Critical and strategic materials: potential bottlenecks and the EU perspective

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Abbreviations

AEL	Alkaline electrolyser
ASM	Artisanal and small-scale mines
CAM	Cathode Active Materials
EV	Electric Vehicle
GW	Gigawatt
GWh	Gigawatt hour
HPAL	High Pressure Acid Leach
IEA	International Energy Agency
Kt	Kiloton
LCE	Lithium carbonate equivalent
LIB	Lithium-ion battery
LFP	Lithium-iron phosphate
LME	London Metal Exchange
REE	Rare Earth Element
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
USGS	United States Geological Survey
WGI	Worldwide Governance Indicators

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1. Introduction

The shift from fossil fuels to renewable energy presents both benefits and risks in terms of energy dependence. While the EU's dependency on fossil fuel imports is likely to decrease significantly, it will be replaced with an increasing dependency on imports of a much broader array of materials critical for the energy transition.

The dependency will undergo significant changes within the next decades as new resources are discovered and existing reserves are utilised. While this bears some similarity to the early stages of oil extraction, due to the speed of the transformation and the resulting scale-up in demand, the spikes in commodity prices will be much larger and there will be increased market uncertainty. However, unlike hydrocarbons, as pointed out by Giuli and Oberthür (2023), most of the critical and strategic materials can be recycled. This will have an impact on the EU's long-term import dependency. As efficiency increases and new technologies are discovered, this dependency may not prove as enduring as than that on fossil fuels.

However, before that happens, the transformative change in the EU and other countries may be slowed down by bottlenecks in availability of materials essential for the transformation. The risks of such bottlenecks have been addressed by the European Commission in its recent Critical Materials Act, the United States through its Inflation Reduction Act, and Australia in its Critical Minerals Strategy 2022, among others (Bazilian and Brew, 2022; Department of Industry Science and Resources, 2022; European Commission, 2023).

However, to provide a proper policy response to the drivers of such bottlenecks, a much more differentiated approach is needed. For many critical and strategic materials, the geological reserves, mining, and processing are heavily concentrated in a few countries. In addition to the bottleneck risks that concentration alone presents, country stability must also be considered, as the level of geopolitical risk of a high concentration over a part of the supply chain varies in different countries. Furthermore, across different time horizons, concentration of reserves, extraction, and processing each requires different policy responses. Even if the materials are available in different countries, bottlenecks may also result from the discrepancy between policy measures driving demand and the speed with which the supply of the materials can be increased. At the same time, the risk of bottlenecks caused by the lack of available materials in the EU may be reduced either by extracting EU resources or recycling products to increase secondary supply.

To initiate a discussion about a more differentiated approach to the risk of bottlenecks in the availability of materials critical for the energy transformations, this paper presents an approach and tests it on four materials essential for the development of EV batteries. To account for the changing character of the new dependencies, the approach is tested for both near- and medium-term time horizons. This approach should be adapted to the specific needs of its users and the specific characteristics of a given product.

This discussion paper begins with an overview of the role of critical and strategic materials in the energy transition, highlighting the diversity and importance of materials required for low carbon technologies. We then move on to a brief overview of the proposed methodology and discussion of the materials selected for this study, presenting results and potential areas subject to bottlenecks. We close with a brief discussion of options for the EU and proposed policy priorities.

2. Critical and strategic materials and the energy transition

Apart from reducing overall energy consumption, to reach its emissions reduction goals, the EU and its member states will have to significantly accelerate the decarbonisation of their energy sectors and increase electrification. All of the technologies needed for decarbonisation require the use of materials that have not been used on such a massive scale in the past. Failing to adequately prepare for this increase in demand will result in a delayed and costly energy transition. To effectively investigate the need for such minerals in the EU, we looked at different studies reflecting the installed capacities of these technologies in 2030 and 2050 compared to 2022. The results are provided in Table 1.

Table 1 Projected green technology capacity expansions in the EU

Technology	2022[1] installed capacity	2030 installed capacity	2050 installed capacity
Solar PV	209 GW	600 - 672 GW	1400 - 7700 GW
Wind onshore	165 GW	254 GW	1000 GW
Wind offshore	14.6 GW	60 GW	300 GW
Heat pumps	197 GW 20 million units	285 – 449 GW 45 million units	NA
Electrolysers	0.135 GW	100 GW	341 - 511 GW
Batteries for Grid Storage	3.8 GW	23.7 - 44.6 GW	100 GW
Batteries for Electric Vehicles	60 GWh	300 GWh (Electrical Energy Storage, 2022)	NA

Based on: (Ansari et al., 2022); (Bhambhani, 2018); (Blackburne, 2022); (COM (2023) 161 Final, 2023); (Corbetta et al., 2015); (Dickson, 2021); (Electrical Energy Storage, 2022); (European Association for Storage of Energy, 2022); (European Commission DG Energy, 2023a); (European Commission DG Energy, 2023b); (European Commission, 2022); (European Electricity Review 2023, 2023); (Heat Pump Record, 2022); (IEA, 2022b); (Janssen, 2020); (Schoenfisch & Dasgupta, 2022); (Sönnichsen, 2019). Single numbers indicate only a single source available, whereas ranges indicate several different sources.

For a clean energy transition and to decrease dependency on fossil fuels in the EU, solar photovoltaics (PV) are key, and one of the fastest technologies to scale up. In its REPowerEU package, the Commission included the target of more than 320 GW of newly installed solar PV systems by 2025, more than double the current level, and nearly 600 GW by 2030 (European Commission, 2022). Another important source of electricity in the EU will be wind energy. In 2022, over 17% of electricity generated in the EU came from wind energy (Wind Energy in Europe, 2023). Significant growth is projected, with a 20-fold increase in current installed offshore capacity

[1] 2022 or latest available year

(European Commission, 2022) and a six-fold increase in installed onshore capacity by 2050 (Dickson, 2021).

Looking beyond electricity generation technologies, the EU maintains a strong position in electrolyser manufacturing capacity worldwide. Currently, roughly 40% of global electrolyser manufacturing capacity is located in the EU (IEA, 2022a), with the EU's 2020 Hydrogen Strategy ambitions requiring significant expansion in electrolyser capacity. By 2025, the manufacturing capacity of electrolysers in the EU should reach 17.5 GW per year (Collins, 2022). Additionally, in response to the Russian invasion of Ukraine, the REPowerEU plan sets targets to deploy individual heat pumps at a rate that is twice as fast as before the crisis, resulting in the installation goal of 45 million heat pumps by 2030 (IEA, 2022d). Finally, the continued investment in a broad range of technologies will contribute to greater electricity security, of which battery development for both grid storage and electric vehicles (EVs) plays a key role.

Table 2 shows the critical and strategic materials necessary for each technology.

Table 2 Critical and strategic materials needs

Uses	Technology and/or Components	Material Needs
Solar PV	Monocrystalline cells, polycrystalline cells, thin-film cells	Amorphous silicon (a-Si), copper, cadmium telluride (CdTe), gallium, indium, selenide, silicon
Electrolysers	Alkaline, polymer electrolyte membrane, proton exchange membrane, and solid oxide	Cerium, copper, graphite, lanthanum, palladium, platinum, nickel, titanium, yttrium, zirconium
Wind offshore & onshore	Geared, direct drive	Copper, rare earth elements (REEs)
Heat pumps		Copper
Electric vehicles	Chassis, motor, batteries	Aluminium, boron, cobalt, copper, graphite, iron, lithium, manganese, nickel, REEs

Source: Own compilation based on (Cummins Inc., 2020; IEA, 2022e; Moreira & Laing, 2022; Noor, 2020; Verma et al., 2022)

Looking specifically towards the focus of this discussion paper, battery materials are becoming increasingly important. With the sale of EVs increasing quickly, and an increasing number of countries phasing out the sale of combustion vehicles after 2035, the availability of the materials used in battery production may increasingly become a bottleneck for the transformation. The critical minerals used in these vehicles are found mainly in their batteries.

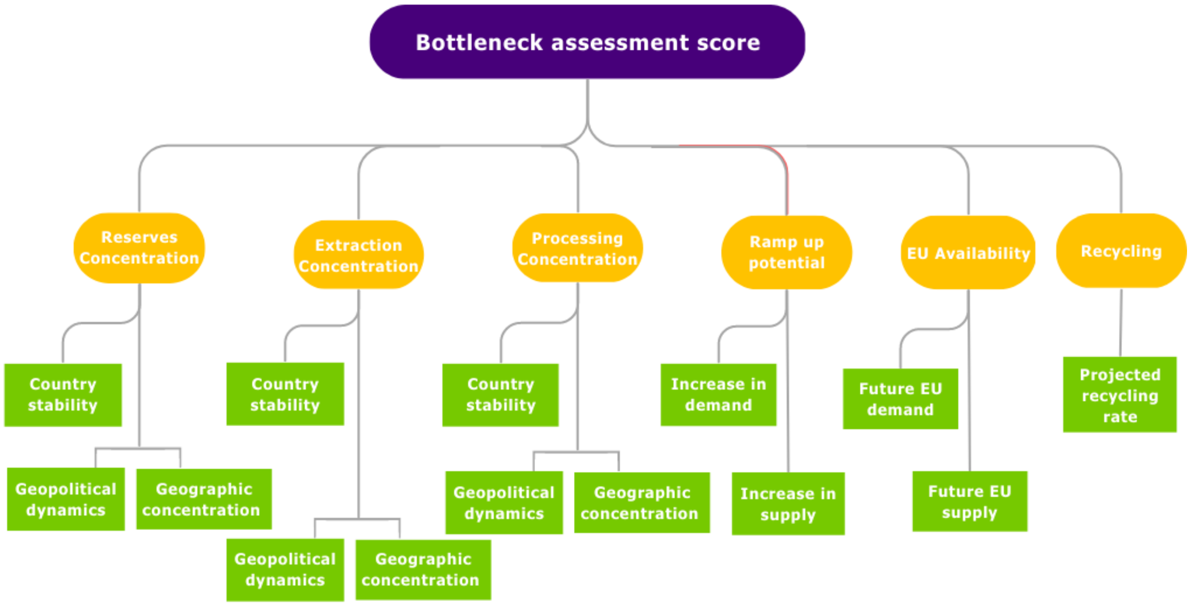
Lithium-ion batteries (LiBs) used in EVs and energy storage are composed of battery cells contained in modules within a battery pack. The cells account for most of the total weight of the battery and contain several minerals in the anode (e.g. graphite), the current collector (e.g. copper) and the cathode active material (CAM), such as lithium, nickel, cobalt and manganese. The modules and pack components consist mostly of aluminium, steel, coolants and electronic parts. The requirement for each mineral in the battery depends significantly on the cathode and anode chemistries.

3. Approach to assessing the potential for clean energy material bottlenecks

The need to scale up imports of critical and strategic materials for the energy transition in the EU creates a potential for bottlenecks that may slow down the transformation to a low-carbon economy. However, the factors that determine the potential for these bottlenecks differ depending on the stage of the transition and may require a differentiated policy response. In this section, we identify several factors that determine the potential for a bottleneck in supply to occur. In the subsequent section, the factors are operationalised and applied to the four selected critical and strategic materials.

We identified six indicators that may influence the likelihood of a bottleneck occurring in the supply chains of the selected materials: reserves concentration, extraction concentration, processing concentration, ramp-up potential, EU availability, and recycling. While not an exhaustive list, these factors consider primary and secondary supply sources, and domestic and international supply chains and politics in a way which may provide additional insight into the near-term prospects for critical and strategic materials. **Figure 1** provides a short explanation of the ways in which these indicators are understood.

Figure 1 Bottleneck assessment score overview



Reserves concentration aims to consider the longer-term extraction prospects for each material. This indicator is based on three sub-indicators. First, it considers the geographic concentration of the reserves of a particular material, looking at the distribution of reserves around the world and calculating the proportion held by the top three countries. This indicator is weighted by two other indicators: the risk of instability and the potential of using exports of the materials for country's geopolitical goals. The risk of instability is assessed by weighting the proportion of reserves which are located in states that are less stable than the average, as indicated by the most recent Worldwide Governance Indicators' (WGI) Political Stability and Absence of Violence measure (Kaufmann et al., 2010; World Bank, 2022). The risk of using the EU's dependency on critical material imports from a given country to accomplish the country's geopolitical interest is based purely qualitative assessment and is subject to short-term changes.

Extraction concentration applies the same approach as reserves concentration but considers active and near-term extraction projects, with evaluation based on mine output per country.

Processing concentration applies the same approach as reserves and processing concentration, considering the concentration of processing capacity (current and projected) per country.

Ramp-up potential aims to account for potential short-term bottlenecks resulting from the discrepancy between the speed of an increase in demand (for example, due to policy measures that encourage the uptake of certain low-carbon products) and the timeline for bringing additional extraction or processing capacity online. This indicator encapsulates the fact that policies, especially in the form of support schemes for certain low carbon products such as batteries or renewable energy installations, may result in a significant and short-term increase in demand for critical and strategic materials used in their manufacturing. This demand can be accelerated by a significant increase in the costs of fossil fuels, or the introduction of policies that promote low carbon alternatives different countries at the same time or affect multiple products using the same materials, for example manganese used for geothermal and concentrated solar. The assessment of demand may vary depending on the availability of the resource and whether the bottleneck occurs at the stage of extraction (long lead time), processing, or recycling (shorter lead time). It may also be affected by the substitutability of the critical material in the specific product.

EU availability considers to what degree supply of a given material can be satisfied by EU resources. It is assessed by considering current and estimated EU demand and production to estimate future import dependency. Should the EU have enough of a critical material to satisfy its whole demand in each period, it may counter high risks of bottlenecks resulting from other indicators.

Recycling considers secondary supply sources of materials. It is assessed by measuring the percentage of future projections of demand that can be met through recycling, also considering the ramp-up potential for recycling capacity. While it has similarity to the EU availability indicator, critical and strategic materials recycling requires a very different policy framework than what is needed to facilitate mining for new materials.

As bottleneck risk indicators, all concentration and ramp up scores are graded on a scale from 1 to 10 using a mix of qualitative and quantitative data. As developments to boost domestic primary and secondary supply can counter the impacts of bottlenecks in concentration and ramp up, the scale is inverted for EU availability and recycling which are graded from -1 to -20. A score of -40 would indicate that all demand in each time horizon could be met by EU primary and secondary supply.

Geological availability

Using the United States Geological Survey (USGS) data on mineral resources, which are defined as material located in or on the Earth's crust "in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible," we found that there is more than enough of each of the minerals we analysed in the ground to meet near and longer-term projections in demand. Resources are inclusive of reserves, which are materials that can currently be economically extracted or produced. Thus, with a very low potential for bottlenecks looking at geological availability alone, we focus the analysis of this paper on other identified indicators with higher bottleneck potential.

4. Testing the approach

In this section, the approach described above will be applied to **cobalt**, **graphite**, **lithium**, and **nickel**. These materials were selected due to their importance to green technology manufacturing and ongoing push for electrification. They are integral to current battery chemistries and will be used extensively for large scale decarbonisation of the transport and electricity sectors. To assess the risk of bottlenecks in the decisive decade for energy transformation, the approach is tested for 2025 and 2030. It can also be used for post-2030, particularly for 2050, though a longer-term analysis should rely on a much more in-depth assessment across all indicators and would require numerous assumptions regarding technology development and geopolitical developments. Instead, we complement this section with a short and more general recap of the availability of these materials to satisfy EU demand in 2050 in subsection 4.3.

4.1. Materials overview

As a critical element of rechargeable LiBs, as well as some superalloys and magnets, **cobalt** is challenging to substitute and will continue to be utilised as long as LiBs remain dominant in EV production and battery-storage applications. It is an often-discussed critical material due to its production concentration in the Democratic Republic of the Congo (DRC) as well as the human rights abuses which are common at its 'artisanal' and small scale mines ("ASM"; Amnesty International, 2020; Baumann-Pauly, 2023; Gross, 2023; Niarchos, 2021). Cobalt demand is expected to rise nearly seven-fold by 2035. The majority of announced investments are in the DRC, meaning it will likely remain the centre of cobalt extraction (Islam, n.d.). The cobalt market is particularly receptive to changes in demand, as ASMs are generally quicker to adjust output and prices to bridge the gap between supply and demand in a way larger above-board operations may not be able to. At the same time, cobalt is a significant by-product of copper and nickel production and instability in these markets is likely to impact the cobalt market (Ibid.) High concentration, demand due to changes in battery chemistry, and increasing cobalt demand are likely to lead to continued volatility.

The market for **graphite** has historically been dominated by industrial uses, but the recent skyrocketing demand for EVs has contributed to its classification as a critical material due to its critical role in current LiB anodes, alkaline electrolysers (AELs), and electric arc furnaces (IEA, 2022e). Currently, China produces 80% of the world's graphite and dominates the entire supply chain for LiBs. Graphite is utilised in two forms, natural and synthetic, and experts predict that the mineral will remain critical for at least the next decade, as substitutes are limited (Ritoe et al., 2022). A scenario under which pure lithium anodes are used would decrease the demand for graphite, though this is unlikely given the demand growth and expected deficit of lithium is expected to be higher than for graphite in coming decades. The International Energy Agency (IEA) projects an eightfold increase in demand for graphite by 2040 compared to 2020 in the Stated Policies (STEPS) scenario and a 25-fold increase in demand in the Sustainable Development

Scenario (SDS) (IEA, 2022e). Global reserves are estimated at 330 Mt with the largest deposits in Turkey, China, and Brazil (U.S. Geological Survey, 2023). Growth in production is expected in Mozambique, Madagascar, Canada, and Norway, though a supply-demand deficit is projected as early as 2023, owing to the rising demand for LiBs (Barrera, 2023).

Lithium plays a critical role in the energy transition as a key element in modern batteries, particularly for EV and battery storage applications. Transitioning to electromobility is a cornerstone of the energy transition, and although alternative chemistry batteries for this purpose are being developed, LiBs utilising lithium hydroxide and lithium carbonate are likely to remain dominant (IEA, 2022f). The IEA's Stated Policies Scenarios (STEPS) estimates a nearly ten-fold increase in demand for battery storage and EVs by 2040, and IEA's Sustainable Development Scenario (SDS) expects that lithium will have the fastest demand growth rate of all the critical minerals over the same period (IEA, 2022e). Total proven reserves of lithium are around 400 Mt lithium carbonate equivalents (LCE; Gielen & Lyons, 2022). While this is adequate to satisfy demand, there are concerns that not all mined lithium will be battery-grade. Uncertainty about quality may lead to shortfalls in the near future. Additionally, variances in lead-times and investment in the battery value chain underscore the need for continued development of lithium production and processing capabilities. Careful coordination, management of energy and water resources, and cooperation between major suppliers and governments is critical to ensuring steady supply and avoiding potential bottlenecks.

Nickel is refined from several different resource types which can be processed to various end types in a complex system. Sulphide deposits are primarily in Russia, Australia, and Canada. Oxide resources are primarily located in Indonesia, the Philippines and the French overseas territory of New Caledonia (U.S. Geological Survey, 2023). Class 1 products, which contain greater than 99.8% nickel metal, are battery grade, whereas class 2 products (less than 99.8% nickel metal) tend to be used in other products such as stainless steel. Currently clean energy technologies make up around 10% of nickel demand for use in batteries or in alloys for renewables installations (IEA, 2022e). Changes in battery chemistry and requirements, as well as demand, mean that nickel demand for use in LiBs is likely to increase through 2030 at least (Ribeiro et al., 2021). The rise in demand for batteries may lead to a deficit in the market for class 1 nickel, as most production growth is expected in areas which generally produce more class 2 materials. High pressure acid leaching (HPAL) is beginning to pick up steam as a means to convert low-grade nickel ore to class 1 materials (IEA, 2022e). There are concerns however that this method's high capital expenditure as well as uncertainty around results and environmental impact may lead to more drawbacks than benefits (Ribeiro et al., 2021).

4.2. Results

Each material was evaluated using the six indicators for 2025 and 2030, with scores ranging from -40 to 40 points. Higher scores are indicative of a greater potential for bottleneck.

For 2025, **cobalt** scores 24, largely due to highly concentrated extraction and processing markets, as well as low secondary supply rates. In 2030 this slightly decreased to 23 out of 40 possible points, as EU demand increases and extraction capacity increases are likely reliant on decisions made in the copper and nickel industry. **Graphite** scores are somewhat more elevated, with 31 for 2025, driven by highly concentrated processing markets, as well as high rates of import dependency in the EU. In 2030, graphite's overall score increases by one point to 32, though we may see greater geographic diversification in extraction and processing, and a jump in bottleneck potential for ramping up. **Lithium** scores 17 points for 2025, with potential for bottleneck in several areas. Looking towards 2030, lithium scores 14 points, as battery recycling is expected to lead to greater secondary supply and the EU ramps up extraction and processing capacity. In the near term, **nickel** scores 10 points, with greater EU availability and recycling partially countering Indonesia's dominance in extraction. Looking towards 2030, the picture for nickel is somewhat altered and at heightened risk of bottleneck in certain areas, scoring 19 out of a maximum of 40 points, as demand for battery-grade nickel increases. **Table 2**, below, presents a summary table of the scores.

Table 2 Bottleneck risk summary

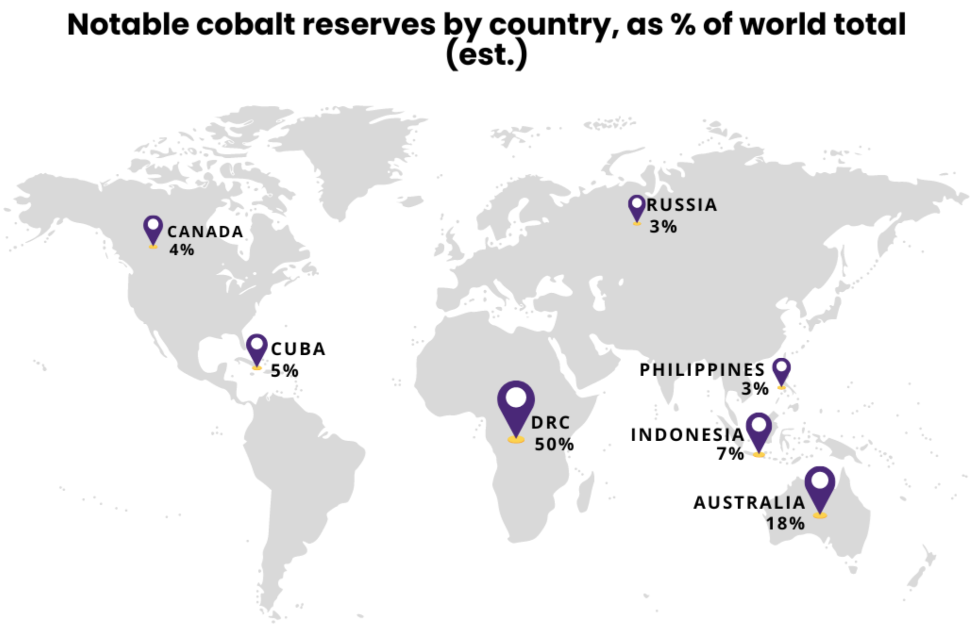
	Cobalt		Graphite		Lithium		Nickel	
	2025	2030	2025	2030	2025	2030	2025	2030
Reserves Concentration	8	8	8	8	5	5	6	6
Extraction Concentration	10	10	7	7	6	6	10	10
Processing Concentration	10	9	10	8	8	8	6	7
Difficulty of Ramping Up	6	8	6	9	6	7	6	8
EU Availability	-8	-8	0	0	-6	-10	-16	-10
Recycling Rate	-2	-4	0	0	-2	-2	-2	-2
Total	24	23	31	32	17	14	10	19

4.2.1. Cobalt

Reserves concentration

Cobalt reserves are highly concentrated in DRC, which has roughly 50% of the world's proven reserves (U.S. Geological Survey, 2023). Other countries with significant reserves include Australia, Indonesia, Cuba, and Canada (18%, 7%, 5%, and 4% of global proven reserves, respectively; Ibid). As cobalt is often produced as a by-product of nickel mining, there is significant similarity between reserves concentration of cobalt and nickel. The balance of reserves is expected to stay highly concentrated in DRC and Indonesia. For 2025, reserves concentration cobalt scores a total 8 out of 10, with 5 points for high geographic concentration and 3 points for the proportion of reserves located in countries with political stability scores which are below the global average. This number remains the same for 2030, at 8 out of 10 as reserves are likely to stay highly geographically concentrated. No change is assumed for political stability values.

Figure 2 Global cobalt reserves



(U.S. Geological Survey, 2023)

Extraction concentration

Cobalt production is expected to continue to rise through 2025, with Indonesia and DRC combined producing nearly 90% of the world's cobalt supply (Bloomberg News, 2023). Cobalt extraction is highly concentrated in DRC, which produced over 70% of the global cobalt supply in 2022 (U.S. Geological Survey, 2023). Indonesia has made significant effort to increase its own cobalt production, taking advantage of the cobalt content in nickel smelting by-products to become the second largest producer in the world (Ibid.) Both DRC and Indonesia produce cobalt as a by-product of copper and/or nickel mining, and there is some thought that the supply of by-products may be more unstable than other commodities, as supply depends on the state of the primary commodity market (van den Brink et al., 2020). Strong concentration of cobalt extraction increases the risk of bottleneck due to the fact that both countries are ranked as significantly less politically stable than the average in the most recent WGI update (Kaufmann et al., 2010; World Bank, 2022). Through 2030, DRC and Indonesia are expected to remain dominant. Indonesia has indicated an informal target of 20% market share for extraction of cobalt by 2030 and seems on track to continue to grow its market share of extraction through then, indicating that while DRC may lose some market share, it will remain highly concentrated in those two countries (Bloomberg News, 2023; Fisher, 2022). For both 2025 and 2030, extraction concentration scores a 10 out of 10 points, indicating significant bottleneck potential that is unlikely to change in coming years.

Processing concentration

Cobalt refining and processing are also strongly concentrated, with around 60% of global refined cobalt coming from China, which has established deep ties with the mining industry in the DRC (Bociaga, 2022; Ed. Mining.com, 2021; Schütte, 2021). Finland is the second largest refiner, producing 10% of global refined cobalt and supplying much of Europe (Ed. Mining.com, 2021). Other sources of refined cobalt include Canada. This balance is expected to stay relatively stable through 2025 as both major producers continue to scale up capacity (CNA, 2022; Jervois, 2022). By 2030 processing concentration may shift slightly as Indonesia scales up supply and European firms expand capacity, although China is expected to maintain its firm grip on downstream cobalt supply (Crane, 2022). For 2025 processing concentration earns 10 out of 10 points, with 5 for high market concentration and 5 for high concentration in states with WGI scores below the global average. This shifts slightly in 2030 to 9 out of 10, as the market is expected to remain quite concentrated, moving only slightly away from China.

Human rights challenges in the cobalt supply chain

Driven by demand for use in rechargeable batteries in consumer electronics and some EV batteries, 'artisanal' and small-scale mining produces a substantial proportion of cobalt in the DRC. Artisanal mining has been connected to significant human rights abuses (Amnesty International, 2020), violence (Fourati et al., 2022; Stoop & Verpoorten, 2021), and significant health impacts (Amnesty International, 2020; Banza Lubaba Nkulu et al., 2018).

Artisanal miners often dig without basic safety equipment, following ore seams deep into the earth and building tunnels without supports (Amnesty International, 2020). Men, women, and children work in and around the mines extracting raw materials to feed into the formal supply chain. Mines often employ thousands of people, and pay a pittance for whatever they extract, often dependent on the current market value (Gross, 2023).

Artisanal mining is technically only allowed through approved cooperatives and in government-designated zones, but in practice miners report that these zones are often unviable and have continued to mine in areas with determined deposits (Al Jazeera, 2022). Attempts at formalisation of this sector by the government have stalled, although there has been movement led by a consortium of companies to formalise ASM at certain mines (Baumann-Pauly, 2023).

Ramp up

Ramp up scores are relatively lower for 2025, primarily due to a nearly balanced (albeit tight) market, as well as an average large-scale mine ramp up time of 12 years (Crane, 2022; IEA, 2022e). Supply and demand projections globally indicate that the cobalt market may see an imbalance by 2030, heightening the potential impact of a bottleneck resulting from slow capacity expansion (Fisher, 2022). For 2025 cobalt scores 6 out of 10, with 5 points for long development of (formal) mining operations and 1 point indicating the relatively balanced market means the impact of a bottleneck in capacity expansions may be lessened. This score increases to 8 out of 10 for 2030. With no expected changes in lead times, but potential market imbalances, the impact of capacity expansion lead times is expected to be more significant. It should be noted that the prevalence of artisanal miners in the cobalt supply chain may add a certain level of elasticity to both average ramp-up time and supply in the market, although at significant human and environmental cost (Leotaud, 2021).

EU availability

In 2022, Asia was the largest consumer of cobalt, accounting for over half of the world's cobalt demand (Crane, 2022). The EU accounts for roughly 20% of global cobalt demand, and this is expected to rise as battery manufacturing capacity increases (Ibid.). Unlike other critical and strategic materials, the EU has a relatively strong domestic source for refined cobalt – roughly 70% of current demand is supplied by Finland. Cobalt ores and intermediates are more likely to be sourced from outside the EU, with 68% of demand satisfied by imports (European Commission, 2022). This share is expected to decrease somewhat by 2025 as demand for cobalt increases, with Transport & Environment estimating the EU will be dependent on imports for 51% of its CAM, which includes cobalt (European Commission, 2020; Transport & Environment, 2023). Finland's refineries are attempting to keep up with expected increases in European demand; Jervois, a leading global cobalt supplier, announced plans to expand capacity at the Kokkola Industrial Park in Finland with the project expected to come on-line in late 2023 (Jervois, 2022). Capacity expansions at mines and refineries means that although EU demand for cobalt is likely to increase, the EU may be able to mitigate a significant uptick in import demand (Transport & Environment, 2023). For 2025 cobalt scores a -8 for EU availability, indicating import dependency is expected to remain relatively stable at current levels, as increases in demand are supported by near-term capacity expansions. In 2030 cobalt maintains a score of -8, with EU import dependency on cobalt expected to rise only slightly between 2025 and 2030.

Recycling

Secondary supply within the EU is expected to pick up, particularly as more LiBs reach the end of their lifetimes. Current secondary supply sources (hard metals, cemented carbide tools, NiMH, and LiBs from consumer electronics) are expected to remain relatively stable through 2025, after which spent EV batteries are expected to contribute a significant share (Leighton, 2021). Through 2025, as a proportion of demand, secondary supply is expected to be roughly 7% (Transport & Environment, 2023). Battery recycling is likely to lead to a significant uptick in cobalt recycling by around 2030, with secondary supply cobalt accounting for a potential 15-25% of battery cobalt demand depending on the scenario (Ibid.; Goldman Sachs Equity Research, 2022). For 2025 recycling earns -2, indicating relatively low levels of secondary sources in EU supply. Due to expectations of increased battery recycling by 2030, cobalt's score of -4 contributes to increased EU domestic cobalt security.

4.2.2. Graphite

Reserves concentration

Worldwide, graphite reserves are moderately concentrated, with 65% of reserves concentrated in three countries (Turkey, Brazil, and China). Looking at all global reserves, 99% are concentrated in countries that are less stable than average, per the WGI stability indicator (U.S. Geological Survey, 2023). While reserves are relatively dispersed, the high concentration in less stable countries suggests a high potential for bottleneck in the event of political or geographic disruptions, contributing to a higher overall score in the reserve concentration category. Using current reserve statistics, graphite scores 8 out of 10 points for 2025, with 3 points for concentration and 5 points for stability. Graphite's score remained the same in 2030 as well, though this could change with new reserves discoveries.

Extraction concentration

In 2022, graphite extraction was highly concentrated, with 86% of mining occurring in China, Mozambique, and Madagascar. The concentration of extraction is worsened by the fact that all three countries ranked less stable than the global average on the WGI indicator. With new mines coming online and extraction capacities ramping up, by 2025, the top three states are projected to mine 63% of global output, with Tanzania overtaking Madagascar as the third largest miner of graphite (Els, 2022). At least 77% of graphite is projected to be mined in countries less stable than average. Thus in 2025, graphite scores 3 out of 5 points for concentration and 4 out of 5 points for stability, for a total score of 7. Due to higher output from mines in Africa as well as a few other countries, graphite mining is projected to see additional diversification by 2030, with the top three countries mining 54% of the global supply (Ibid). While this shorter-term diversification isn't enough to lower graphite's score in 2030, it indicates promise for post-2030 graphite concentration.

Synthetic vs. natural graphite

There are two main types of graphite: synthetic and natural. Synthetic graphite is created by heating coke, leftover carbon from oil and coal refined to a very high temperature. Natural graphite is mined. Both types of graphite are used in battery anodes, though natural graphite must first undergo refining and processing to become battery-grade spherical graphite. Synthetic graphite is additionally used in electric arc furnaces and solar energy storage (Pistilli, 2023). About two thirds of current global graphite consumption is synthetic and one third natural (Natural Resources Canada, 2022). Within battery anodes, synthetic graphite makes up about 78% of battery anode material while natural graphite accounts for 14% (Luo, 2022). There is a wide range of anode chemistries, with factors such as cost, environmental impact and performance differences such as battery longevity and charging capacity resulting in many different compositions, which often include a mixture of synthetic and natural graphite.

Synthetic graphite behaves more predictably in its application than natural graphite and can be developed more quickly as it is not mined. However, synthetic graphite is more expensive and energy-intensive to produce, therefore some countries are ramping up natural graphite production for economic and environmental reasons. By 2030, the demand for natural graphite in LIB anodes is projected to become double that of synthetic graphite (Mills, 2022b).

Processing concentration

Graphite processing in the short-term is particularly concentrated, with China currently producing nearly 100% of spherical graphite (Nouveau Monde Graphite, 2021). In 2030, China is projected to continue to dominate the lion's share of spherical graphite production, at an estimated 80% (Els, 2022). China additionally holds a monopoly in synthetic graphite production, manufacturing 55% of the global supply in 2021 (OEC, 2022). There is uncertainty in the future breakdown of synthetic and spherical graphite used in battery anodes, however some projections suggest that natural graphite demand within batteries (and therefore the demand for spherical graphite) could grow to double the demand of synthetic graphite by 2030. This suggests China's monopoly on spherical graphite processing will become even more significant in the longer term when evaluating bottleneck potential (Mills, 2022b).

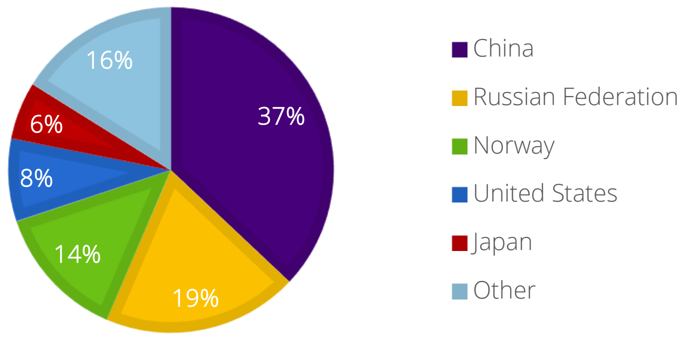
Ramp up

Ranges on lead times across the graphite supply chain were challenging to find with certainty, though mine development times for natural graphite accounted for the longest leg, with estimates of the exploration to development stage taking 10 or more years to complete (Mitchell & Deady, 2021). The demand for graphite outstripped the supply in 2022, with the gap between demand and supply slated to increase to 17% by 2025 (Mills, 2022a). Graphite scores 5 out of 5 points for lead time development and 1 out of 5 points for market imbalance in 2025 for a total score of 6. In the short term, the graphite market is expected to experience supply deficits, particularly for battery-grade graphite, meaning that long lead times for capacity expansion are likely to have a larger impact on an already tight market. Lead times for mining will likely remain similarly long in 2030, and the imbalance between supply and demand for graphite increases significantly, with a projected market balance of -76% (Mills, 2022a). Therefore, the ramp up bottleneck potential increases in the longer term as demand increases much faster than supply can keep up, earning graphite a score of 9 out of 10 points for 2030. Lead times for synthetic graphite manufacturing are significantly shorter, with ranges between 1.5 and 3 years (Roschger, 2021), highlighting a potential for more rapid domestic ramp up in battery-grade graphite. However, given the sparse information available on expansions in synthetic graphite production in the EU, we use natural graphite figures to measure ramp up potential.

EU availability

The EU is 100% import-reliant for natural battery-grade graphite. In 2022, less than 2% of the world's supply of natural graphite was mined in the EU (in Austria and Germany), though none was battery-grade. New mining developments in Finland and Sweden suggest potential for growth in EU domestic graphite extraction, though these projects likely will not contribute to near term availability (Fleming et al., 2022). It is possible that the EU will be able to meet as much as 20% of domestic demand for natural flake graphite by 2030, owing to the ramping up of mining capacities in Scandinavian countries (Stibbs, 2022). However, permitting hurdles to producing spherical graphite are expected to remain, which could result in continued reliance on foreign supply in at least the medium term. As such, zero points are allocated for both 2025 and 2030.

Figure 3 EU synthetic graphite imports by country, 2019



(World Bank, 2023)

Recycling

Recycling potential for graphite from LiBs is still in the exploratory stage, as few LiBs have reached the end-of-life stage and recycling efforts have largely been focused on lithium, cobalt, and nickel. In the EU, graphite is not currently recovered from battery recycling. Given the increased demand for battery-grade graphite in the coming decade and limited possibility for general and battery-grade recycling, graphite scores zero, indicating limited or no secondary supply satisfying EU demand. Graphite recycling potential within the EU remains uncertain for 2030, thus its score remains at zero, though there are a number of promising explorations into battery-grade graphite recycling, including a recent development focusing on graphite recycling in LiBs (D'Souza, 2022).

4.2.3. Lithium

Reserves concentration

Reserves are more broadly spread than current extraction, which may indicate a slightly lower risk of bottleneck (U.S. Geological Survey, 2023). Reserves concentration is expected to stay roughly the same between 2025 and 2030, with Australia, Chile, and Argentina making up the majority of reserves. A recent announcement from the government of Iran on the discovery of an 8.5 million tonne deposit would place the country second to Chile in terms of reserves and be the single largest reserve outside of South America (Ross, 2023). Questions with regards to the quality of the deposit as well as extraction feasibility and capabilities remain unanswered. Iran's reported reserves are excluded due to the lack of information about the alleged deposit. Where reserves are highly concentrated but in states with political stability scores which are above the global average, reserves concentration scores are 5 out of 10 points for both 2025 and 2030.

Extraction concentration

Extraction is highly concentrated with Australia, Chile, and China mining over 90% of all raw lithium. This indicates that supply of the material can be influenced by political and geographic events that occur in any of the major supplying countries. However, of all extracted lithium, 23% comes from states which are less stable than average. This is a much lower share than in the cases of cobalt and graphite. Due to the relatively long lead times for the development of new hard rock mines and some brining operations, extraction concentration is expected to stay relatively stable through 2030. However, an analysis of who controls the mines shows that Chinese shareholders control about one-third of the market and about half of the formal industry (Leruth et al., 2022). There are no substantial ultimate shareholders based in Europe, and the United States' presence is through passive funds. For both 2025 and 2030 extraction concentration scores 6 out of 10.

Processing concentration

Processing is highly concentrated, with China controlling 58% of chemical processing and Chile and Argentina contributing an additional 37% (Scott, 2022). Most processing occurs within countries that are rated as less politically stable than the global average as indicated by the WGI, namely China and Argentina. Planned expansions are set to maintain these numbers (European Metals, 2023; IEA, 2022e; Transport and Environment, 2023). Highly concentrated production of lithium chemicals and a higher proportion of processing occurring in states which are less politically stable than the global average leads to higher bottleneck indicators for processing than extraction. For 2030, we maintain stability weighting as largely the same, with high levels of market concentration in states like Australia, Chile, and China becoming somewhat diluted as large blocs like the EU seek to develop regional processing capacity. However, this is not expected to significantly shift processing concentration which stays at 8 out of 10 for 2025 and 2030.

Ramp up

Lead times for lithium mines can range from 4-10 years and the IEA indicates that some mining projects can take as long as 15-17 years to ramp up from the exploration to output stages (IEA, 2022e). Projected negative market balances mean that the impact of long lead times may be more significant, leading to a slight uptick for 2030 (Schmidt, 2023). For 2025, lithium scores 6 out of 10 points, and 7 out of 10 points for 2030.

EU availability

The short-term picture for lithium in the EU indicates continued dependence on imports. As of 2022, the European Commission considers EU production of lithium chemicals to be negligible, creating complete dependence on imported lithium products (European Commission, 2020). As the EU pushes to become a regional hub for electromobility and LiB manufacturing, industry groups and firms have announced plans to add additional extraction and refining capacity across the EU, indicating that in the short- to medium-term the EU could reduce its import dependency. A paper by Transport & Environment (2023) concluded that between announced plans and increased availability of recycled materials, by 2025 the EU could increase domestic production to meet roughly 25% of projected demand and 50% by 2030. Several projects are already underway within the EU to develop additional extraction and processing capacity, in addition to a push for lithium recycling supported by the Commission. Lithium mining and processing projects have been announced in Germany, Austria, France, and other EU countries (European Lithium, 2023; Jamasmie, 2023; Vif, 2022). Transport & Environment estimates that, conservatively, annual production of 65 kt lithium could be achieved by 2030 (Transport & Environment, 2023). For 2025, EU availability of lithium scores -6, shifting to -10 out of -20 points as potential domestic production increases up to 2030.

Recycling

Current recycling rates of lithium are quite low, at under 1% of demand, especially as available volumes of recyclable LiBs are relatively low and mostly from consumer electronics and rechargeable batteries (IEA, 2022f; Transport and Environment, 2023). As of December 2022, the EU Commission and Parliament have reached a preliminary agreement on regulating battery recycling, increasing recycling obligations and setting a minimum value for secondary supply use in new batteries (Schmaltz, 2023). This could increase lithium availability as recycling rates increase. However, as a proportion of overall demand, secondary supply is unlikely to be significant, although this is expected to increase over time as the number of spent batteries increases. Given the extremely low current recycling rate in the EU, lithium scores -2 out of -20 points for both 2025 and 2030, though as larger LiBs reach the end of their lives post-2030, secondary supply may increase.

Alternatives and substitutes

Another dimension of the critical and strategic materials issue is substitutability and the question of if, as technology advances, the materials identified here will continue to be critical to the green transition. There are two general types of substitution which may occur and shift the bottleneck potential of critical and strategic materials in the EU: material substitution, which means finding an alternate material to substitute for the same application, or process for process substitution whereby the same outcome is achieved through an entirely different means not requiring the material in question in the first place (Goddin, 2020). An example of material substitution is the use of cobalt in LIB cathodes, as battery manufacturers respond to volatile markets and social pressure to move away from a material with human rights violations deeply embedded in the supply chain (Airhart, 2018). EV manufacturers like BMW, Nissan, VW, and Tesla have all moved to reduce the amount of cobalt in their supply chains, turning towards alternatives that include substituting manganese, increasing the amount of aluminium, or otherwise changing the chemical structure of the battery (Ibid.; Lee and Manthiram, 2022). Tesla announced in 2021 it was seeking to develop cobalt-free batteries, shifting to produce all of its cheaper standard Model 3 and Model Y vehicles to lithium-ion phosphate batteries (LFP) batteries (Lambert, 2022). Battery manufacturers turned towards iron in the 1990s – essentially developing a phosphate salt much in the same way it has been done since the late 1800s (Blois, 2023). Chinese firms began domestic manufacturing of LFP batteries in earnest in the late 2000s, with expansion to European and North American manufacturers occurring only within the past couple of years (Ibid.). Other options for moving away from cobalt include developing solid state batteries, although they are generally not yet commercially viable but may be in coming years (Centre for Energy Finance, 2022).

Outside of China, LiBs that include nickel are dominant due to their relatively higher energy density as opposed to cheaper, lower-density LFP batteries. They are however, more costly and concerns about materials availability have supported development of substitutes (Nissan, 2022b). The IEA projects that by 2030 battery chemistries are likely to be diversified as companies develop battery characteristics to suit specific vehicles (IEA, 2022b). Nissan announced that by FY2028 it expects to introduce high-energy density all-solid-state batteries with shorter charge time than the conventional LiB for use in several vehicle segments, including premium EVs and pickup trucks (Nissan, 2022a). Similarly, Volkswagen announced it will be moving forward with different battery chemistries depending on vehicle category – expensive, high-density batteries with nickel chemistries in premium EVs, lower cost LFP batteries in mass-market, smaller and mostly urban vehicles (Ribeiro, 2021).

Volatile commodities markets and increased concern about critical and strategic materials supply chains means that battery chemistries are likely to continue to shift. Battery and EV manufacturers continue to develop alternative LiB chemistries which use manganese, or substitute sulphur for graphene (Lambert, 2022; Mernit, 2022). Other recent updates include the replacement of graphite anodes in LiBs with a novel nanomaterial using copper, iron, and iron oxide as well as increasing the silicone content of anodes, although this has been noted to decrease the number of charge/discharge cycles a battery could successfully complete (Bedwell, 2022; Bellini, 2021). Alternatives also include sodium-ion batteries which use sodium rather than lithium. Commercial applicability for grid storage and EVs is clear, but there are concerns about energy density that may limit applicability elsewhere (Centre for Energy Finance, 2022).

4.2.4. Nickel

Reserves concentration

Australia, Brazil, and Indonesia have the largest reserves, accounting for roughly 60% of the world's total. Reserves are fairly spread out globally and split roughly 50-50 between states which are below the political stability indicator average and those which are above. Lateritic reserves (lower quality, high tonnage deposits typically located close to the Earth's surface) are more common, however there is some concern about the supply of class 1 nickel, given that lateritic reserves tend to be more often suited for producing class 2 products (see Box below) (IEA, 2022e; The Nickel Institute, 2023). Looking towards 2030, reserves concentration is expected to stay relatively stable. For 2025 and 2030 reserves concentration scores 6 out of 10.

Nickel product classes

Nickel is generally sorted into two materials classes, indicating purity levels and product type. Also called battery grade nickel, class 1 products are of the highest purity and are produced from nickel sulphide ores. Class 1 nickel contains greater than 99.8% nickel and includes London Metal Exchange (LME) deliverables, powders, and briquettes. Class 1 nickel is used in batteries, as well as in superalloys (The Nickel Institute, 2023).

Class 2 nickel is lower purity, containing more iron, and is produced from laterite ores. With less than 99.8% nickel content, class 2 material is not LME deliverable and is sold as ferronickel (2-45% nickel) or nickel pig iron (2-17% nickel). Class 2 nickel is primarily used for the production of stainless steel (ZEB Nickel, 2022).

Extraction concentration

Indonesia stands out as the single largest producer of nickel, responsible for over 40% of extraction through 2025. The Philippines is a distant second, with 15%, followed by Russia at an estimated 11%. Nickel mining is highly concentrated, therefore raw material supplies are highly likely to be impacted by domestic political and physical events in Indonesia. The Indonesian government has already attempted to exert significant influence on the market, culminating in a complete ban on nickel ore exports in 2020 and domestic processing requirements (IEA, 2022c). With a domestic stability index score of -0.51, Indonesia is less stable than the average state (Kaufmann et al., 2010; World Bank, 2022). Extraction is expected to remain highly concentrated, and the emergence of China is still limited as shown in Leruth et al. (2022). Nickel earns 5 points for each, or 10 out of 10 points for 2025 and 2030.

Processing concentration

Other major players include China, which holds a plurality of nickel refining capacity and is continuing with expansion plans (Fitch Solutions, 2023; The Nickel Institute, 2023; U.S. Geological Survey, 2023). Through 2025, over 80% of both extraction and processing will occur in states which are less stable than the average. Processing is likely to see some changes between 2025 and 2030 although exactly where and by how much are subject to some uncertainty. Between 2023 and 2025 hydro-pyrometallurgic processing (typically using HPAL) to convert lower quality laterite ores to Class 1 and 2 products is likely to continue to receive significant investment in Indonesia, and may be subject to continued investment through 2030 from Chinese firms in particular (Durrant, 2022). The processing market earns a total 6 out of 10 score for 2025, increasing to 7 out of 10 for 2030 due to potential further processing concentration in Indonesia.

Ramp up

Ramping up production for nickel is much the same as for other mined ores, with mine lead times dominating the timeline, ranging from 4 to 27 years with a median of 12 years (Heijlen et al., 2021; IEA, 2023). The nickel market for both class 1 and 2 metals is expected to remain in surplus for only a further few years as demand for class 1 nickel rises, driven by demand for EV batteries (IEA, 2022e). Given that the market is expected to be relatively close to balanced in 2025, the impact of long lead times is estimated to not be as severe as in other cases (Ibid). At the same time, demand for class 1 nickel is expected to rise through 2030 as demand for LiBs increases. Due in part to the higher proportion of lower quality reserves and decreasing ore quality, it is likely that the nickel market will see imbalance through 2030, elevating the potential for bottleneck in the ramp up category (Azevedo et al., 2020; European Commission Joint Research Centre & Roskill, 2021; IEA, 2022e). In 2025 nickel earns 6 out of 10, increasing to 8 out of 10 for 2030.

EU availability

The EU is expected to be fairly reliant on imports, particularly as demand for class 1 materials for EV battery manufacturing increases (European Commission Joint Research Centre and Roskill, 2021). Nickel refining capacity within the EU is expected to grow, particularly driven by increases in capacity in Finland. Class 1 nickel production is expected to grow in Finland and France as well (European Commission Joint Research Centre and Roskill, 2021). Overall domestic availability of class 1 and 2 nickel products is expected to be quite high in 2025, earning -16 points out of -40. Despite increased EU production of nickel primary and secondary products, demand is set to outstrip supply, leading to higher overall import dependency in the medium-term (European Commission Joint Research Centre and Roskill, 2021), resulting in a score of -10 for 2030.

Russian invasion of Ukraine and the EU's nickel supply

The impacts of Russia's illegal invasion of Ukraine continue to reverberate, particularly in extractive industries. Due to nickel's relative abundance, price competition is fierce and battery manufacturers and EV producers are particularly focused on establishing cost-efficient supply lines (Onstad, 2022). Russia supplies around 11% of the world's nickel, and is considered one of the "world's top suppliers of high-grade nickel at a competitive price" (Pickrell, 2022). Nornickel, Russia's largest mining and metals company produces around 15-20% of the world's battery-grade nickel alone (Onstad, 2022).

Uncertainty surrounding sanctions and supply lead to significant volatility in the nickel market in spring 2022 with prices skyrocketing to a record high of USD 101,365 per tonne in March 2022 before trading was halted by the LME (Sotinel, 2022). Volatility and concerns about the invasion have not stopped Europe from continuing to import Russian nickel, with EU imports rising nearly 70% in 2022 (Ibid.) At the same time, Nornickel has announced a projected 10% drop in supply in 2023 due to challenges sourcing parts and equipment for repairs and challenges with international transactions (Lyrchikova and Marrow, 2023). Concerns about market volatility and class 1 nickel supply has prompted several companies to push for a more diverse supply line, including Volkswagen which recently announced joint ventures with two Chinese firms to secure raw nickel and cobalt supplies from Indonesia (Sullivan, 2022).

Recycling

Nickel is already recycled extensively compared to other critical and strategic materials due to its mass use in alloys and other relatively homogenous and easily collectible industrial materials (IEA, 2022e). By 2025, an estimated 8% of EV battery demand for nickel is expected to be fulfilled by secondary supply (Transport and Environment, 2023). Recycling rate receives the same score for both 2025 and 2030 as recycling rates and demand are projected to increase in tandem ±1% or so (Transport & Environment, 2023). For both years, recycling scores -2 points.

4.3. 2050 projections

Analysis for 2050 is incomplete, primarily due to data availability and variability issues. Instead, we present selected projections for EU supply, demand, and recycling rates for 2050. The critical and strategic materials landscape is highly dynamic, facing changing political, geologic, and demand circumstances which can radically impact projections for 2050.

With the EU meeting and extending its announced political ambitions, demand for cobalt is projected to rise to 80-100 kt in 2050 (KU Leuven, 2022), with another report suggesting demand could be as high as 288 kt (Roelfsema et al., 2022), dependent on EU low carbon technology ramp-up and commitment adjustments. A report from the Hague Centre for Strategic Studies suggests that the EU could become self-reliant on cobalt by 2050, though this projection hinges on actions to increase recycling rates, decrease demand, and develop domestic mining capabilities, the last of which faces steep challenges, including public opposition, permitting, and mine development lead times. Secondary supply in the EU is projected to reach up to 60 kt, which would meet anywhere from 21% to 75% of total projected 2050 demand (KU Leuven, 2022).

As graphite has more recently become widely viewed as a mineral critical to the energy transition, there are fewer long-term projections in comparison to the other minerals analysed. However, it is clear demand for the mineral will likely continue to increase drastically through 2050, with an estimate of 13-fold growth, based on the commitments outlined in the European Green Deal (Ituen, 2021).

Lithium demand is expected to grow significantly in the EU through 2050, particularly if the EU is successful in ramping up its battery manufacturing capacity. A report commissioned by Eurometaux, the European non-ferrous metals association, projects that total EU lithium demand could increase to over 800 kt LCE by 2050 (KU Leuven, 2022). Of that, the green transition is expected to account for between 600-800 kt LCE. Looking towards secondary supply, the Eurometaux report projections estimate the secondary supply of lithium could increase significantly by 2050, estimating up to 600 kt if the secondary supply chain is successfully scaled-up.

Total EU nickel demand is projected to rise to 800-900 kt by 2050, with the green transition accounting for roughly 300-400 kt (KU Leuven, 2022). Demand estimates for nickel are highly subject to change, particularly past 2030 as battery chemistries change and technologies which have not demonstrated commercial viability may see increased successes. The secondary supply of nickel is additionally expected to grow to up to 400 kt by 2050 but note that this estimate does not differentiate between battery-grade nickel and other types of nickel (Ibid).

4.4. Lessons learnt from the availability of Cobalt, Lithium, Nickel, and Graphite

The cases of cobalt, graphite, lithium, and nickel are used here to illustrate the approach and highlight areas where further study is needed. In all the cases, extraction and processing concentration is highlighted as an area where bottlenecks may occur (or have already). Extractive industries are highly subject to the regulatory and political environments they operate in, and while market concentration is certainly a question of geologic chance, it means that some states may exercise outsized influence on critical trade networks. This is seen to an even greater degree in the state of critical minerals **processing**, where China has developed enough capacity to wield significant market power, dominating the downstream competition. In addition to China's dominance in battery, wind turbine, and solar panel manufacturing, without significant change, the global energy transition is highly dependent on a single actor (Castillo and Purdy, 2022). This dependence begs careful analysis of the risks and benefits of the situation, particularly as states move to develop and secure their own critical and strategic materials supply chains. Other potential concerns in this arena include capacity ramp-up, where long lead times and regulatory hurdles may worsen supply imbalances if capacity expansion investments are not made far enough in advance.

There is room for further analysis in several areas, including substitution, new technology development and innovations, materials efficiency, and sustainable development of critical minerals extraction and materials processing in both the EU and third countries. Materials substitution is a key strategy to addressing material criticality, and further assessment would strengthen this methodology. At the same time, one of the core assumptions of this methodology is that the technologies we use today will remain dominant through 2030, and the materials required for those technologies will remain critical. Further analysis of technology development and innovation could introduce an additional dimension to this methodology.

5. Policy responses

The disaggregated approach should help to determine the policy responses needed to mitigate the risks of bottlenecks. Depending on the driver of that risk for a given critical material and its time horizon, the EU and its member states have different tools at their disposal. The below subsections shortly describe the policies and measures that could be used to mitigate the risk of bottleneck in the coming two to three years, and until 2030 and 2050, years for which the EU already has concrete emissions reduction targets. These policies could be introduced immediately even if the risk of bottleneck is set to occur far in the future because of a significant increase in demand. The final subsection takes a brief look at how these different responses have been addressed in the European Commission's Critical Raw Materials Act adopted in March 2023.

5.1. Policy options up to 2025

The number of policy options to reduce the risks of bottlenecks up to 2025 is limited. To improve resilience to supply manipulation or disruption, the EU and its member states may stockpile critical and strategic materials similarly to the ways in which they currently do so with oil. They may also try to develop strategic relations with countries less inclined to leverage their dominant exporting positions. If the risk results from concentration of processing, due to the much shorter lead time the EU may attempt to develop its own processing plants by streamlining permitting procedures and providing the necessary funding for their construction. In this case, stockpiling processed materials may help to close the gap until these processing plants are ready.

As mentioned earlier, the risk of the bottleneck can also be driven by ramping up the uptake of low carbon products across different countries simultaneously, driving demand that is not consistent with the supply of the material. In that case, the EU may encourage member states to introduce such policies in staged way, with acceleration over time. If several low carbon products require the same material, those with higher emissions mitigation potential should be prioritized. Countries within the EU and beyond may also coordinate their policies to avoid a boom-and-bust in the demand for the specific material.

The availability of the material in the EU due to domestic extraction or recycling may reduce the risk of bottleneck but its potential up to 2025 is very limited due to the long lead time for extraction capacity expansion, and in many cases insufficient amounts of waste material. However, there is the potential to scale up existing extraction plants and recycle currently available waste products in the EU.

5.2. Policies and actions approaching 2030

Should the assessment result in the conclusion that the greater risk of the bottleneck will take place around 2030 as the EU aims to meet its emissions reduction target, the EU and its member states have more tools at their disposal. To mitigate the risks resulting from the concentration of extraction and processing, the EU should facilitate the development of products using less challenging materials. It should also attempt to develop extraction within its own territory by simplifying the permitting process and supporting such projects using different regulatory and financial instruments. New processing plants in the EU or other countries with less geopolitical risk could also play a much more important role in satisfying EU demand. At the same time, due to the longer time horizon and possibly higher amounts of a given material, stockpiling could be a less preferred option as it may result in higher price for other countries. However, it should not be completely excluded to mitigate the risk of short-term imbalance between supply and demand that could otherwise result in boom-and-bust markets and volatile prices of the materials.

The risk of bottlenecks resulting from ramping up of demand for low carbon products across different markets and countries is often higher by 2030 than 2025. This is the result of the Final Investment Decisions for large scale projects, which often require a few years of negotiations, resulting in concrete actions. Simultaneous deployment of numerous gigawatt-scale projects, e.g. in the area of large-scale batteries replacing gas power plants, transmission cables, photovoltaics, offshore and floating wind farms, or electrolysers for green hydrogen, may result in demand for critical and strategic materials significantly outstripping their supply. In such cases, better coordination between projects facilitated by public authorities may reduce the risk of bottlenecks around a given material's availability or temporary price spikes that could make such projects unprofitable and undermine trust in similar projects in the future.

Should the material be available in the EU, streamlining permitting and financial support for such projects, for example through loan guarantees, could result in a significant reduction in the lead time for their deployment to make them operational by the end of the decade. In addition, to ensure that already by 2030 a significant share of demand will be covered from recycling, the export of products that include the material outside the EU should be limited and binding targets for recycling of such products should be adopted.

5.3. Policies in the lead up to climate neutrality in 2050

Reaching climate neutrality by 2050 at the latest will result in a significant demand increase for some of the critical and strategic materials. However, this longer time horizon creates new opportunities resulting from radical innovation that requires some time before the products are mainstreamed. It also creates risk for private investors: innovation may make investments worthless if new and cheaper technologies are developed. These two elements – facilitating innovation and risk-sharing – are the main elements of the policies and measures aiming at reducing the risks of bottlenecks.

Innovation is of great importance to mitigate the risks of bottleneck resulting from concentration, especially in terms of reserves and extraction. In these two cases, the EU should promote research and deployment of low carbon products which use materials for which the risk of bottleneck is lower. In addition, to move towards a circular economy and use the materials already accumulated in products in the preceding decades, the EU and its member states should already begin creating a legal framework that ensures that new products are designed in ways which makes the clean energy materials easier to separate and recover.

While essential for decarbonisation, innovation also creates a risk for investors who are planning to invest in new extraction projects. Faced with the risk of demand for certain materials not materialising either due to development of products with alternative materials, or as a result of satisfying large portion of demand due to recycling, they may decide not to invest in new extraction installations. This would increase the risk of bottlenecks in the long term and make it more challenging to reach the EU's climate neutrality goal. To avoid a situation in which such risk will inhibit investments in new extraction, processing, or recycling plants, a certain share of that risk could be borne by the public. This may take the form of loan guarantees or purchase guarantees. However, this risk-sharing approach should be carefully designed to avoid disincentivising innovation in alternative products and should also reward the public in case the investment is more profitable than initially expected.

Table 3, below, summarizes potential policy responses.

Table 3 Bottleneck policy responses

Driver of the bottleneck	Period of bottleneck's occurrence		
	Up to 2025	**Around 2030**	**Around 2050**
Concentration of reserves in a limited number of countries	Stockpile critical material Facilitate cooperation with countries where reserves are concentrated	Facilitate cooperation with countries where reserves are concentrated Facilitate development of solutions with alternative materials	Facilitate development of products with alternative materials
Concentration of extraction in a limited number of countries	Stockpile critical material Facilitate cooperation with countries where extraction is concentrated	Facilitate cooperation with countries where extraction is concentrated	Facilitate development of solutions using alternative materials

Concentration of processing in a limited number of countries	Stockpile critical and strategic materials Facilitate development of processing plants	Facilitate development of processing plants	Reduce long-term investment risk in new processing plants
High potential of ramp-up in demand	Staged ramping up of support policies for low carbon technologies Prioritisation of products with higher emissions mitigation potential Coordination with other countries	Better coordination between large scale projects requiring the same materials Prioritisation of products with higher emissions mitigation potential	Promote innovation to replace the material in products in which it is possible or easier
EU availability	Expand existing extraction installations	Facilitate development of new extraction projects in the EU	Reduce long-term investment risk in new extraction projects
Recycling	Facilitate recycling of waste products whenever possible	Limit export of waste that include the critical material Facilitate recycling of relevant products	Design products to make them easier to recycle Limit export of waste products that include the clean energy material

5.4. The European Critical Raw Materials Act

In March 2023, the European Commission tabled the European Critical Raw Materials Act (CRM Act) that seeks to address several of the potential sources of bottlenecks identified in this paper. It first sets several aspirational benchmarks for each stage of the value chain, indicating that by 2030:

1. EU extracted materials should account for 10% of consumption
2. Processing capacity should increase to 40% of consumption
3. EU recycling capacity should increase to at least 15% of consumption

4. The EU should not be dependent on one single third country for more than 65% of imports of any strategic raw material (European Commission, 2023)

The proposed act includes various policy mechanisms to facilitate meeting these goals, including developing a simplified bureaucratic pathway for new extraction projects. The proposed law would require member states to identify domestic strategic projects that will come online over roughly the next decade and support them with improved access to finance and streamlined permitting procedures. The CRM Act states that permitting for new strategic projects should be "streamlined and predictable" and member states should designate a national competent authority to address strategic projects, essentially creating a 'one-stop-shop' for strategic project development. The Act additionally sets hard time limits for the permitting process, indicating that the permitting process for recycling or processing projects is not to exceed one year, and two years for extraction projects. With regards to financing new extraction projects, the Act states that there will be a dedicated working group to better coordinate investments between the Commission, member states, and financial institutions and to promote better access to financing for strategic projects.

The CRM Act additionally seeks to support geographic diversification of extraction projects in third countries by supporting the development of strategic projects abroad and proposes a series of steps to address supply and stockpile security. Accordingly, member states should develop measures to monitor their own stockpile capacity and coordinate stockpiles with the private sector. Member states should also provide the Commission with data on their strategic stocks, including amounts, outlooks, operators, and procedures which the Commission will then use to draft stock benchmarks and issue non-binding recommendations to encourage stock build-up.

Finally, the CRM Act includes provisions to support the development of the circular economy and secondary supply flows. Member states should increase the availability of information about the recycling of critical and strategic materials and analyse the potential recoverability of CRMs from waste materials of legacy extraction projects. The EU is expected to further support this through the development of additional standards for waste management and materials recovery from waste, particularly from mine tailings. Operators of waste sites will be obligated to run an economic assessment on the recovery potential of CRMs from waste materials, and to assess a suite of options with regards to processes and operations to enable economically viable CRM recovery options.

Overall, the CRM Act is a step in the right direction as it sets clear targets and introduces measures that could reduce the risks of bottlenecks. However, as the EU decreases its dependency on fossil fuels by moving to low carbon products that require a wide array of clean energy materials, a more disaggregated approach is needed, which goes beyond 2030. Meeting the CRM Act's 2030 goals, which are set as an average for all critical and strategic materials, may result in overachievement in less challenging materials, and continued high dependency for more challenging ones. The CRM Act also needs to ensure that the opportunities and investment risks resulting from innovation post-2030 are taken into consideration. Finally, it also needs to account for the fact that risk of bottleneck in clean energy materials are driven less by the **level** of import dependency and more by **where** these imports coming from.

6. Conclusions

The EU's transition away from fossil fuels offers significant opportunities, with a significant decrease in energy dependency being one of them. However, there will be numerous challenges along the way, as the imports of critical and strategic materials will increase significantly. Whereas some of the critical and strategic materials may constitute only a small part of the final product, without some of them, the whole product needed for the transformation cannot be manufactured – creating a threat that the energy transformation will be slowed down. This applies especially to materials needed for batteries that were the focus on this paper. Even more worryingly, highly concentrated markets may allow one actor – state or private – to leverage their position at any stage of the value chain, e.g. extraction or processing, to trigger a bottleneck or a significant spike in the price of a critical or strategic material.

Complete independence from imports of the critical and strategic materials needed for the energy transformation is neither feasible nor desirable as it would significantly increase the costs of the transformation and possibly slow it down. However, gaining a better understanding of the main drivers of these bottlenecks across different time horizons would allow for more targeted preparation through an array of different policies and measures. While in the short term the number of these policy options is limited, the more distant the threat of the bottleneck – as a result of scaling up deployment of low carbon products by 2030 or 2050 – the more options become available. This would allow the EU and its member states to choose an instrument that would not only decrease the risk of bottleneck from occurring but would also come with co-benefits (such as job creation), decrease other impacts on the environment (often as a result of mining), and facilitate climate action beyond the EU (through increasing the number of technological options).

The approach presented here should be understood as a contribution to a discussion that is still ongoing, as the EU and many other countries accelerate their shift away from fossil fuels. While action is still lagging behind what is needed to be in line with a 1.5°C-compatible trajectory, the accelerated deployment of solar PV, batteries – both for EVs and grid stabilisation – and electrolysers in the recent years, indicates that new trade patterns focusing on critical and strategic materials will replace old dependencies on fossil fuel imports.

In this rapidly changing environment, the presented approach may also need to be adapted depending on the purpose and time horizon. The four materials – nickel, lithium, cobalt, and graphite – that it was tested on may be further expanded to encompass other materials. Using this method, a more disaggregated approach to the assessment of risk of supply and demand bottlenecks occurring can be taken and measures may be implemented to mitigate the assessed risks.

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Annex A

Methodology notes

Each bottleneck indicator was developed with a 10-point scale, with zero indicating lowest potential of bottleneck risk, and 10 indicating the highest potential. The indicators measuring EU availability and recycling rates were inversely scaled, from -10 to 0, as both measure projected increase in EU primary and secondary supply, which can counter bottleneck in other areas. Several indicators included several sub-scores added to get a total score out of 10. Concentration indicators were all modified to include a political stability score, weighted equally to geographic concentration such that the total score out of 10 equalled a stability score out of five plus the concentration score out of five. Concentration was determined by calculating the top-three market share by country and translating that percentage to the five-point scale using quintile bins. Stability scores were calculated by evaluating what proportion of reserves, extraction, or processing is present in states with WGI scores that are lower than the global average and translating that proportion to the five-point scale using quintile bins. Ramp-up is similarly divided into two sub-scores totalled to 10, with five possible points allocated for lead times, and five points allocated for projected market balance. Lead time was scored based on the longest lead time for capacity addition along any step of the supply chain for the selected materials, which was mine development in the selected cases. Using the global average actual lead time for critical and strategic materials mines as estimated by the IEA (2022e) as reference, lead times per material were sorted into quintiles and scored out of five where zero is the lowest quintile and five is the highest. Market balance was estimated as a percentage and translated to the five-point scale using quintile bins, any positive balances indicating oversupply are graded as zero points. EU availability translates the import dependency of the EU, where $ID = \frac{(Import - Export)}{(Domestic\ production + Imports - Exports)}$, to a 10-point scale, where -10 is completely independent and 0 is completely dependent. Recycling rate uses the percentage of domestic demand which is satisfied through secondary sources translated to a 10-point scale where -10 is 100% of demand and 0 is 0% of demand.

Statement on data availability and sources

Data for this discussion paper was sourced from a variety of data sets. The most widely used of which are the annual Mineral Commodity Summaries from the USGS. In addition, other open sources of data used include open data from the British Geological Survey and industry groups such as the Nickel Institute and the Cobalt Institute. Other sources include market-watchers like Fitch Solutions, Benchmark Minerals and S&P Global. All these sources give annual updates and compile their data from a combination of government information, academic publications, industry reporting, and private or in-house databases. At the same time, the source data for end publications are often unclear or untraceable and end evaluations and publications often have wide variability.

About the project

4i-TRACTION – innovation, investment, infrastructure and sector integration:
TRAnsformative policies for a ClimaTe-neutral European UnION

To achieve climate neutrality by 2050, EU policy will have to be reoriented – from incremental towards structural change. As expressed in the European Green Deal, the challenge is to initiate the necessary transformation to climate neutrality in the coming years, while enhancing competitiveness, productivity, employment.

To mobilise the creative, financial and political resources, the EU also needs a governance framework that facilitates cross-sectoral policy integration and that allows citizens, public and private stakeholders to participate in the process and to own the results. The 4i-TRACTION project analyses how this can be done.

Project partners

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