TYPES AND QUANTITIES OF CRITICAL RAW MATERIALS NEEDED TO MEET GROWING DEMANDS IN THE EUROPEAN UNION AND WORLDWIDE

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The data provided in the European Commission's Joint Research Centre (JRC) 2023 report (Carrara et al. 2023) identify those raw materials (RM) where production needs to significantly increase in order to meet the low-demand (LDS) and high-demand (HDS) scenarios in the EU and worldwide. This Briefing Paper highlights the key findings of the JRC report, provides available data, and comments on mineral demand and projected supply from an economic geology perspective.

JRC calculated the demand for 2030 and 2050 for a number of technologies, split into the EU, US, China and "rest of the world". They include 5 strategic sectors and 15 technologies. The sectors are: renewable energy, E-mobility, energy-intensive industry, ICT (information, communication and digital technologies), aerospace and defence. The forecast demand is provided separately for each technology, for each sector and for all sectors, and is also split into EU, USA, China and World. Here, we will first comment on the "world situation" for all technologies without splitting them up, to identify those raw materials where additional resources have to be identified first.

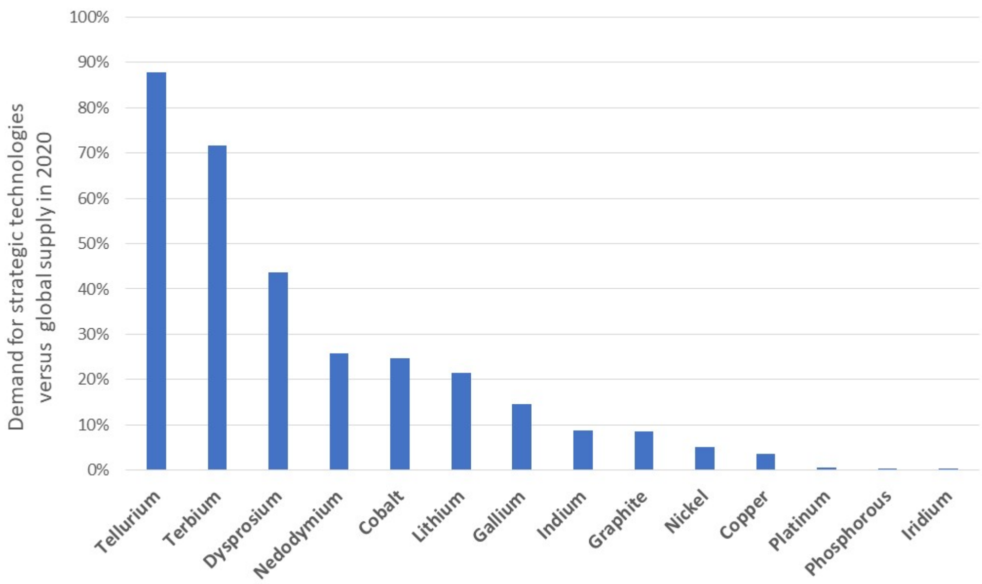


Figure 1. Ratios of demand for strategic technologies in 2020 and their supply. Source: own figure.

Although the 15 strategic technologies will likely grow more than others, their current share of the production is surprisingly low for most raw materials. The ratio between the demand of a given raw material for all strategic technologies in 2020 was first calculated relative to their 2020 production in percent. Sixteen raw materials have shares greater than 5%, led by tellurium and terbium (Figure 1). For cobalt, lithium, nickel and graphite, a very high future demand is predicted.

Production data indicated in the JRC report build the basis of this Briefing Paper, albeit these data are slightly inconsistent. Deviation from other major sources of data on mine production, the World Mining Data (WMD, 2024) and the Mineral Commodity Summaries published by the United States Geological Survey (USGS), in most cases is between -10 and +10 %. Compared to the data used by Carrara et al. (2023), WMD reports higher production numbers for arsenic, cobalt, lithium, niobium and zirconium, but lower numbers for barium, antimony, selenium and tellurium (Table 1).

World supply and demand forecast for 2030. For a number of important materials, the share needed by strategic technologies was quite low in 2020: copper 3.6%, steel 1.2%, aluminium 0.6%, phosphorous 0.4%, concrete 0.15%, iron 0.13%, fluorspar 0%. This means that an increasing demand can partly be compensated by savings in other sectors with less demand, assuming that world mine production cannot be significantly increased. However, the development of these “other sectors” (chemical industries, construction, infrastructure, steel production, just to name a few) in the future has not been taken into account in the JRC report, but should not be and might not be neglected, because they still dominate world demand.

Mine production (tons)	JRC 2020	WMD 2020	WMD 2021	WMD 2022	USGS 2022	USGS 2023
Cobalt	92 662	129 651	134 692	166 030	197 000	230 000
Copper	20 546 921	21 074 917	21 447 064	22 225 410	21 900 000	22 000 000
Dysprosium	1 682					
Gallium	301	304	431	616	610	610
Graphite	1 019 167	1 388 356	1 662 844	1 727 486	1 680 000	1 600 000
Indium	845	943	916	1 008	999	990
Lithium (Li_2O)	130 896	187 000	232 576	345 829	334 340	412 200
Neodymium	27 095					
Nickel	2 143 025	2 490 804	2 852 212	3 248 896	3 270 000	3 600 000
Phosphorous	1 196 000					
Phosphate rock (P_2O_5 content*)		67 491 740*	72 449 210*	70 787 780*	228 000 000	220 000 000
Platinum	181	163	189	183	174	180
REE (total oxide)		229 162	269 003	296 837	300 000	350 000
Tellurium	891	459	742	681	584	640
Terbium	332					

Table 1. Production data of some critical raw materials mentioned in the text according to different sources: JRC 2020 (Carrara et al., 2023); WMD 2020 to 2022, World Mining Data; USGS 2022-2023, USGS Mineral Commodity Summaries. Empty cells: no data available. Source: own table.

JRC calculated tonnages for raw materials used in the 15 strategic technologies. It is obvious that the demand for some of them will significantly increase in the future compared to the demand in 2020 (see Figures 2 and 3). In the low-demand scenario, highest growth rates are expected for phosphorus, zirconium, fluorspar, graphite, lithium, nickel, cobalt, ruthenium, and platinum. In the high-demand scenario, extreme growth rates are postulated for germanium, phosphorus, fluorspar, graphite, lithium, platinum, zirconium, and yttrium.

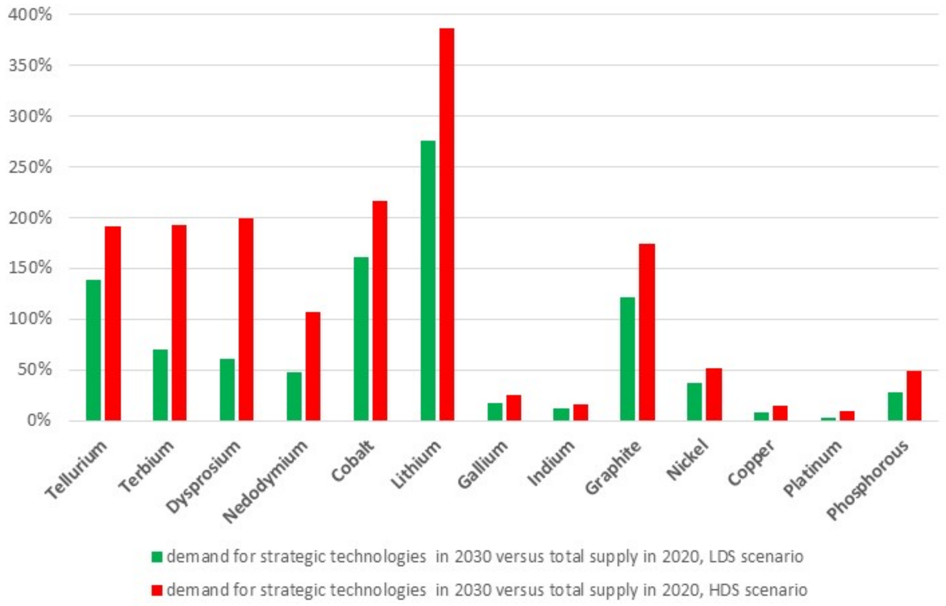


Figure 2. Comparison of the world supply in 2020 with the demand for strategic technologies forecast for 2030, with a low-demand (green) and a high-demand scenario (red). Source: own figure.

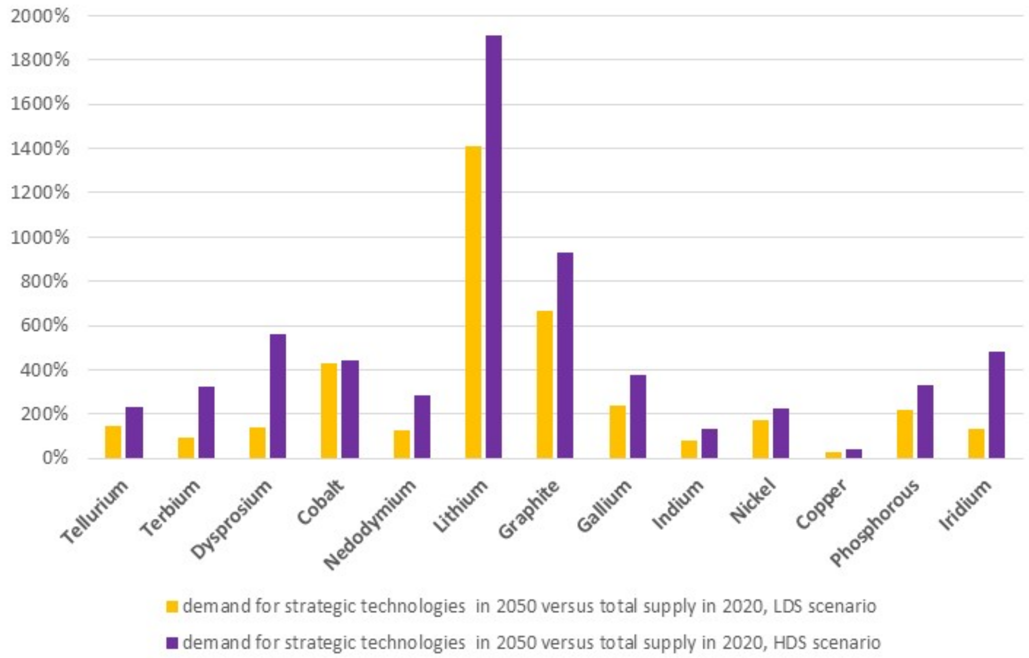


Figure 3. Comparison of the world supply in 2020 with the demand for strategic technologies forecast for 2050, with a low-demand (yellow) and a high-demand scenario (violet). Source: own figure.

Info Box. Important principles of ore geology.

Ore deposits form by geological processes that lead to enrichment of metals or other components by abstraction from a source rock, transport in a magma or hydrous solution (fluid), and precipitation in a trap. Thereby, a large number of ore deposit types are known that all are characterised by certain element associations. Economic geologists distinguish deposit types based on their formation mechanism, host rock and element association, and their geotectonic position.

Some of the most important deposit types are illustrated in a modified "metal wheel" (Figure 4; after Reuter et al. 2005; Melcher and Wilken 2013). For reference of element abbreviations see Appendix A, Figure A1. The inner blue circle denotes 14 different ore deposit types that form in sedimentary, magmatic or hydrothermal settings - for a full list of ore deposit types see Appendix A, table A1. The major products mined from these are highlighted in the inner blue ring; these "pay the bill". Co-products (white ring) are often recovered if their concentration exceeds the limits for economic production; for these, processing and metallurgical infrastructure is often in place. A good example is gold that is often economic due to its high price and well-developed metallurgical techniques. By-products (outer blue ring) are associated with the major metals, albeit in non-economic concentrations and are therefore often not recovered because infrastructure is limited. They will mostly end up in waste streams such as tailings or waste dumps (outer ring), or are disseminated into the environment as dusts.

Recovery of metals from wastes is associated with high energy costs and huge investments in technologies. From the graphical model in Figure 4 it is obvious that critical raw materials are often not recovered because infrastructure is missing due to economic constraints. Their production in many cases is tightly connected to the production of the major product. If these products are no longer needed the associated co- and by-products will also be unavailable.

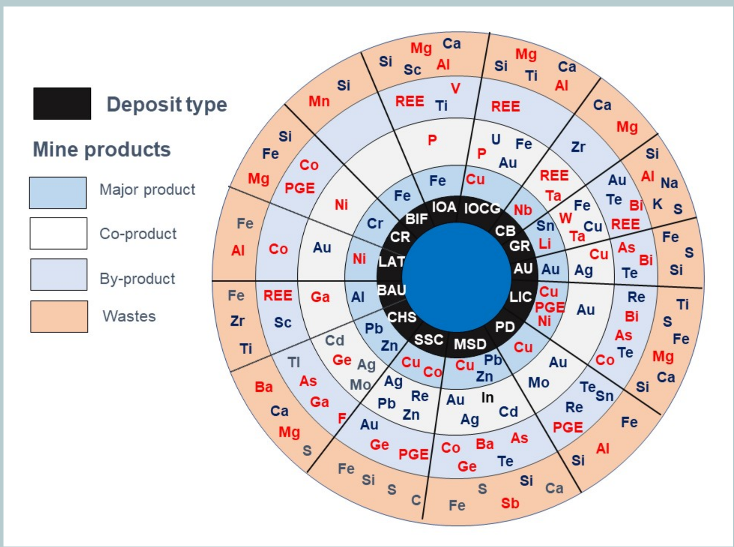


Figure 4. A modified "metal wheel" (Reuter et al. 2005, Melcher and Wilken 2013) showing element/metal associations related to ore deposit types. Major products, co-products, by-products and waste materials are distributed in 4 rings of the wheel. Elements coloured in red are critical raw materials in the 2023 EU criticality assessment. Abbreviations of deposit types: AU: vein-type gold deposits; BAU: bauxite deposits; BIF: banded iron formation; CB: carbonatite-hosted deposits; CHS: carbonate-hosted Pb-Zn sulphide deposits; CR: chromitite deposits; GR: granite-related deposits; IOA: iron oxide-apatite deposits; IOCG: iron oxide-copper-gold deposits; LAT: laterite deposits; LIC: layered igneous complexes (sulphide); MSD: massive sulphide deposits; PD: porphyry deposits; SSC: sediment-hosted stratiform sulphide. Source: own figure.

Assuming that production cannot increase by more than 20 % annually over a period of 10 years, which of these materials could be supplied from mining?

Most problematic in terms of growing demand for strategic applications are lithium, cobalt, tellurium, and graphite for the low-demand scenario, and in addition germanium and nine others for the high-demand scenario. Lithium, cobalt, graphite, nickel and phosphorus are important for e-mobility. It appears highly unlikely that additional economically mineable deposits for these raw materials can be developed in time. The competition in non-strategic sectors is high (lithium and cobalt 70-80 %, graphite and nickel >90 %). These raw materials are usually mined as major products.

Cobalt might be recovered as a by-product from some sulphide ores, especially from pyrite, and from nickel laterites forming in tropical climates. Cobalt is a major product of weathered sulphide ores in Katanga/Democratic Republic of the Congo, but reserves will run out in a few years, necessitating mining of primary cobalt-bearing sulphide ores, which requires different metallurgical techniques and pose environmental challenges in a hostile socio-economic environment prone to conflict. The predicted annual demand of 200,000 tons cobalt (low-demand, 2050) or 410,000 tons (high demand, 2050) appears manageable.

Cobalt, nickel and to a smaller extent lithium might be recovered from deep-sea marine manganese nodules. These comprise large resources but mining has not started due to political, environmental and logistical concerns and problems. The supply of nickel from land-based deposits is limited: nickel laterites exist in large areas in tropical rain forests (Indonesia, Philippines, Brazil, New Caledonia in a different biome), whereas nickel sulphides pose a sulphur emission problem, and large reserves in Russia are not available for the EU because of the current war in the Ukraine. As of today, in New Caledonia exploitable nickel from rock and from laterites is estimated to last another 30 years (Kowasch & Merlin 2024).

Graphite is recovered only on land, and larger economic deposits occur in a small number of countries only, among them China, North Korea, Ukraine and several African nations (Madagascar, Mozambique, Namibia). Additional supply for batteries could be met by synthetic graphite which is, however, energy-intensive and thus expensive. The predicted 9.6 million tons graphite of the high-demand scenario (2050) for the strategic sectors can most likely not be provided by primary mining.

Iridium will be one of the important raw materials in fuel cell technology. Currently just 7 tons per year are produced; predicted requirements are 13,6 and 33,6 tons in 2050, for the low and high-demand scenarios, respectively. We need to be aware that there is not a single iridium mine in the world. Iridium is a by-product from platinum-group element (PGE: includes the elements platinum, palladium, rhodium, iridium, ruthenium and osmium) mining in South Africa with a focus on platinum, palladium and rhodium for catalysts. That production is threatened due to lower demand for automotive catalysts given the rise in electric vehicles. Platinum prices have dropped dramatically from a high around 2,000 to 900 US$ per ounce (1 ounce is 31.1 grams). There is only a very limited capacity for iridium supply because it commonly makes up less than 5 % in a PGE concentrate.

Iridium production can only increase if platinum and palladium as the major and much more common PGE also increase. As these are not on top of the list above, this is unlikely to happen. Palladium demand is forecast to slightly decrease (no use for automotive catalysts any more), whereas platinum is predicted to just slightly increase. Additional amounts of iridium, along with the rare metal ruthenium, are known to occur in chromium deposits in ophiolite complexes that form when oceanic mantle rocks are thrust onto continents such as in Oman, Iran, New Caledonia and Albania. However, these chromium orebodies are mostly small, low grade, and the iridium minerals are very tiny (<0.01 mm) and difficult to concentrate. Recovery from alluvial placer deposits (heavy mineral accumulations in rivers and along beaches formed by transport of weathered minerals from the hinterland) will add only a little to the iridium market.

Several rare earth elements (REE) have high criticality: terbium, dysprosium and neodymium are in high demand for supermagnets driving wind turbines. Unfortunately, terbium and dysprosium are part of the group termed “heavy REE” (HREE), where production is almost 100 % from ion adsorption clays in China. Demand for the “light REE” (LREE) will not increase at the same level, so that recovery of HREE will be as a co-product mostly from the more common LREE-rich deposits (e.g. in carbonatites that occur in eastern Africa and Scandinavia).

Gallium, germanium and indium, also on the list, are by-products from base metal (copper, zinc) and bauxite (aluminium) production and are therefore invariably linked to these industries (Figure 4). There are no mines for these metals. Only few deposits carry a higher content of germanium and indium associated with copper-zinc-lead-iron sulphide ores; however, small quantities (in the 5-20 gram per ton range) occur in most of the base metal ores, but are not yet recoverable economically. Here, it is more the lack of metallurgical capacity than the lack of ores that is critical.

Gallium can be extracted from bauxite ore and in some cases also from zinc sulphide ores; if metallurgical capacities increase, the demand likely can be met, considering the rather small tonnages needed. Germanium is also extracted from the ash of lignite coal in China, but due to environmental concerns this is most likely not the most sustainable production route. It is clear that the high-demand scenario for germanium (44,000 and 71,000 tons in 2030 and 2050) cannot be met; global production in the past 38 years ranged from 50-150 tons per year (total production 1984-2021 was <3000 tons).

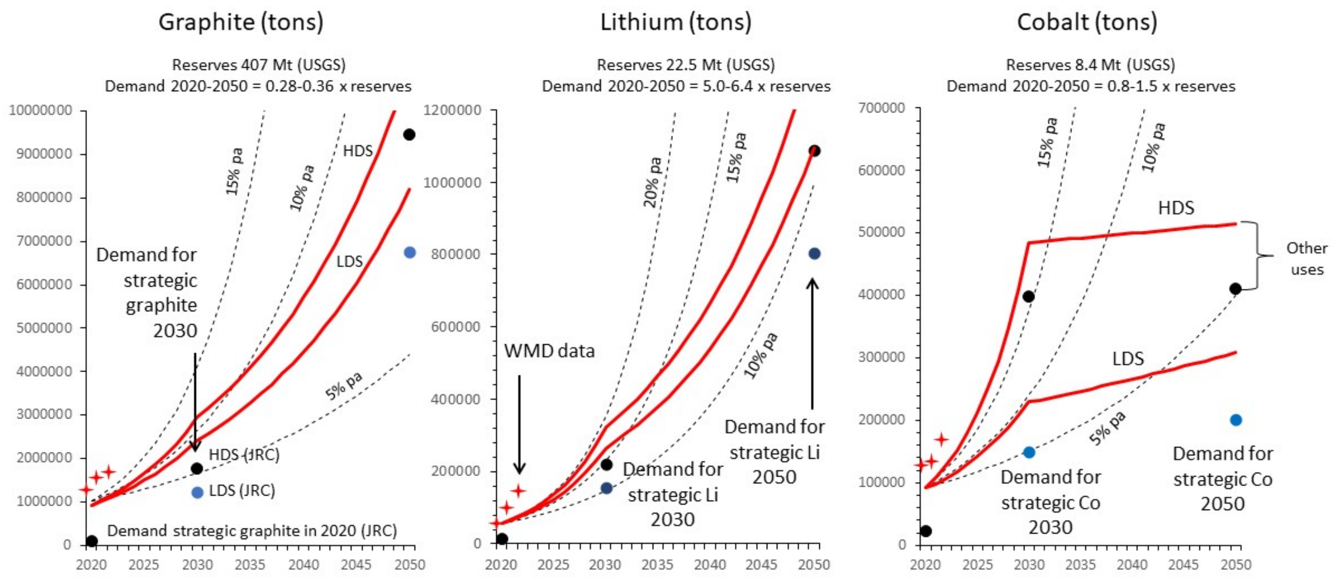
The production of phosphorus must increase significantly, if lithium-cobalt-nickel batteries are replaced by iron-phosphate batteries, a technology already used by some car manufacturers, Whereas 0.4 % of the phosphorus production in 2020 was used in strategic technologies, this may increase to 28 and 49 % for 2030 and 2050 in the low-, and to 216 and 332 % in the high-demand scenario. As phosphorus is produced from phosphate resources needed for fertiliser production, there is a demand conflict. However, 1.2 Mt phosphorus versus 85 Mt phosphate rock production in 2021 leave room for solutions. There is certainly a problem with future phosphate rock resources to meet global demand for fertiliser phosphates alone. Just recently, however, a 70 billion ton phosphate deposit was discovered in Norway (Harper 2023).

Tellurium is also high in demand on the list of strategic raw materials. Already, almost 90 % of production is used in strategic sectors. Current production is small (891 tons), and must increase to 1704 and 2067 tons in 2050 if no other major uses for tellurium are developed in the meantime. As a typical by-product of copper sulphide and gold ore processing, these amounts should be achievable, provided that the trace amounts mined especially in gold mining do not end up in tailings.

Growth scenarios. Using the JRC data, case scenarios were calculated for the quantities of lithium, graphite and cobalt that need to be made available to fulfill the low- and high-demand scenarios (Figure 5). The big uncertainty here is calculating the demand for the raw materials in products that are not included in the strategic technologies according to the JRC (2023). According to the JRC figures, this is currently almost 80 % of total demand for lithium. Interestingly, however, the USGS gives a figure of 80 % for US consumption of lithium for batteries.

The necessary increase for the strategic technologies can be calculated based on the data. For lithium, they are 29 and 33.5 % per year for low- and high demand scenarios until 2030, leveling off to 8.5 and 8.3 % per year thereafter.

Possible production paths to meet the JRC low- and high-demand tonnages for graphite, lithium and cobalt are illustrated in Figure 5. Assuming very moderate growth rates of 1-2 % per year for uses other than strategic technologies, the world mining plus recycling production must increase by 10-12 % per year until 2030 for graphite, 17-19 % per year for lithium, and 10-18 % for cobalt. After 2030, cobalt demand will drop very significantly, whereas graphite and lithium are forecast to increase moderately at rates of 6-7 % per year. By 2050 we must produce between 7 and 9 million tons of graphite compared to 1 million tons at present, and 800,000 to 1 million tons of lithium might be needed annually. Recycling of batteries - being a fundamental part of the European Green Deal policy - is complex in terms of technology and costly, and thus, at the moment of limited economic interest to industry.



Graphite:

	2020-2030	2030-2050
Strategic, LDS	10.0 %	6.3 %
Strategic, HDS	12.2 %	6.8 %
Other uses	2 %	1 %

Lithium:

	2020-2030	2030-2050
Strategic, LDS	16.6 %	7.2 %
Strategic, HDS	18.9 %	7.2 %
Other uses	2%	1 %

Cobalt:

	2020-2030	2030-2050
Strategic, LDS	10.0 %	1.5 %
Strategic, HDS	18.0 %	0.03 %
Other uses	1 %	1%

Figure 5: Growth scenarios for the production of graphite, lithium and cobalt (red lines) to meet the low- and high-demand scenarios (blue points in the graphs: LDS, black points: HDS) forecast by Carrara et al. (2023), taking into account non-strategic uses and exponential growth. Red crosses indicate mine production figures from 2020 to 2022 according to the World Mining Data (WMD). Source: own figure.

According to the USGS Mineral Commodity Summaries (2023), the current lithium reserves are 22.5 million tons, the resources (currently not economic) are 98 million tons. The forecast demand overruns the available reserves by a factor of five until 2050. Reserves would be depleted by 2032 according to the low and high-demand scenarios and a 2% increase per year of other lithium uses. However, a significant proportion of lithium from battery recycling is expected from around 2030, which is not factored into this Briefing Paper.

There is considerable doubt that the scenarios calculated by the JRC in the Carrara et al. (2023) report may be implemented for lithium and graphite, due to the usually slow development of new mining projects and insufficient recycling streams available until 2030. However, the most recent World Mining Data prove a substantial increase in production of lithium and cobalt in 2022 as compared to 2020 (Figure 5). This said, the fast reaction of the mining industry to the demand scenarios is surprising.

More realistically, at least for the 2030 goals, are production increases for rare earth elements, tellurium and gallium. The expectations on indium and germanium are based on significant investment in metallurgical processing facilities for both primary and secondary raw materials, especially metallurgical residues. Nickel and copper production must significantly increase from both, primary and secondary sources, and we might see the start of large-scale deep-sea mining due to these constraints - and this will certainly start discussions on environmental issues related to marine ecosystems that are already under pressure.

CRM related developments outside the EU, US and China. A note on the partitioning of strategic raw materials into the different regions (EU, US, China and "rest of the world") as used in Carrara et al.'s JRC report (2023): their calculations show that the most significant demand for strategic raw materials will not be associated with the EU, USA or China, but with "the rest of the world". Figure 6 illustrates the expected demand for lithium in

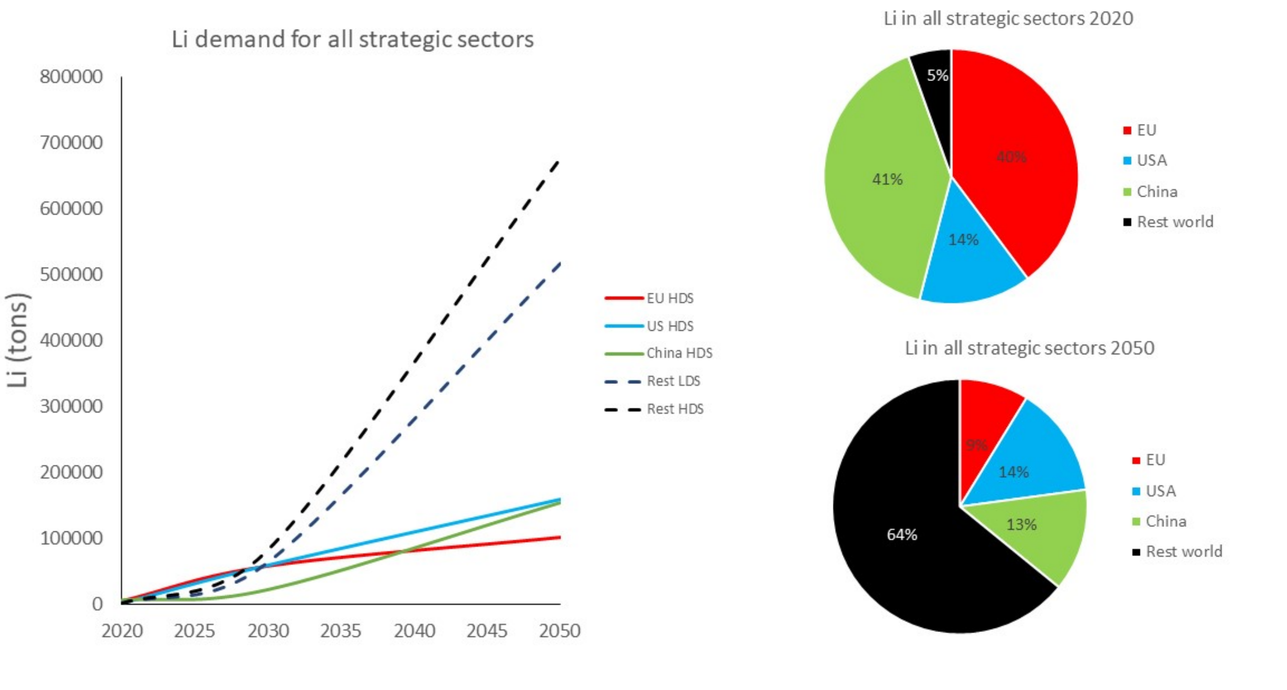


Figure 6. Forecast lithium demand for strategic technologies split into the economic regions EU, USA, China (HDS data only) and "rest of the world" (LDS and HDS data) using the data of Carrara et al. (2023). Source: own figure.

strategic technologies until 2050. Whereas the EU and China dominated the demand in 2020, the rest of the world will be the driving force for lithium demand in 2050. In that respect, Europe's demand for lithium in the electromobility sector will increase by more than 20 % annually until 2030, but then slow down to less than 3 %.

Predictions of the development of individual areas outside of the 'western countries' are very difficult. But demand will probably explode in Asian, South American and African countries. If forecasted developments in these regions lag behind due to whatever circumstances, the world demand would be significantly lower. Calculations based on the EU demand show comparatively moderate increases for many strategic raw materials after 2030; however, almost all of them need to be imported because domestic production is almost non-existent. But this is another story!

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Appendix A

Additional information to Figure 4 („metal wheel“)

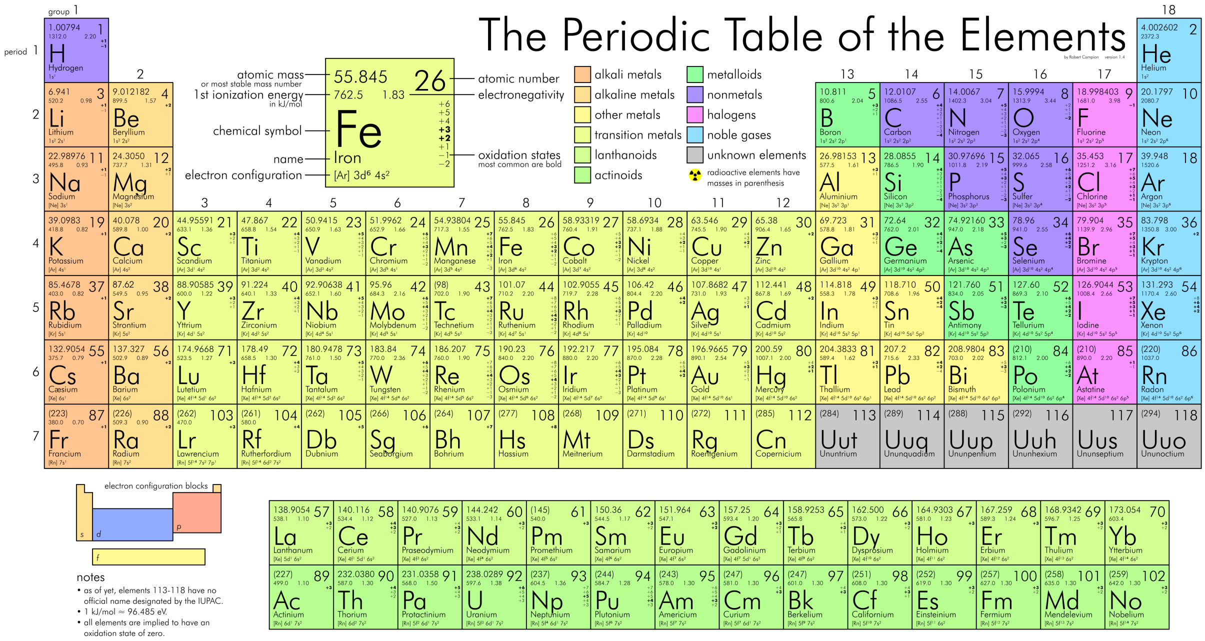

Figure A1. Periodic table of the elements. Source: https://commons.wikimedia.org/wiki/

Abbrev.	Deposit type	Major commodities	Formation process	Continents of major production
LIC	Layered igneous complexes (sulphide)	Ni, Cu, PGE	magmatic	Africa, North America, South America, Europe
CR	Chromitite deposits	Cr (PGE)	magmatic	Africa, Asia, Europe
CB	Carbonatite-related deposits	Nb	magmatic	Africa, North America, Europe
GR	Granite-related deposits	Li, Sn (W)	magmatic-hydrothermal	Europe, Asia, Africa, North America, South America
PD	Porphyry deposits	Cu (Mo, Au)	magmatic-hydrothermal	South America, North America, Asia, Europe
IOA	Iron oxide-apatite deposits	Fe	magmatic-hydrothermal	Europe, Asia
IOCG	Iron oxide-copper-gold deposits	Cu (Au)	magmatic-hydrothermal	Australia, South America, Europe
CHS	Carbonate-hosted Pb-Zn sulphide deposits (MVT, APT, IRT)	Pb, Zn	hydrothermal	Europe, Asia, North America
SSC	Sedimentary stratiform sulphide deposits	Cu, Co	hydrothermal	Europe, Africa
MSD	Massive sulphide deposits (VS, SEDEX)	Cu, Zn, Pb	hydrothermal	North America, Australia, Europe
AU	Vein-type gold deposits	Au	hydrothermal	All continents
BIF	Banded iron formation	Fe	sedimentary	Australia, South America, North America, Europe
LAT	Laterite deposits	Ni	supergene	Asia, South America, Europe
BAU	Bauxite deposits	Al	supergene	South America, Africa, Australia, Europe

Table A1. List of ore deposit types. Explains abbreviations in Figure 4. Source: own table.