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Critical Raw Material Supply Matters and the Potential of the Circular Economy to Contribute to Security

Metals and other materials are essential for enabling modern societies and welfare. Demand for some metals has increased sharply in recent years because of the ongoing energy transition and digitalisation. The energy transition increases demand for metals used in batteries, such as lithium; electric motors and generators, such as rare earths; and solar photovoltaics (PVs), such as silicon. Future demand for these metals is projected by some to increase strongly for several decades; for example, the International Energy Agency (IEA) projects that global demand for many critical metals will increase by 400% up to 2040 (IEA, 2022). The challenges of securing raw material supplies have contributed to states' responses by developing policies to enhance their supply security (Lee et al., 2020). Some of these initiatives enable enhanced collaboration and governance arrangements while others risk increasing state rivalry and conflicts as they are incompatible with the interests of other states.

The European Union is already import dependent on many raw materials, for example, fossil fuels and semiconductors. These dependencies have exposed some of the Union's sensitivity to disrupted imports in recent years. Politicians have become increasingly aware of these dependencies, and some have highlighted their risks. Or, as European Commission President Ursula von der Leyen put it when announcing the European Critical Raw Materials Act: "Lithium and rare earths will soon be more important than oil and gas. Our demand for rare earths alone will increase fivefold by 2030. …We must avoid becoming dependent again, as we did with oil and gas" (European Commission, 2022).

Focussing on critical raw materials (CRM), this article explores the potential for increased circularity to contribute to (supply) security and strengthen the EU's autonomy, i.e. the Union's capacity to act independently of other actors.

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The article starts by providing an overview of the contemporary academic debate on critical metal demand for sustainability transitions and outlines the key supply chain bottlenecks that are often identified as a cause for concern for supply security. It then moves on to assess how the circular economy can impact these concerns, focussing on the EU. Finally, it discusses how the circular economy can be leveraged to increase EU strategic autonomy and the potential for conflicting policy goals this may bring.

Which raw materials are critical and why?

Metals are not critical in themselves. It is rather a combination of several factors that explains why some materials are classified as critical. The two most important factors are related to a high likelihood of supply disruption combined with high vulnerability to disruption (see e.g. Schrijvers et al., 2020). Thus, it is a combination of demand- and supply-side factors. The EU's current critical material list includes 34 materials (EU, 2023). It is based on a screening of supply risk and the economic importance of the material studied. In addition to critical materials, the EU has also identified a group of 16 strategic materials on the basis of a high projected supply-demand imbalance.

The supply and demand factors used for criticality assessments are both dynamic and context dependent. The recent upsurge in demand for renewable energy technologies has increased the demand for some metals, and this has in turn contributed to increasing the number of metals classified as critical. For example, the EU added lithium to its list of critical raw materials for the first time in 2020 (EU, 2020a). One of the reasons for this was the increased lithium demand for producing lithium batteries in electric vehicles. The EU is import dependent on this raw material; metal reserves and extraction are found in just a few countries, and one country (China) dominates the metal refining stage of the supply chain. Other actors may perceive lithium as less critical because of different material factors (e.g. import dependency), context (valuation of import dependency) or a combination thereof.

Helium was removed from the EU's CRM list in 2020 because its economic importance had declined, although it was later reintroduced in 2023. The supply of helium remained a concern during the period in between; for some of its remaining applications, there are no substitutes as helium is the only option when very low temperatures are required, for example for magnetic resonance imaging (MRI) systems used in hospitals. This illustrates one of the limitations of focussing on a material's economic importance or share of consumption for applications that are small but can be vital or strategic for society, such as some technologies used for medicine and defence.

Historically, the list of metals classified as critical looks different from today's CRM lists. For example, mercury was perceived as critical in Sweden in the early 1900s because it was needed to produce soda and chlorine at that time (Vikström, 2018). Global mercury production from mines has been in decline since the 1970s due to technological developments and environmental legislation aimed at reducing demand due to toxic properties (Swain et al., 2007). Similarly, sulphur was thought to be critical in the 1800s due to increased demand for chemicals, in particular processing textiles (Ferrara, 2016). The USA invented new extraction techniques, which helped it outcompete Sicily to gain market dominance. Today, sulphur is removed from fossil fuels during fuel processing or post combustion to prevent sulphur oxide emissions that contribute to acid rain. This source is greater than consumption, and there is a global sulphur surplus. Sulphur is therefore unlikely to be classified as critical by states today, at least until the use of fossil fuels has declined (Månberger, 2021).

The energy transition is one of the key drivers of demand for many, but far from all, materials on the EU's CRM list. Although demand from this sector is likely to increase rapidly in the coming years, a word of caution is needed as the historical examples have illustrated that criticality is not static. The rapidly evolving renewable energy technologies may therefore both increase, reduce and replace metals on the list. The EU has the ability to influence some of these factors, and its decisions and strategies can therefore contribute to making metals more or less critical in the future. Importantly, the historical examples illustrate that both increased supply and decreased demand can reduce criticality.

Finally, it should be noted that although lists with critical raw material can draw attention to increased mining activities, other parts of the supply chain should not be overlooked. For example, there is a whole range of activities that takes place before a mine can open, including exploration, financing and permitting. Downstream from the mine there is also a range of processes that needs to function, including metal refining to reach the right purity grades for a particular application. In some cases, these downstream processes are geographically located in close proximity to the mine, sometimes in a third country and sometimes close to the metal user.

What are the supply constraints for critical raw materials?

To comply with the Paris Agreement, IEA (2022) estimates that demand for many critical metals is likely to increase by 400% by 2040, but this could be even higher if more ambitious climate policies are implemented. Research has provided similar estimates but their variety is broad. Estimates of annual demand in 2050 diverge by more than an order of magnitude for several critical metals (Watari et al., 2020).

In addition to different assumptions about what a low-carbon transition looks like, e.g. the number of electric vehicles (EVs) manufactured each year, the estimated metal demand is also sensitive to assumptions about how metal intensities will develop, the specific end-use technologies that will be applied, and their lifetime and recycling rates (Månberger and Stenqvist, 2018). When combined, these factors provide very different results for both the aggregated metal demand over the studied period, the annual demand each year and the share supplied by mining and recycled materials.

Supply constraints are sometimes classified as "below ground" and "above ground" factors. The below ground factors, also known as availability, compare metal demand with reserve estimates using primarily geological data. The above ground factors focus on, for example, the institutional conditions that can hinder extraction, and then use this knowledge to assess whether the metal reserve is accessible or not.

Concerning below ground factors, the geological extractable metals are likely to be sufficient for the energy transition (Wang et al., 2023). In the long term, increased use of recycled material will be needed, as mineral reserves are finite. However, the finite nature of metal reserves is probably not a constraint in the near term. Furthermore, reserves tend to be revised upwards when demand increases, a phenomenon often referred to as reserve growth.[1]

Above ground factors are a heterogeneous group of issues that can constrain extraction. The impact can cause short-term disruptions as well as restrict mining rates over time. The ESG cluster (environmental, social and governance) is a prime example that has been highlighted by several authors as a potential limitation for future mine supply (Jowitt et al., 2020). Many mines for critical raw materials are located in water-scarce regions, where the interests of the mining industry are incompatible with lo-

1 See e.g. Mudd and Jowitt (2017) for a study of how gold, nickel and copper reserve estimates have developed over time.

cal indigenous and/or peasants groups. For example, a study of global mine projects found that 94% of bauxite, 90% of graphite and 87% of lithium projects are located at or in close proximity to indigenous and/or peasant lands (Owen et al., 2023).

The majority of metal reserves of many critical raw materials are geographically concentrated in just a handful of countries. For some critical metals, this also holds for the proceeding refining step in the supply chain. The geographical concentration makes supply sensitive to local events such as political instability. In addition, it makes it possible for hostile suppliers to weaponise the supply and use it as a foreign policy tool. However, it is far from certain that such actions would be successful, i.e. forcing the targeted state to concede and change its behaviour (Månberger and Johansson, 2019). States are not as sensitive to a disruption of metal supplies as they are to disrupted energy supply in the short term. Reduced energy access immediately disrupts societies and hurts economic activity, whereas reduced metal supplies impact the manufacturing sectors ability to produce new goods. Existing technologies and infrastructure are not impacted by the metal shortage. In the longer term, markets respond to reduced metal supplies from one country with developing technological substitutes and increased investment in other mines. This makes it difficult for exporting states to succeed by repeatedly restricting supplies over time (Overland, 2019).

The security matters of a circular economy

The circular economy can be conceptualised as changing the current linear resource flows by closing, narrowing and slowing the loop (Geissdoerfer et al., 2017). Closing the loop includes end-of-life recycling. Narrowing the loop is about reducing the use of materials, for example by dematerialisation. Finally, strategies to slow the loop aim to increase the lifetime of products through, e.g. repairs, upgradability and reuse.

Closing the loop

Some EU policy documents for the circular economy mention how circularity can benefit the Union's security, for example by increasing the usage of recycled raw materials thus focusing on "closing the loop". The rationale is often presented as though recycled material is more secure than primary raw materials. For example, the EU briefing on its circular economy package stated that "a circular economy would mitigate risks associated with the supply of raw materials, such as price volatility, availability and import dependency" (EU, 2016). However, it is not a given that recycled material is more physically secure than primary extracted materials, nor that its price is more stable as there are typically volatility spillover effects between markets that limit the arbitrage. Furthermore, the EU is currently integrated in international trade networks and is an exporter of critical materials embedded in waste streams that are then processed in other states. Increased use of recycled material may therefore shift the EU's import dependence from primary to secondary raw materials, unless domestic recycling supply chains are developed.

In 2020, the EU exported 32.7 million tonnes of waste, of which slightly more than half (17.4 million tonnes) was ferrous metals (Eurostat, 2021). Turkey was the main destination (with 13.7 million tonnes), followed by India (2.9), UK (1.8), Switzerland (1.6), Norway (1.5), Indonesia (1.4) and Pakistan (1.4). Some reports on waste trade have argued that implementing strategies to reduce waste exports will bring additional costs for waste treatment due to lower economies of scale and could also deprive developing countries of an industry that provides economic growth and jobs (see e.g. Barrie et al., 2022; Langsdorf and Duin, 2022). There could thus be a trade-off between, on the one hand, increased self-sufficiency and, on the other hand, promoting international trade, development in emerging economies and the EU's ambition to collaborate and strengthen its ties with its neighbourhood. The Critical Raw Materials Act states "the EU is committed to supporting our partner countries to move up the value chain" (EU, 2023). However, at the same time the act defines targets for domestic processing and recycling that are higher than the target for domestic extraction. The EU's strategy is thus partly inconsistent and not scalable to all other importers.

The rapidly increasing demand for critical raw materials and the long lifetime for many of their main applications means that even if collection and recycling increase, it will take time until secondary raw materials can meaningfully replace primary raw materials. For example, Kastanaki and Giannis (2023) estimated that in 2030, improved battery recycling could meet between 5.2% and 7.2% of EU's demand for lithium, cobalt, nickel and copper used in new batteries. These values are in line with the EU's proposed requirements for the minimum share of recycled material content in new batteries after 2030 (EU, 2020b). The infrastructure required to process waste lithium batteries is currently not in place within the EU, and domestic recycling could require adding capacity equivalent to 15-28 GWh in 2030 (Kastanaki and Giannis, 2023).

Narrowing the loop

Reducing the use of CRM can be accomplished by improved resource efficiency and shifting to material substitutes that are less critical. This mitigates the issue with

CRM demand but sometimes at the expense of other policy objectives and priorities. Material efficiencies are developing rapidly and responding to price signals for many materials used in renewable energy technologies. Some of the examples include the reduced use of cobalt in lithium batteries and the precious metal silver in solar PVs. One of the drawbacks with this development is the trade-off with recycling economics (Ardente et al., 2019). As the share of critical material in a product decreases, it also becomes more expensive to recover during recycling.

In some cases, there is a trade-off with general dematerialisation aimed at reducing the total material use and with dematerialisation that is aimed at reducing the use of CRM in particular. CRM substitutes can result in lower performance. For example, replacing permanent magnets in wind turbine generators and electric motors with copper coils increases the weight of the motor and generator but may also require additional mechanical components such as a gearbox for the wind turbine and reinforcing structural components to not compromise durability.

Some of the EU legislation is targeted at narrowing CRM loops or supporting such developments. This includes research programmes like Horizon 2020 aimed at developing alternative technologies that do not rely on CRM to the same extent.

Radical reduction in future CRM demand is possible by extending the system boundaries of the resource supply chains studied. For example, Riofrancos et al. (2023) compared future CRM use in different transport systems, i.e. expanding the boundary from individual technologies to systems of technologies that represent different organisations and society metabolism, while delivering the same mobility service to the final user. Doing so, they found substantial potential to reduce the use of CRM by reducing vehicle ownership and weight, and increasing utilisation of the vehicle fleet. Realising this potential and maintaining the same level of mobility could require both technological development as well as institutional changes to facilitate car sharing.

Slowing the loop

Impacts from strategies to slow CRM resource cycles by lifetime extensions, reuse and remanufacturing have received much less attention from researchers than strategies for closing and narrowing resource cycles (Watari, Nansai and Nakajima, 2020). Similar to recycling, the potential to offset primary materials is limited in the short term as lifetimes are long and demand is growing rapidly. The long-term potential is substantial. For example, in 2050, reuse could correspond to 70% of demand for neodymium in permanent magnets in the USA (Maani et al., 2023).

Material recycling could sometimes be preferable over reuse if the material intensity has improved to the extent that manufacturing a new product can reduce the material footprint. However, the drawback with recycling is that it often results in material quality losses due to the mixing of materials. Dilution with primary material is required to mitigate material down-cycling; reusing, therefore, holds greater potential than recycling to maintain material quality longer. Also, during recycling it is unavoidable that some material is lost or would be very expensive to recover, e.g. material that ends up in aluminium dross (Meshram and Singh, 2018).

Repurposing extends the lifetime by changing the use of the product after the first life cycle has reached its end. One example that is highly relevant for CRM demand is spent lithium batteries from electric vehicles. The performance of such batteries can be too low for remanufacturing into new vehicle batteries but still sufficient for use as stationary storage. Repurposing spent EV batteries into stationary storage increases the use of variable renewable electricity but it also locks-in the materials in the lithium batteries for a longer time (Bobba et al., 2019). At the same time, demand for primary lithium and some other metals used in EV batteries may not decline much during the lifetime extension because the alternative to using second life EV batteries could be other battery technologies such as redox flow batteries that use vanadium. From a security perspective, the dependence on vanadium or lithium battery supply chains should therefore be assessed and compared to better understand the potential trade-off with second life batteries.

Concluding discussion

Circular economy policies will relieve some pressure on primary metal extraction. However, if the potential for closing and slowing the loop is realised, its impact on primary demand is likely to be minor in the 2020s but then increase exponentially as more renewable energy technologies reach their end-of-life. However, even in small doses, the use of recycled material will increase the diversity of the resource base. In general, increased diversity is a hedging strategy that is useful when uncertainty is high, e.g. in the supply constraints mentioned in the previous section.

The EU does not currently have sufficient recycling infrastructure in place to recover the CRM from its waste flows. The choice between developing such capacity domestically or in cooperation with other countries is not straightforward as both options have different strengths and weaknesses from a security perspective and other priorities should be considered too. In short, the choice is whether to prioritise a deeper integration with the neighbourhood and become more (inter)dependent or reduce exposure to import risk.

Of the different circular economy strategies, the potential to narrow CRM resource loops seems to have the greatest impact on demand in the short to medium term. Some obvious trade-offs have been identified but, in general, not many policies seem to target this area. The possibility of strengthening policy coherence can thus be substantially increased if the study of policy impact on CRM demand is broadened. This also includes studies of how society resilience and adaptive capacity can be strengthened by including more policy areas, i.e. shifting the focus from threats to security enabling capacities (Månsson, 2016; Kivimaa et al., 2022). Developing such capacity can contribute to the Union's strategic autonomy.

Finally, it should be noted that reduced use of fossil energy enabled by enhanced circularity and energy transition, is likely to have a greater impact on the EU's security and autonomy than the increased use of (critical) materials. As noted above, this is because the imported (fossil) energy is a flow that disrupts many other flows while most CRMs are converted into a stock. However, there are a handful of CRMs for which the use resembles a flow similar to energy. In particular, this applies to the soil nutrients phosphate and potash used in fertilisers, although the latter is not classified as a CRM by the EU. Improving the circularity of these flows could thus be beneficial to strengthening food security and the EU's autonomy.

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