise, research is ongoing to reduce the use of platinum group metals in electrolyser manufacturing (Carrara et al., 2023). Lower CRM requirements also occur as an indirect consequence of technology innovation. Improvements in energy densities, for instance, are expected to drive substantial reductions material requirements per kWh for all battery chemistries in the future (Transport & Environment, 2021)[19], as well as lower requirements for rare earths in motors (Gielen, 2022).

4.2 TRADE POLICY AND INTERNATIONAL COOPERATION

Irrespective of its efforts to augment domestic CRM production capacity and curtail demand, the EU will continue to resort to CRM imports in the foreseeable future, and especially in the short term. According to Transport & Environment (2023b), fully leveraging EU mineral extraction, refining and recycling capacity would still leave more than half of CRM demand to be met from extra-EU sourcing. Securing CRM supplies in a situation of continued reliance on imports will thus inevitably require, to the extent feasible, diversifying and strengthening CRM import routes and enhancing international cooperation efforts.

CRMs are highly and increasingly traded commodities. According to the OECD (Kowalski & Legendre, 2023), the value of trade in CRMs increased by 38 % between 2009 and 2020, i.e. faster than all other raw materials (35 %) and merchandised products (31 %). At the same time, data show that export restrictions on CRMs have also been steadily rising, marking a fivefold increase over the same decade. These restrictions are often explicitly motivated by economic objectives, such as the willingness to support domestic downstream segments in CRM value chains (like metal refining or the manufacturing of final goods) or simply generate tax revenue. In some cases – notably the Chinese and Russian ones – motives are typically not or vaguely stated (e.g. 'national security concerns'), and the timing often suggests they are used as geopolitical levers (often referred to as 'weaponisation' of raw material supplies) (Seaman, 2023).

[19] For instance, Transport & Environment calculates that the amount of lithium requirements per kWh of battery will decrease from 0.10 kg/kWh in 2020 to 0.05 kg/kWh in 2030, for cobalt from 0.13 kg/kWh in 2020 to 0.03 kg/kWh in 2030 and for nickel from 0.48 kg/kWh in 2020 to 0.39 kg/kWh in 2030 (Transport & Environment, 2021).

Regardless of whether CRM trade restrictions are economically or politically motivated, the increasing CRM market tightness, the draw to develop higher value-added downstream capacity and the rising geopolitical tensions all point to their likely increase in the future. At the same time, rising demand – and quite possibly prices – of CRMs could improve the economics of primary and secondary production, thereby incentivising countries with unexploited capacity to enter an increasingly profitable business. In either scenario, changes in the global geography of CRM production are likely to occur.

Against this changing environment, the EU can lower supply risks by strengthening and rebalancing its CRM trade and cooperation network. The primary avenue to do so is via 'traditional' trade policy. In short, this entails negotiating lower CRM trade barriers within existing free trade agreements (FTAs), or striking new and more favourable ones. Notably, some observers have pointed out that the scope for the EU to diversify and secure its CRM imports via trade policy might be limited (Rietveld et al., 2023; Findeisen & Wernert, 2023). This is partly due to the fact that EU's FTA network is already extensive – 72 countries, the largest in the world – and also because a large part (92 %) of CRM import value is already free of import duties, with the remaining share having relatively low import tariffs (European Commission, 2023b).

Still, beyond limiting CRM export duties (which should nonetheless be kept at the core of trade negotiations), other provisions aimed at lowering non-tariff trade barriers can be enforced. For instance, these include actions preventing the creation of export and import monopolies, or deterring trade partners from adopting dual pricing policies[20] or other forms of export price controls on CRMs that prevent market access and equal treatment (Crochet and Zhou, 2023). Trade agreements could also be leveraged to address technical or regulatory barriers to CRM trade (e.g. unaligned safety or quality standards) (WTO, 2021) and ensure CRMs are sustainably sourced in the exporting country (Blot, 2023). Such provisions have recently been set as part of the negotiated FTAs with, e.g. Chile, specifically as part of dedicated 'Energy and Raw Material' chapters within. Furthermore, the rise of CRMs trade restrictions might require the EU increasingly resort to the WTO's dispute settlement and negotiating functions – which proved successful against past CRM restrictions[21] – or enforce trade defence instruments such as anti-dumping or anti-subsidy duties to protect domestic production (Crochet and Zhou, 2023; Buysse & Essers, 2023).

[20] This refers to a form of subsidy whereby a certain share of domestic raw material production is reserved to the domestic market at a preferential price, below the market price, to support the competitiveness of domestic downstream production (Crochet and Zhou, 2023).

[21] The EU initiated three WTO disputes against China for raw materials-related export restrictions: in 2009 (for bauxite, magnesium and zinc); in 2012 (for rare earths, tungsten and molybdenum) and in 2016 (for chromium, cobalt, copper, lead and tin). The first and second cases were won in 2013 and 2015, respectively, while the decision on the third is still pending (Buysse & Essers, 2019; WTO, 2023).

Outside the scope of trade policy, other 'softer' tools can be used to diversify and secure international CRM supplies. Among these are the strategic partnerships with CRM-rich countries. In practice, these consist of formal (yet non-binding) commitments to explore and expand mutually beneficial forms of bilateral cooperation in the CRM domain and to integrate the respective CRM value chains[22]. While possibly useful in building frameworks for future trade relations in CRMs, strategic partnerships have been predominantly designed to strengthen cooperation, e.g. on investment, research and innovation or skills development.

The non-binding nature of strategic partnerships might limit their efficacy in the short term, particularly against sudden supply disruptions[23]. However, long term, they can be a useful tool to expand extra-EU CRM production capacity, notably in countries with significant resource potential but limited means to exploit it (e.g. the African continent). This per se indirectly benefits the EU insofar as such additional production capacity ultimately 'thickens' and diversifies global CRM markets, which are currently tight and highly concentrated (Evenett & Fritz, 2023). Also, within these frameworks the EU can leverage its leadership position in exploration and mining technologies as well as deep expertise on ESG criteria and standards setting to gain privileged access to partners' resources, while allowing partners to derive local value addition from (and beyond) their CRM value chain – including from downstream segments. Indeed, the key added value brought forward by the EU through these partnerships is their inclusive, 'win-win' character (European Commission, 2023b) – i.e. in stark opposition to a possibly more 'extractive', neo-colonialist approach as could be perceived by developing countries (Crochet and Zhou, 2023). Taking such a supportive approach and helping partners to develop downstream capacities could ultimately prevent them from adopting trade restrictions outlined above.

Similar forms of cooperation can also be pursued on a multilateral basis. Examples already exist. The Minerals Security Partnership was established in 2022 between 13 countries[24] and the European Commission to share information across partners and catalyse investment into CRM projects that 'adhere to the highest ESG standards' (United States Department of State, 2023). The European Commission's plan to develop a Critical Raw Materials Club goes in a similar direction, with the yet more explicit intent of bringing together resource-seeking and resource-rich countries (European Commission, 2023b). Although the actual scope of the club is yet to be clearly defined, the primary focus of both initiatives seems on channelling capital into CRM projects and sharing knowledge rather than fostering trade per se. As such, these platforms hold significant potential for expanding global supply capacity by channelling capital and know-how from where they are abundant (i.e. resource-seeking countries) to where they are most

[22] At the time of writing, the EU had signed strategic partnerships on CRMs with Canada and Ukraine in 2021; Kazakhstan and Namibia in 2022; and Argentina, Chile, the Democratic Republic of Congo, Zambia and Greenland in 2023.

[23] For instance, the strategic partnership signed in late 2022 between the EU and Namibia did not prevent the country from banning exports of several unprocessed CRMs in June 2023 (Nyaungwa, 2023).

[24] These include Australia, Canada, Finland, France, Germany, India, Italy, Japan, the Republic of Korea, Norway, Sweden, the United Kingdom and the United States.

needed (i.e. resource-rich ones). Also, and equally important, they might provide a platform to enhance CRM market monitoring and transparency – provided there is sufficient willingness from members to share possibly sensitive information – and for converging on a coherent reporting and standardisation framework for mining and refining activities.

As an EU-led initiative, the Critical Raw Materials Club may give significant leeway to the EU determine its structure, focus and level of commitment by members. In terms of scope, an initial prioritisation towards those areas where the EU could take the lead while possibly causing less divide could be functional. For one, the EU might be particularly well-placed to guide work on standardisation, given its past and ongoing work in this domain – as in, for instance, the Corporate Sustainability Due Diligence Directive (Buysse & Essers, 2023). Other more sensitive areas such as the sharing of information (and possibly the coordination) of strategic reserves across members (see subsection 4.3) or the striking of full-blown trade and investment agreements could then be gradually included.

4.3 STOCKPILING

Although global CRM production capacity is set to increase, different assessments expect supply to fall short of the short-term surge in demand, exposing the EU to the risk of disruptive shortages[25]. According to the ETC (2023), some 10-15 % of copper and nickel demand, 30 % of lithium and neodymium demand and up to 40 % of cobalt demand could go unmet by 2030. On top of possible supply-demand imbalances, increasing the tendency to impose trade restrictions for CRMs could further worsen the frequency and magnitude of disruptions. And even if actual material shortages were not to materialise, price spikes or extreme volatility would also be increasingly likely to occur.

To buffer against these short-term supply or price shocks, one option is to set up strategic material reserves, i.e. 'stockpile' the materials at risk. Building strategic reserves has long been an established practice in the EU for energy commodities, notably oil and gas. Member States have been obliged to hold stocks of crude oil and/or petroleum products since 1968[26], with obligations being gradually increased and adapted over time. Recently, the Council's emergency regulation on gas storage[27] – which strengthened pre-existing obligations – proved effective in coping with the gas supply disruptions that followed Russian curtailments. While a stockpiling system for CRMs would fundamentally differ from the oil and gas examples, in light of the above risks there is an opportunity for policymakers to adapt such practices to the CRM domain.

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[25] This is also partly the result of relatively inelastic supply in metal commodities markets, whereby a positive demand shock typically leads to a less than proportional supply response – even in the medium to long term (Boer et al., 2021).

[26] Council Directive (EC) No 119/2009 requires Member States to hold reserves equivalent to at least 90 days of net imports or 61 days of inland consumption.

[27] As per Regulation No 1032/2022, overall EU underground gas storage should have been filled to at least 80 % of its capacity prior to 2022-2023, and 90 % before the following winter period.

Although with varying setups and scope, forms of CRM stockpiling programmes already exist (or have existed) both within and outside the EU. In the US, the National Defense Stockpile was set up as early as 1939 to supply 'military, industrial, and essential civilian' demand in case of emergencies (Chappell et al., 2006). More recently, the Biden administration confirmed the importance of stockpiling to safeguard supply-chain resilience (Biden, 2021). In Asia, Japan and China share long experience in CRM stockpiling, while South Korea set its strategic reserve in 2021. While in Japan and South Korea CRM stockpiles are primarily meant to cope with their long-standing condition of being 'resource-poor' countries, China's dominant role in CRM production and refining suggests that its stocks – for which no official figures exist – might possibly retain an 'offensive' (supplying resources below market price to domestic industry) rather than 'defensive' (supply risk management) character (Hache & Jeannin, 2023). In the EU, stockpiling programmes were adopted in France, Sweden, Slovakia and the UK, but they were all discontinued due to, e.g. high costs or lower perceived risks of supply disruptions (Rietveld et al., 2023; Hache & Jeannin, 2023). At the time of writing, the only active stockpiling programme in Europe is in Switzerland.

A seemingly straightforward approach, the setup of strategic reserves requires assessing and defining a wide range of elements. These include their scope (i.e. which materials), composition (i.e. at which processing stage), ultimate objective (i.e. volume vs price risk management), governance and institutional arrangements (i.e. centralised vs decentralised) and size.

While virtually all CRMs could be stored in strategic reserves, the very high costs of stockpiling would likely require some prioritisation, especially at the early stages. The SRMs subgroup would naturally be a good place to start, but a narrower selection (based on, e.g. supply risk indicators) might be required against financial or technical constraints. In terms of composition, materials could possibly be stored at any stage of the value chain, from ore to the material-containing application. Storing materials at earlier stages would likely be cheaper (Rietveld et al., 2023) but could prove ineffective if there is limited downstream capacity, as materials would need to be exported for further processing or for the manufacturing of final goods (Villalobos et al., 2022). Given the often very diverse supply-chain conditions across CRMs, different approaches might be required for different materials. Systematic assessment and monitoring of technological and market conditions and continuous adjustments are therefore crucial to guarantee the most cost-efficient and optimal setup of strategic reserves (Karpinski, 2023).

As for the objective, strategic reserves can either be limited to 'passive' volume risk mitigation (i.e. compensate for material shortages when they occur) or have a more 'active' role in managing price-related risks (Wolf, 2022; Hache & Jeannin; 2023). In the latter case, materials could, for example, be released in a situation of prolonged high prices, or against extreme price volatility. This type of market intervention could offer some benefits in the short term, but would likely require greater administrative capacity and – crucially – carry a significant risk of market distortions. Keeping material prices artificially low would indeed prevent the market from conveying the necessary scarcity signals and hence the private sector from adopting the necessary technological adaptations (Hache & Jeannin; 2023). Further, this would limit incentives to invest in domestic primary and secondary production capacity. While forms of price controls to be triggered only in predetermined, 'extreme' circumstances (e.g. on the same lines as the gas market correction mechanism[28]) could limit these risks, a purely 'passive' role would be preferable (Wolf, 2022)

In terms of governance, key element to consider is the level of decentralisation of strategic reserves. In the EU, the model could range from an entirely centralised one in which the European Commission (or a delegated agency) sets up and manages the whole EU stockpiling capacity, to a purely decentralised system where such responsibility is left to private entities at the national level (Wolf, 2022). On the one hand, centralised solutions would decrease overall storage costs thanks to economies of scale and avoid possible coordination or free riding issues, but limit incentives for privately-led risk management initiatives as well as the speed and efficiency of stock releases. On the other hand, autonomous stockpiling by companies would leverage their deeper expertise in supply chain management and knowledge of CRM market dynamics, though at the expense of limited coordination and higher risk of under-provision (Wolf, 2022; Rietveld et al., 2023).

In light of the above, different assessments have shown that the most efficient and feasible solution in the EU would be a hybrid one, whereby reserves are operationalised by the private sector but centrally coordinated at the EU level (Wolf, 2022; Rietveld et al., 2023; Karpinski, 2023). In such a system, the reserve volumes could be left on a purely voluntary basis in the initial set-up phase, with minimum requirements gradually enforced to avoid free riding and guarantee sufficient hedging. Financial incentives designed by Member States could also support the establishment of strategic reserves. The Swiss stockpiling system, with both minimum mandatory and additional voluntary reserves prescribed by the federal government and incentivised via loan guarantees and tax advantages, could offer a useful example (FONES, 2023).

Irrespective of the model chosen, strong coordination and market monitoring capacity are vital to limit market distortions and guarantee a cost-effective stockpiling system. As storing CRMs would ultimately require withdrawing them from existing (tight) markets, the cost, technical feasibility and possible impacts of such an option need to be carefully assessed. Ultimately, if not intelligently managed, strategic reserves could exacerbate the same supply and price risks they seek to avoid.

[28] Mechanism set by Council Regulation (EU) 2022/2578 of 22 December 2022 establishing a market correction mechanism to protect Union citizens and the economy against excessively high prices.

5. CONCLUSIONS

There is no escaping the fact that the progressive transition towards a digitalised and climate-neutral economy will build upon the uptake of CRM-intensive technologies. In the short term, this will put heavy pressure on CRM markets, with the risk of CRM price spikes and supply crunches. At the same time, growing geopolitical divides and legitimate desires to develop homegrown refining and manufacturing capacities intensify the risks of CRM trade restrictions. This generates a significant degree of uncertainty for regions like the EU, which have long outsourced the production of the CRMs they need.

The challenge posed by CRM supply risks calls for a systematic assessment of all available sourcing options, and the development of comprehensive strategies to secure access to these resources. Amid a mushrooming of CRM policies and strategies, the Critical Raw Materials Act represents the EU's response to that call.

While the EU has long seen its mineral production decline, there is potential to expand primary and secondary output. Indeed, market pressures are now sparking new interest in the – possibly significant – European extractive potential. Expanding primary production capacity still faces major hurdles, however. Structural deficiencies in the sector coupled with harsh (incidental) market conditions, such as volatile material prices and high energy prices, will make it hard to attract investment in the sector, if not backed by a certain degree of public support. Against increasingly constrained EU and national budgets, careful prioritisation of the projects to support production will be necessary.

On top of this, the timing needs careful consideration. Augmenting domestic production will take years, if not decades. Recycling output, too, will take time to scale up substantially because of the time lag between market uptake and saturation of strategic technologies. Still, the conditions should be set now for the EU to sustainably exploit its domestic mining and recycling potential in the medium to long run. For the former, this means developing the necessary trained workforce, winning the trust of local communities and ensuring enough market transparency. For the latter, it means developing and deploying an efficient and economically viable recycling infrastructure for when sufficient volumes of products reach the end of life.

The inherent limitations of domestic sourcing will require the EU to leverage the whole policy toolkit at its disposal, especially in the short term. To start with, this means accounting for and capitalising the often overlooked contribution of material substitution and resource efficiency. In many ways, market dynamics are and will continue driving consumption choices that rationalise the use of CRMs, thereby limiting pressure on overall demand. Batteries are a great example of this trend. In some cases, however, alternative materials or technologies are available but not yet cost competitive. In others, substitutes are still being developed at lab scale. Either way, continued support for research and innovation on raw materials should be prioritised in the years to come.

The EU's CRM strategy cannot prescind from a strong international component. With increasing international competition for these resources and a possible geographical shift in global production, cultivating solid and reliable CRM trade and cooperation relationships will be imperative to secure extra-EU supplies. On the one hand, and in line with past and ongoing efforts, the EU should continue to strengthen and renew its network of free trade agreements, including through specific provisions aimed at easing trade and investment in CRMs (notably in dedicated 'Energy & Raw Materials chapters'). On the other hand, it should keep forging business-oriented strategic partnerships with resource-rich countries, with the aim of channelling EU know-how and financial resources into extra-EU CRM production capacities, increasing overall market thickness.

Beyond bilateral trade and cooperation, dedicated multilateral fora will also become increasingly important in coordinating action across international players. Where existing initiatives like the Minerals Security Partnership have largely focused on bringing resource-hungry countries to the table, the new EU-led idea of a Critical Raw Materials Club has the significant advantage of involving resource-rich countries as well. While the setup of the platform is still being discussed, the EU should take the opportunity of sitting in the driving seat to push for the most inclusive yet effective format possible.

As supply disruptions loom, discussions over the setup of strategic reserves of CRMs have also grown more widespread. If properly managed, material stockpiling could arguably be one of the most promising options for offsetting the risk of short-term supply disruptions. As a well-established practice already, the EU could take inspiration from its existing oil and gas reserves or from CRM stockpiles across the world to set up its own, European CRM reserves. That being stated, the high costs, technical difficulties and the potential counterproductive effects of poorly managed reserves should be carefully assessed a priori. If this option were to gain momentum in the future, the greatest possible degree of central coordination would be beneficial.

None of the avenues outlined above will, by themselves, remove the EU's CRM supply risks. The magnitude and urgency of the dilemma will require adoption of a mix of solutions. On the domestic front, the ideal type of policy action might be driven by each Member State's specific experience with it, preferences or resource potential. Some may have significant resource endowments to exploit, but others may be inclined to leverage recycling or alternative materials. Also, although CRMs are often regarded as a homogeneous group of materials, their geological, technological and market conditions can vary widely. While some issues are common to all CRMs, others might only be relevant for some. Therefore, different materials may require different responses, and actions should increasingly be tailored to each material value chain, avoiding 'one size fits all' solutions.

Finally, the need for coordinated mapping and monitoring cannot be emphasised enough. Indeed, our assessment shows that all the options discussed can only be effective if they are informed by comprehensive assessments of resources, markets and technological developments. Upscaling resource extraction in the EU, for instance, can only build on a deep understanding of the EU's underground potential. Likewise, in order to attract investment in recycling or innovative materials, it is crucial to ascertain – to the extent feasible –ongoing and future technological trends. For some policies, such as stockpiling, a lack of reliable or up-to-date information can even exacerbate the very risks they seek to address. Filling existing knowledge gaps and building a solid – preferably centralised – monitoring system is the one horizontal, 'no regrets' action that should underpin any future policy in this domain.

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