Lithium: The fastest-growing mineral, driven by surging EV deployment

Lithium is mainly used for lithium-ion batteries, followed by ceramics, glass and grease. It is supplied from two very different types of resource: brine and spodumene (a type of pegmatite).

Brine resources are located in dry areas such as Atacama (northwestern South America) and western China, where the dry climate accelerates brine evaporation and accumulates mineral elements including lithium. Chile has been the largest producer from brine resources. Production occurs in three steps: (i) accumulating lithium contents to about 1-6% through a solar evaporation process in large pools for hundreds of days; (ii) removing other elements (e.g. boron, magnesium) via chemical processes; and (iii) extracting lithium carbonate from the solvent. Lithium carbonate is widely traded as the main material for battery cathodes, especially for relatively low nickel-content cathodes. Another major lithium product is lithium hydroxide, which is made through an additional process of adding slaked lime to heated lithium carbonate.

Spodumene is a mineral composed of lithium and aluminium, and its mines are mainly located in Australia, where lithium concentrate is produced via beneficiation processes. Concentrates are mainly exported to China by offtake contracts and refined to lithium carbonate or lithium hydroxide. Although brine was the dominant source of lithium historically, soaring demand for lithium has recently spurred the development of spodumene mines. As a result, Australia has emerged as the largest lithium mining country since 2017.

With regard to refining, China accounts for close to 60% of global lithium chemical production, importing increasing volumes of concentrate from Australia. Some companies in Australia are pursuing an integrated scheme to produce lithium chemicals in the country. These are likely to gain traction as producing lithium hydroxide directly from spodumene is less expensive than converting brine resources to carbonate and then to hydroxide.

Lithium demand for clean energy technologies is growing at the fastest pace among major minerals, largely reflecting the dramatic increase in EV deployment. While other minerals used in EVs are subject to uncertainty around different chemistry choices, lithium demand is relatively immune to these risks, with additional upsides if all-solid-state batteries are widely adopted (see Chapter 2). Clean energy technologies represent around 30% of total lithium demand today (up from a minuscule share in 2010), and the rapid uptake of EV deployment raises the share to some 75% in the STEPS and over 90% in the SDS by 2040. While lithium carbonate is currently the main chemical product used in EVs, lithium hydroxide is expected to take its place as it is more suitable for battery cathodes with high nickel content.

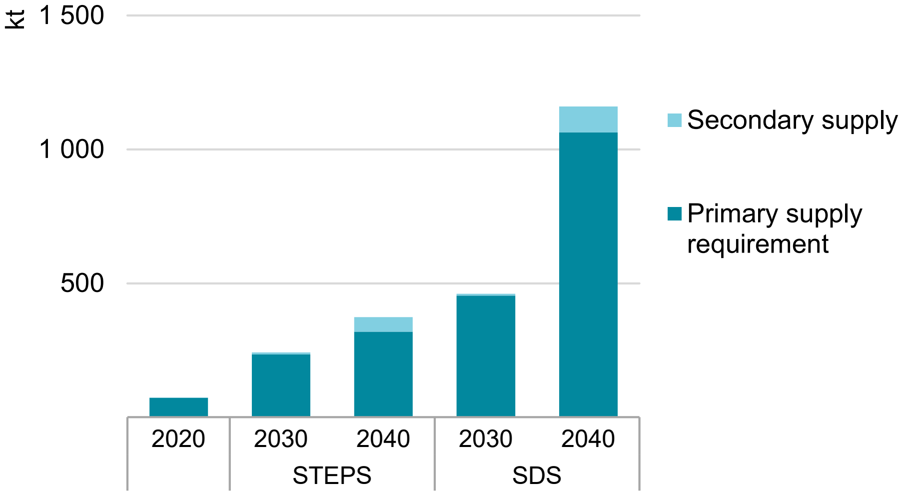
Lithium: The adequacy of lithium raw material supply depends critically on the demand trajectories. New extraction technologies could help broaden the supply pool

As EV deployment started to take off in earnest in the mid-2010s, surging demand sent major shockwaves through the lithium market, lifting prices threefold between 2015 and 2017. This triggered a wave of investment in supply in Australia and other regions, which resulted in the plunge in prices seen in the late-2010s (lithium resources can be developed with relatively short lead times compared to other minerals).

The production expansion is set to continue until the mid-2020s, with major producers (both brine and spodumene resources) planning to expand their capacity through to the medium term. Both the largest mine and brine production site, Greenbushes in Australia and Salar de Atacama in Chile, are expanding their production capacity by more than 2.5 times. Additional production from these two sites amounts to 320 kt of lithium carbonate equivalent per year, equivalent to over 70% of today’s global production. In addition, at least six projects are scheduled to start operations by 2025, including Cauchari-Olaroz in Argentina and Maricunga in Chile. Whether these supplies are sufficient to support demand critically depends upon how demand evolves.

Expected production volumes from existing mines and projects under construction look able to cover projected demand in the STEPS until the late 2020s, but they are not sufficient to support demand growth envisaged in the SDS. Satisfying SDS demand would require all these projects to be developed and be complemented by additional exploration. There is a host of projects at varying stages of development, with their combined production totalling around 2 500 kt of lithium carbonate equivalent per year.

Primary supply requirements for lithium by scenario



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New types of resources and development technologies may play an important role in the decade to come. Efforts are ongoing to recover lithium from unconventional resources. For example, processing clay minerals is simpler and less energy-intensive than spodumene as calcination processes are not needed, but their lower ore grades and complicated compositions pose challenges for commercialisation. At least three clay mineral projects are under development in the United States. Rio Tinto has invested AUD 14.5 million (USD 11 million) in a pilot project to produce lithium from waste rock at the Boron mine site in California (The West Australian, 2021).

Direct lithium extraction technologies are also on the horizon. Instead of evaporating all the water and chemically removing all the impurities, this process extracts the lithium directly from an unconcentrated brine to produce a lithium eluate, which can be processed to lithium chemicals without evaporation ponds (Grant, 2019). This holds the potential to reduce cost and lead times as brine accumulation takes more than a year and represents a major part of the capital expenditure of a brine project. Some developers are focusing on technology to recover lithium from oil and gas produced water and geothermal brine. Together, these new technologies could widen the pool of future lithium supply.

New technologies for lithium production

Technology	Mechanism	Developer
Unconventional resources		
Sedimentary rocks	Lithium production from hectorite (clay mineral), lepidolite and searlesite	Lithium Americas, Lepidico, Lithium Australia, ioneer
Waste rocks	Lithium production from waste of borate production	Rio Tinto
Direct lithium extraction (Brine/oil and gas produced water/geothermal water)		
Phosphate precipitation	Lithium phosphate precipitated upon addition of phosphoric acid	POSCO
Ion exchange	Lithium ions intercalated into layers of metal hydroxide or oxide	Dow, FMC, Simbol, Eramet, JOGMEC, Neometals
Solvent extraction	Selectively recover lithium from diluted water using solvent	Tenova
Nano filtration	Lithium ions concentrated by membrane	MGX
Others	Utilising subsurface technology expertise, etc.	NeoLith Energy (Schlumberger)

Sources: Kumar (2019); JOGMEC (2019a).

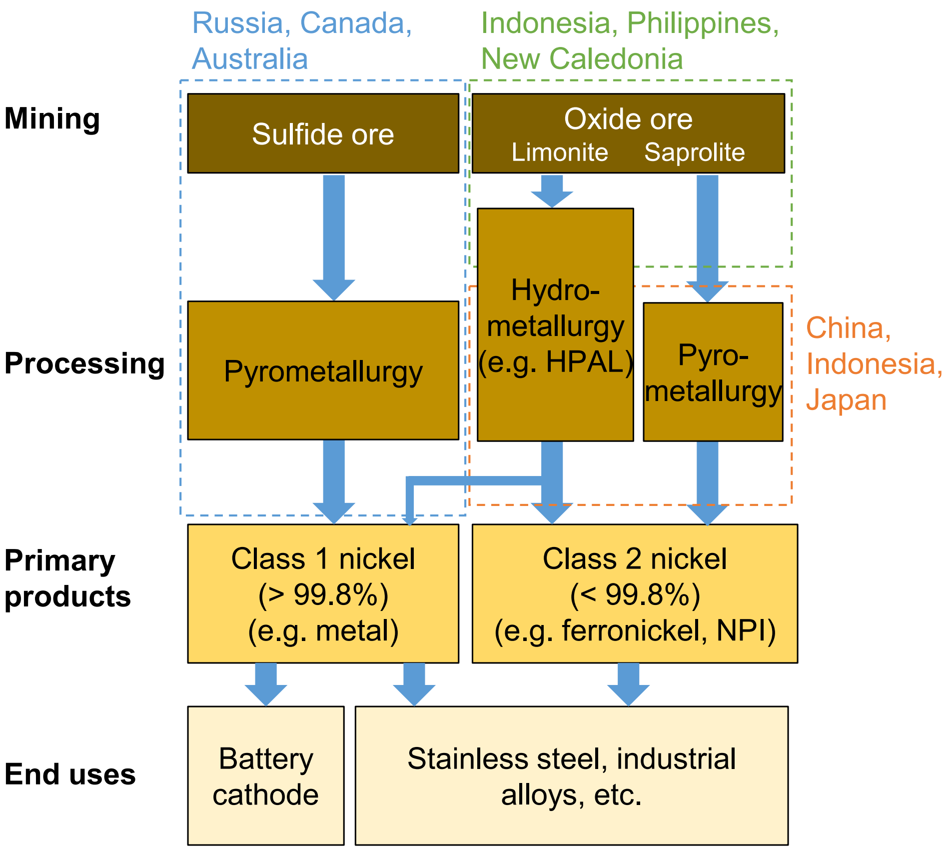
Lithium: The supply of lithium chemicals, lithium hydroxide in particular, could become a bottleneck

While lithium raw material is expected to remain well supplied in the near term, major strains are likely to come from the midstream value chain that converts raw materials into lithium chemicals. Only a handful of companies can produce high-quality, high-purity lithium chemical products – five major companies are responsible for three-quarters of global production capacity. While several planned expansion projects are in the pipeline, there is a question mark over how rapidly their capacity can come online to keep up with demand growth given that there are few deep-pocketed companies that can finance expansion projects, especially after several years of depressed prices. Many smaller companies are financially constrained and some have delayed planned expansion projects. The recent price rally for lithium carbonate partly reflects the potential concerns. Looking ahead, the strains could be particularly great for lithium hydroxide, which is set to drive future demand growth (as it is favoured for high-nickel cathode chemistries).

A higher level of concentration is another challenge. Close to 60% of global lithium chemicals are produced in China. Chinese companies have also invested in companies in South America. For example, Tianqi Lithium, a large lithium chemical producer in China, acquired a minority stake (23.8%) in Chilean company SQM. The picture is even more skewed for lithium hydroxide – in 2019 over 80% of lithium hydroxide was produced in China. Some projects to produce lithium hydroxide are being planned in Australia, the United States, the European Union and others, which could help diversify sources of supply, if successfully implemented.

As in the case of copper, mounting water stress poses a further challenge for lithium raw material producers in drought-concerned regions such as South America and Australia. In the case of brine resources, production operations may have adverse impacts on the water balance in the region. Recent studies identified a negative correlation between the continuous expansion of lithium extraction activities and the soil moisture index, a proxy for drought conditions (Liu et al., 2019). New direct lithium extraction technologies could help alleviate pressure around water sourcing.

Nickel: From resource to consumer



Nickel supply chain

Russia, Canada, Australia

Indonesia, Philippines, New Caledonia

China, Indonesia, Japan

Mining

Sulfide ore

Oxide ore
Limonite Saprolite

Processing

Pyrometallurgy

Hydro-metallurgy (e.g. HPAL)

Pyro-metallurgy

Primary products

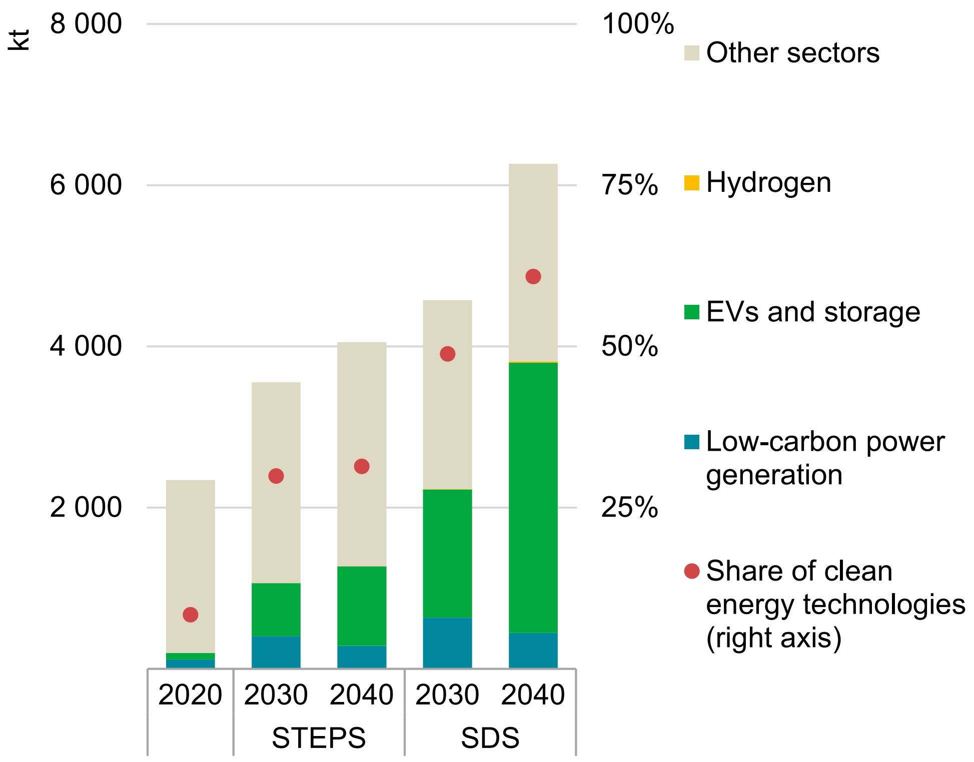
Class 1 nickel
(> 99.8%)
(e.g. metal)

Class 2 nickel
(< 99.8%)
(e.g. ferronickel, NPI)

End uses

Battery cathode

Stainless steel, industrial alloys, etc.



Total nickel demand by sector and scenario

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Nickel: A versatile mineral used in a wide range of clean energy technologies

Historically nickel has been used mainly for industrial alloys, to which it contributes corrosion resistance and workability. Around two-thirds of stainless steel currently contains nickel. However, lithium-ion batteries have recently emerged as a new source of demand. They account for around 7% of nickel demand today.

There are two types of primary nickel products: high-purity Class 1 products (containing 99.8% nickel or above) and lower-purity Class 2 products (containing less than 99.8% nickel). Battery cathodes need nickel sulfate, which is synthesised from Class 1 products.

There are complex relationships between different resource types (sulfide, saprolite and limonite) and product types (Class 1 and Class 2).

Sulfide deposits are mainly located in Russia, Canada and Australia, and have been the main source of supply for over a century. Nickel is concentrated in the ore at a relatively high grade, typically in the range of 0.4-3.2%.

Meanwhile, oxide resources (often called laterite) such as saprolite and limonite are located mainly in Indonesia, the Philippines and New Caledonia. Laterite resources are formed by weathering in a high-temperature and humid climate. More weathered upper soil is called limonite, and less weathered lower soil is called saprolite. Nickel is mainly absorbed in clay in the ore rather than in minerals. Saprolite has a relatively higher grade (1.8-3.0%) than limonite (0.8-1.8%). Due to these differences, methods of producing nickel products differ by resource type.

Sulfide ore is suitable for pyrometallurgical processes, as ore grades are relatively high and it is easy to concentrate the grade by flotation. Currently sulfide ore is the main source of high-purity Class 1 products. Limonite ore is usually processed via hydrometallurgical processes such as HPAL (high-pressure acid leaching), as it is easy to leach the absorbed nickel from clay and has less acid-consuming magnesium than saprolite. Also, there are many existing limonite tailings, which were once discarded during saprolite mining before HPAL technology became commercialised. Although the number of operating HPAL projects is currently small, several new projects are being built or are planned. Saprolite ore is generally not suitable for Class 1 products, and is mainly used to produce Class 2 products for stainless steel (e.g. ferronickel and nickel pig iron).

Around 10% of nickel demand is used for various clean energy technologies, either as a cathode material for batteries or in the form of alloys for renewables and hydrogen. Clean energy technologies' share of total nickel demand grows further to over 30% in the STEPS and to around 60% in the SDS by 2040. In the SDS, batteries take over from stainless steel as the largest consumer of nickel by 2040.

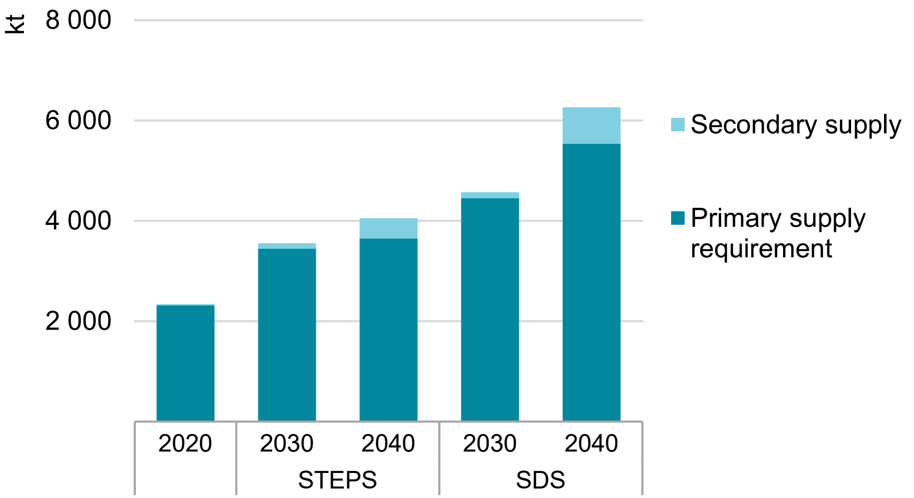
Nickel: All eyes on Indonesia

Global nickel production has increased by 20% over the past five years, mainly driven by expansion projects in Asia Pacific, most notably Indonesia and the Philippines. These two countries represent 45% of global output today.

Their domination of nickel production is set to intensify in the coming years, as they are responsible for around 70% of global production growth over the period to 2025. Indonesia alone accounts for around half of the growth. In the longer term several projects are being planned outside Indonesia, such as the Kabanga project in Tanzania (one of the largest nickel sulfide deposits, with 2.6% high-grade ore) and the Wingellina project in Australia.

This suggests that future nickel supply is highly likely to be driven by progress in Indonesia, and therefore global nickel supply chains may be affected significantly by physical events or policy change in Indonesia. On 1 January 2020 the government of Indonesia implemented a ban on nickel ore exports, two years ahead of the previously announced date, with the aim of processing its ore in domestic smelters (instead of exporting to China) and thereby nurturing a downstream industry. In 2020 nickel ore exports to China dropped by nearly 90% and nickel pig iron exports doubled compared to 2019 (Reuters, 2021b). This in turn forced Chinese refiners to find new sources of ore supply from the Philippines or New Caledonia, but also to seek investment opportunities in Indonesia. Chinese companies invested and committed some USD 30 billion in the Indonesian nickel supply chain, with Tshingshan's investments in the Morowali and Weda Bay industrial parks being the most prominent examples.

Primary supply requirements for nickel by scenario



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Nickel: Quality challenge compounded by resource challenge, with Indonesia pivotal on both

The prospects for nickel supply are mixed. The overall nickel market is likely to remain well supplied, but the picture becomes vastly different for battery-grade Class 1 products. Class 1 nickel is in slight surplus, but the rapid rise in demand from batteries is soon set to change this to deficits. In general, sulfide resources are a good fit for producing battery-grade Class 1 nickel. However, most of the production growth in the coming years is poised to come from the regions with vast amounts of laterite resources, such as Indonesia and the Philippines, which are generally more suitable for Class 2 products.

As such, HPAL is gaining traction as a way to produce Class 1 products from laterite resources. The five hydrometallurgy projects under development in Indonesia all employ HPAL. However, this brings several challenges. First, past HPAL projects have track records of large cost overruns and delays. Second, HPAL is technically difficult to operate stably, as it processes low-grade ore under high temperature and pressure. Third, as HPAL uses acid to leach metals from the deposits, acid production facilities are required on site, which incurs additional cost. Capital costs for HPAL projects are typically more than double those for conventional smelters for oxide ore (BloombergNEF, 2020). And fourth, HPAL projects tend to take four to five years to ramp up to 80% capacity.

HPAL's past track record may not be a good guide to the prospects for Indonesian HPAL projects. They are planned to leverage existing infrastructure, which could help reduce capital costs. Two of the projects are planned to be built at the Morowali Industrial Park, a nickel mining and export hub in Indonesia. As a result, the capital cost of the planned HPAL projects in Indonesia is estimated to be 60% of the average for a typical HPAL project (BloombergNEF, 2020a).

While promising, it remains to be seen if these projects come online as scheduled. The first, PT Halmahera Persada, plans to start operations in 2021. If it comes online successfully, other projects could follow using the first project as a template.

There are environmental issues that need to be addressed, such as higher CO_2 emissions arising from the use of coal-based electricity and tailings disposal. While land-based tailings storage facilities are widely used globally, deep-sea tailings placement is being considered as an option in Indonesia because of the country's unique geographical conditions (e.g. high precipitation and frequent seismic activities) and its lower cost. However, deep-sea tailings placement is causing concern about the marine environment. Economic and sustainable tailings treatment is set to remain a major challenge for HPAL projects in Indonesia.

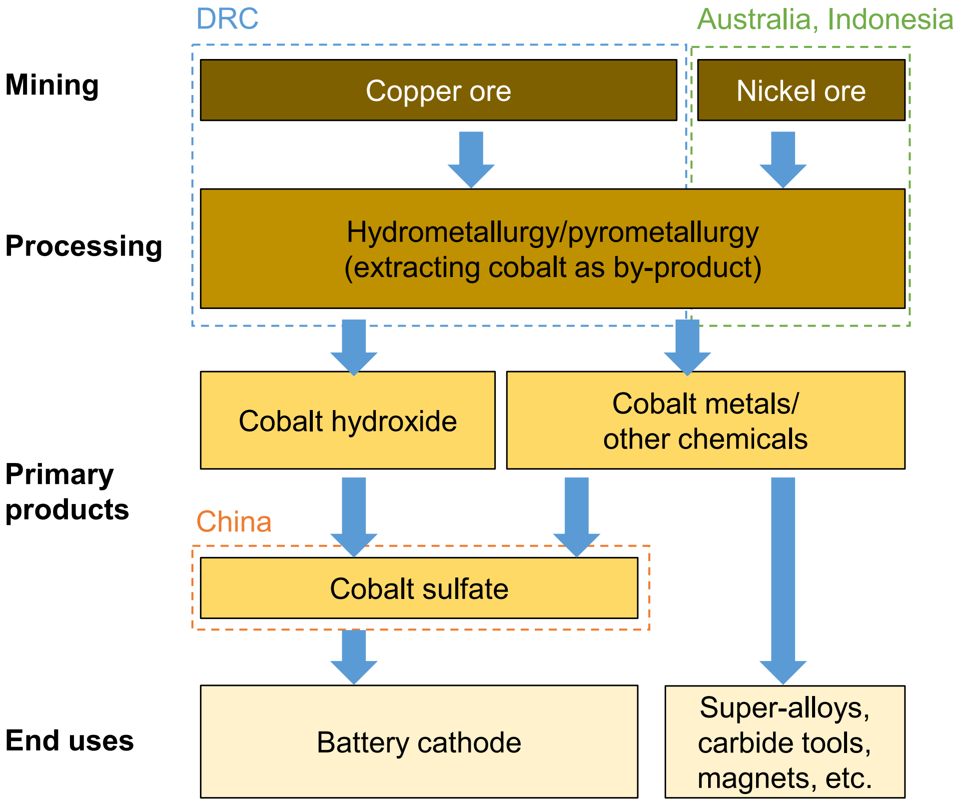
While the prospects for HPAL projects in Indonesia are crucial, there are other pathways that could meet the demand for Class 1 products :

- Some of the current Class 1 consumption in the non-battery sector could be switched to Class 2, freeing up Class 1 nickel supply for batteries. Higher prices would be required to incentivise such a switch.
- Increasing stainless steel production from scrap materials would make some Class 1 supply available for other uses.
- Conventional oxide smelters, instead of HPAL, could produce Class 1 products from saprolite resources: Tsingshan, the world's largest nickel producer, plans to convert nickel pig iron to nickel matte from its operations in Indonesia, which could then be further refined into Class 1 products (Roskill, 2021a). This is, however, highly energy-intensive and adds more cost.
- Given that Class 2 products are expected to be well supplied, it is conceivable to use Class 2 products such as ferronickel or nickel pig iron as feedstock to produce nickel sulfate for batteries. While technically possible, this process is likely to be cost-prohibitive.
- As explored in Chapter 2, recent movements towards high-nickel chemistries in battery cathode could be slowed if Class 1 nickel supply becomes tight and prices remain elevated, which could instead raise demand for cobalt.

If all planned HPAL projects in Indonesia go smoothly, it would provide sizeable volumes of Class 1 supply, easing pressure on prices in the medium term. Several options are available to satisfy the need for Class 1 products in the case of failure or delay, but all options have some drawbacks and would need higher prices for them to materialise. Given that there is no long list of projects in the pipeline outside Indonesia, progress in Indonesia will be key to future nickel supply for batteries, at least in the near term.

Cobalt: From resource to consumer

Cobalt supply chain



DRC

Australia, Indonesia

Mining

Copper ore

Nickel ore

Processing

Hydrometallurgy/pyrometallurgy (extracting cobalt as by-product)

Primary products

Cobalt hydroxide

Cobalt metals/ other chemicals

China

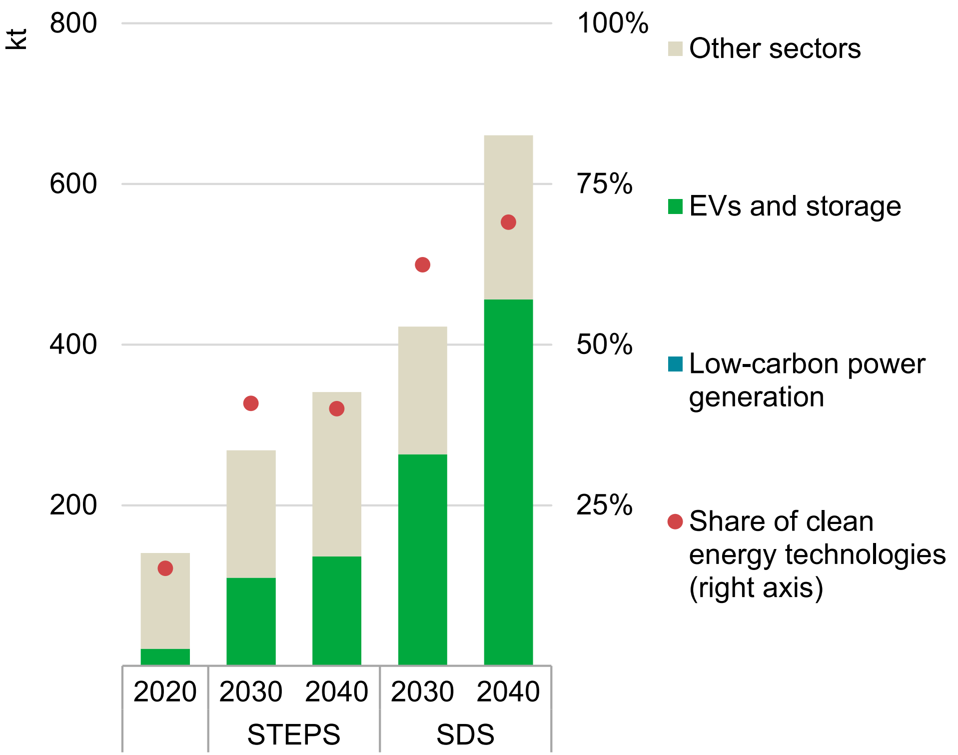
Cobalt sulfate

End uses

Battery cathode

Super-alloys, carbide tools, magnets, etc.

Total cobalt demand by sector and scenario



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Note: There are mines that produce cobalt as a primary product, but volumes are smaller than those produced as a by-product.

Cobalt: Strong EV-driven demand growth despite uncertainties around cathode chemistry development

Lithium-ion batteries are the main user of cobalt today, followed by super-alloys, carbide tools and magnets. As in the case of lithium, the rapid increase in EV deployment in the mid-2010s shook the relatively smaller cobalt market and underpinned rollercoaster price movement. As rapid demand growth put strains on supply, prices registered a fivefold increase between 2016 and early 2018. This triggered a range of supply responses, both large-scale project investment and a surge in artisanal small-scale mining activities, which helped to stabilise prices.

Some 70% of cobalt is produced in the DRC as a by-product of its copper mines. Cobalt is also produced as a by-product of nickel mines in some countries. The Bou Azzer mine in Morocco is the only major active mine that produces cobalt as a primary product. In the DRC, Glencore produced around 40% of the country's production in 2019, followed by China Molybdenum (12%). In recent years Eurasian Resources Group has emerged as a major producer in the country as its Metakol RTR mine ramps up. While Glencore recently reduced production due to mine maintenance and low market prices, the facilities could restart and expand production capacity once maintenance is completed. Gécamines, a state-owned trading and mining company, is participating in production by owning stakes of 20-50% in certain mines. Some 10-20% of cobalt production in the DRC occurs in the form of artisanal and small-scale mining (Roskill, 2021b).

China processes around 70% of mined cobalt globally, followed by Finland, Belgium and Canada. The DRC exports intermediate chemical products (cobalt hydroxide) to China, which are then converted to cobalt sulfate for use in batteries.

The development of cobalt demand is highly dependent on the direction in which battery cathode chemistries evolve. The composition of cathode chemistries is increasingly shifting towards those with high-nickel content, which could weigh on the appetite for cobalt. However, even under our default assumptions where this trend is sustained, the strong uptake of EVs underpins sevenfold growth in cobalt demand for clean energy technologies in the STEPS and over twenty-fold growth in the SDS over the period to 2040. This raises the share of clean energy technologies in total demand from 15% today to 40% by 2040 in the STEPS and over two-thirds in the SDS.

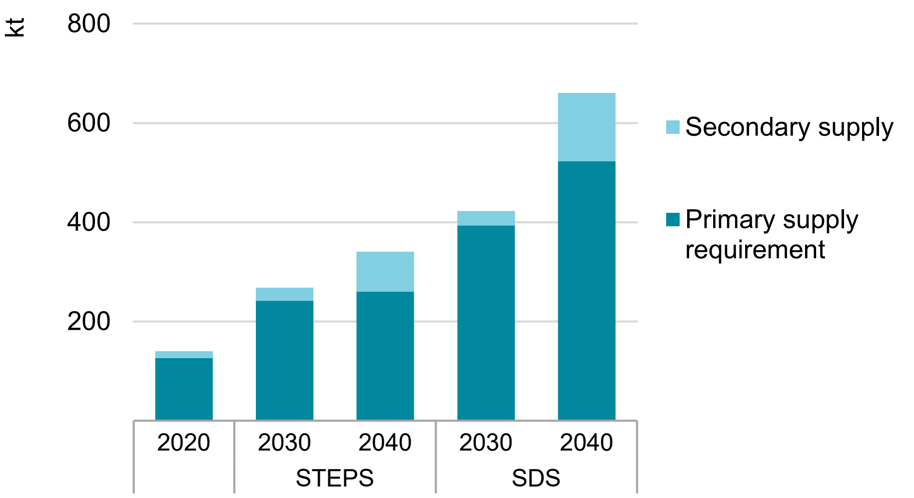
Cobalt: Production of cobalt is likely to remain concentrated in the DRC and China

Global cobalt production has increased by 10% over the past five years, mainly driven by the DRC. While some capacity has been subject to temporary suspension due to the recent plunge in prices, two large mines (Kamoto and Metalkol RTR) are under expansion and a new project (Musunoi) is set to start operations in the early 2020s. These projects together would add around 20 kt of annual production by 2025. The Metalkol RTR project alone plans to produce 20 kt by processing cobalt-copper tailings through a hydrometallurgical process. The planned projects in the DRC account for the majority of the current project pipeline, implying that the DRC is set to remain the dominant source of cobalt supply for the time being.

However, outside the DRC, Australia, Canada, Madagascar and Russia have plans to increase cobalt production, mainly through enhanced recovery of cobalt from nickel and copper mines. For example, the CleanTeQ Sunrise project in Australia plans to produce cobalt from one of the world's largest cobalt-rich nickel laterite deposits. Overall, the expected output from existing mines and projects under construction would be sufficient to serve STEPS demand until the medium term, but meeting SDS demand requires a further acceleration in project development.

Mining and processing operations for cobalt are highly concentrated in two countries, the DRC and China, and there is a close tie between the two countries. The supply chains for cobalt could therefore be highly affected by regional incidents on the trade route or policy changes in these countries. In addition, China has influence over many assets in the DRC through foreign direct investment. It is estimated that one-third of China's imported intermediate products are from mines or smelters in which it has a stake.

Primary supply requirements for cobalt by scenario



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Cobalt: Efforts to formalise the ASM sector and promote enhanced recovery could mitigate negative social impacts while reducing uncertainty around future production volumes

The significant share of artisanal and small-scale mining (ASM) in the DRC is another challenge in cobalt supply. On the one hand, ASM production can have a stabilising effect on markets, as producers are sensitive to price changes and can reduce or ramp up production quickly. On the other hand, ASM may be more vulnerable to economic and social events such as the Covid-19 pandemic. While large-scale mining also has environmental and social impacts, ASM sites often present particular challenges due to their unregulated and informal nature, including unsafe conditions for workers and the presence of child labour.

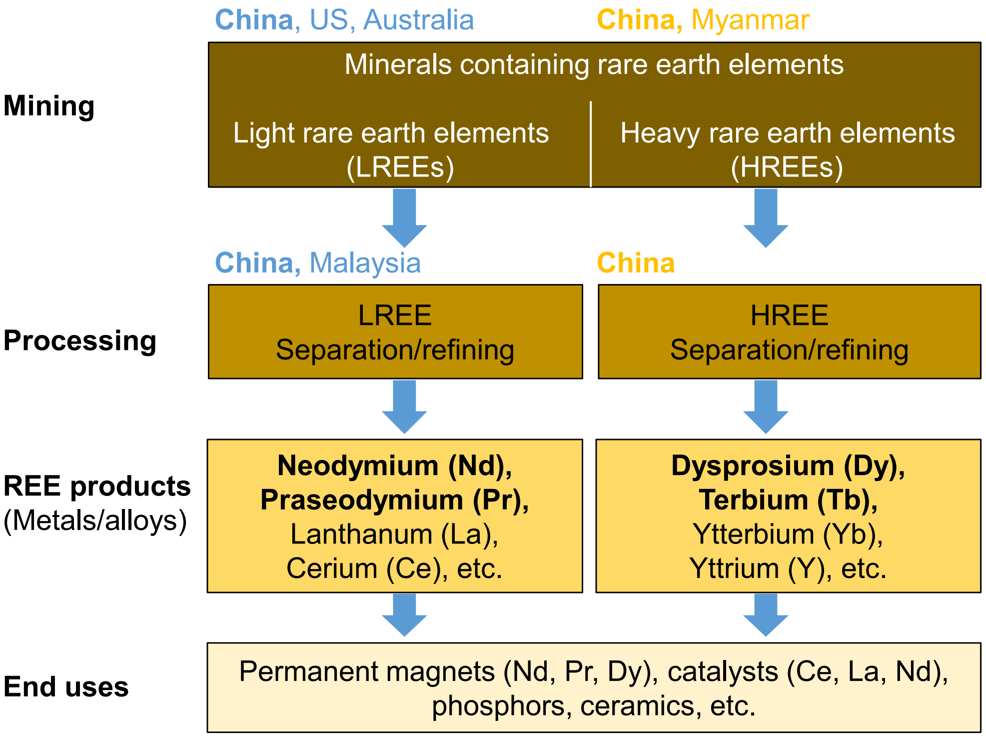
Given these risks, there is a temptation for companies to disengage from the ASM supply chain entirely. However, disengagement may paradoxically worsen the situation. ASM provides an important source of income for many local communities, which, with appropriate mitigation efforts, can help to address the root cause of child labour: poverty. In recognition of this, a growing number of companies are adopting due diligence practices aimed at identifying, assessing and mitigating these risks (see Box 4.8).

Companies and governments are also developing “on the ground” efforts to formalise the sector and prevent irresponsible practices. The DRC government has announced support for formalising ASM through the state-owned Entreprise Générale du Cobalt, and some companies have established formalised or semi-formalised ASM pilot projects. However, the long-term viability of this approach is unclear as early pilot projects closed down in 2020 due to the Covid-19 pandemic (Mining Technology, 2020). Separately, a number of industry initiatives exist to provide additional support for formalisation. For example, the “Cobalt for Development” project was launched by BMW, BASF, Samsung SDI and Samsung Electronics (recently joined by Volkswagen), aiming to improve working and living conditions for surrounding communities. However, given the scale of the problem, further efforts would be needed to reduce uncertainty and provide more stability to the market.

Another complication is that cobalt is usually produced as a by-product of copper and nickel. It means that investment decisions for new project development or capacity expansion are not necessarily linked to cobalt market dynamics, but rather more susceptible to the market conditions for copper and nickel. While this raises uncertainty about future supply, efforts to adopt processing methods that maximise cobalt recovery can play an important role in mitigating risks. For example, Kamoto Copper Company in the DRC has adopted a new leaching method – whole ore leach – which improves cobalt recovery rates from 34% to 65% (JOGMEC, 2019b). Methods of this kind have the potential to provide sizeable by-product volumes and ease supply-side pressure if widely adopted.

Rare earth elements: From resource to consumer

Rare earth elements supply chain



Mining

China, US, Australia

China, Myanmar

Minerals containing rare earth elements

Light rare earth elements (LREEs)

Heavy rare earth elements (HREEs)

Processing

China, Malaysia

China

LREE Separation/refining

HREE Separation/refining

REE products (Metals/alloys)

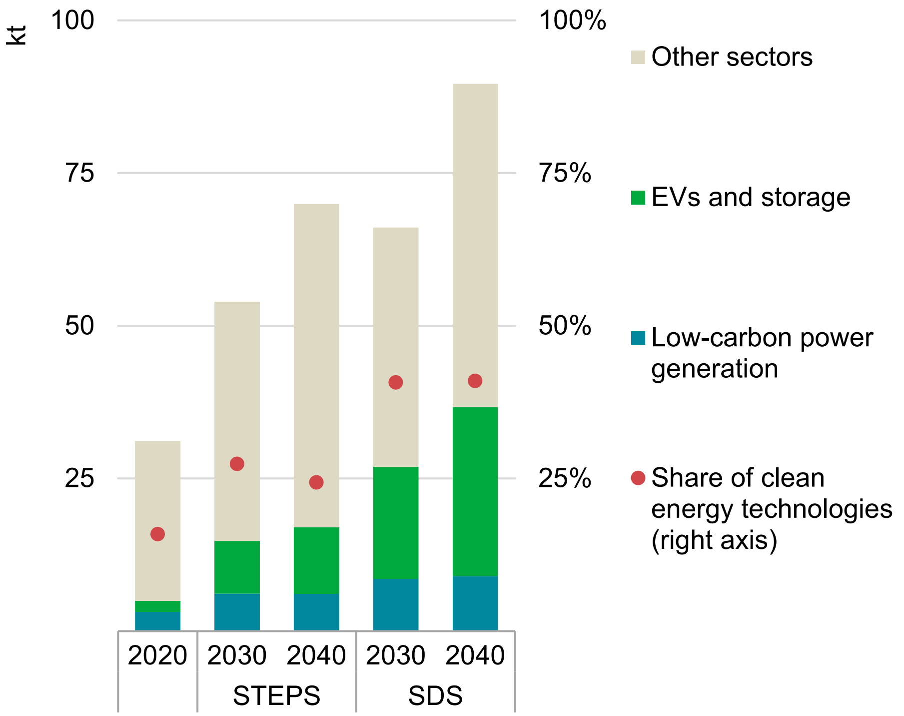
Neodymium (Nd), Praseodymium (Pr), Lanthanum (La), Cerium (Ce), etc.

Dysprosium (Dy), Terbium (Tb), Ytterbium (Yb), Yttrium (Y), etc.

End uses

Permanent magnets (Nd, Pr, Dy), catalysts (Ce, La, Nd), phosphors, ceramics, etc.

Total neodymium demand by sector and scenario



Rare earth elements: A story of concentration and diversification

REEs are a family of 17 elements comprising 15 elements in the lanthanides group (ranging from lanthanum to lutetium), plus scandium and yttrium. On the basis of atomic weight, among the lanthanides group the lighter six elements are classified as the light rare earth elements (LREEs) and the other nine elements as the heavy rare earth elements (HREEs) (IUPAC, 2005). REEs are contained in the same orebody, the composition of which varies widely by deposit. Typically mined orebodies have LREEs as a large proportion of cerium and lanthanum and a modest amount of magnetic rare earths, plus a small fraction of HREEs (CRU, 2020b). To separate individual elements, mineral concentrate is fed into high-temperature concentrated acids to liberate the REEs they contain and remove radioactive elements (e.g. thorium, uranium).

While each REE is used in different applications, four elements – neodymium, dysprosium, praseodymium and terbium – are of particular importance to the clean energy sector. One of the major uses is permanent magnets for motors. Demand for permanent magnets accounts for the majority of total REE demand today in dollar terms, and is expected to grow faster than any other sector, driven by the strong rise in demand for clean energy technologies. REEs are also used in the catalytic converters of conventional cars to remove pollutants.

Demand for neodymium – one of the most important REEs in the clean energy sector – more than doubles in the STEPS and triples in the SDS, reaching 70 kt and over 90 kt by 2040 respectively. Clean energy technologies represent 15% of total neodymium demand today, and their share is set to increase to 25% by 2040 in the STEPS and over 40% in the SDS.

The United States had been leading the production of REEs until the mid-1990s, when China started to emerge as a major producer. Since then, China's share of global production rose to over 95% in 2010, since when its share has fallen to just over 60% in 2019, as the United States, Myanmar and Australia started to boost production (USGS, 2021).

However, separation and refining operations are still heavily concentrated in China, with almost 90% market share in 2019. There are currently four plants operating outside China, in Malaysia, France, India and Estonia. These plants, however, process only LREEs and the processing of HREEs is entirely dominated by China. This is due in part to the fact that China hosts abundant ion-adsorption clay deposits, which are easy to mine and often rich in HREEs. For example, the highest HREE composition outside China and Myanmar is only 5% (Mt. Weld in Australia), while the HREE content in Xinfeng in China is nearly 50% (JOGMEC, 2020).

While China's share of mining has declined in recent years, its presence in the downstream operations – from processing to metals production to magnet making – has continued apace, with the country holding some 90% market share across the value chain.

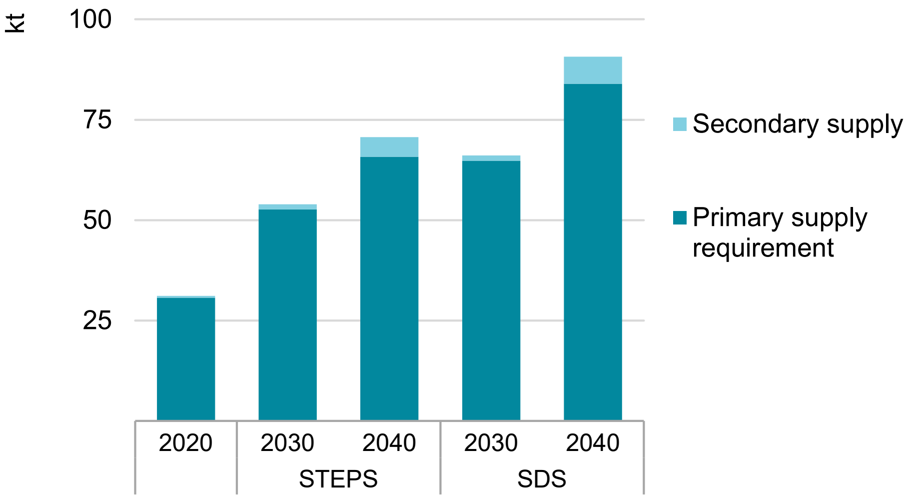
China's attempt to limit REE exports in 2010 was an alarm bell for many countries that rely on imports. In the immediate aftermath, prices spiked by more than 10 times for many REEs, although prices subsequently declined. This extreme price movement triggered many countries to consider options to reduce material intensity, find substitutes and diversify sources of production. Japan introduced a comprehensive policy package ("ABCD+R" initiative) that encompasses measures to reduce consumption, secure diversified supply sources and promote recycling. As part of the package, the country offered a USD 250 million loan to Lynas, an Australian REE producer, which was the only sizeable non-Chinese company in the business at that time, to secure non-Chinese supply options.

Several new projects have been launched outside China, and today some 20 projects are under development in Australia, Canada and the United States, of which 5 projects plan to start operations in the early 2020s.

On the processing side, a plant in Malaysia run by Lynas is the only large non-Chinese facility in operation today, but several others are under development. In 2020 the US government funded two projects – one by Lynas and the other by MP Materials – while another project by Texas Mineral Resources is under review. In addition, MP Materials plans to upgrade inactive refining facilities at a mine site.

Meanwhile, the Chinese government has been trying to control the illegal mining of REEs. Before 2014 the country used an export quota to restrict unsanctioned production, which was not effective in controlling production. The quota was lifted in 2014 after the decision by the World Trade Organization (see Box 3.4). In 2015 the country consolidated the REE industry into six state-owned enterprises as part of efforts to bring the industry under control and strengthen environmental oversight. These companies account for 80-85% of REE production in China today and production from illegal mining has registered a notable decline since 2015 (BloombergNEF, 2020b).

Primary supply requirements for neodymium by scenario



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Rare earth elements: Demand soaring to new heights, imbalances looming

While the surge in EV sales and renewables deployment presage a period of booming demand for the four REEs that are vital to clean energy technologies, it is not yet clear if supply can keep up with the demand trajectory as bottlenecks are hampering investment decisions.

A key consideration is China's position along the value chain. A country could open a mine site or build a processing plant, but, as things stand, it would need to bring the output to China for further processing as it would be difficult for a single country to build a presence along the whole value chain. Limited transparency about the market and pricing further complicates investment decisions.

The second issue arises from a unique feature of REEs. All naturally occuring REEs co-exist in the same orebody. They are therefore produced together when processing the ore despite the fact that each element faces different market prospects. While the four elements widely used in clean energy technologies are poised to be in high demand in the years to come, other elements such as cerium and lanthanum, which are used for polishing powders, alloy manufacturing and refining catalysts, do not share the same positive outlook. If a company is to produce neodymium to meet rising demand, it also needs to deal with surplus cerium, the price of which is likely to remain subdued. This could weigh on aggregate profits from REE production, implying that higher prices for neodymium might not necessarily trigger new investment.

There are also environmental concerns: processing REEs often generates toxic and radioactive materials. These can leak into groundwater, causing major health and safety issues, including fatalities. This has been a serious issue in China. The Chinese government started to tackle this issue, although further efforts will be needed. On 1 September 2020 the country announced the revised law on the Prevention and Control of Solid Waste Pollution, which raised penalties and introduced a credit record system.

Given the rapid rise in projected demand, production would need to increase both within and outside China, but these volumes need to be produced under higher environmental standards. In China tightening environmental regulations would help avoid an influx of unregulated volumes and incentivise investment. At the same time, it would be important to secure diversified sources of supply, which would need international co-ordination and policy support.

New technologies could also unlock additional supply. For example, REEs could be recovered from the deposits of nuclear fuels. The US Department of Energy has funded several projects to develop commercially viable technologies to extract REEs from coal and coal by-product sources.

Box 3.1. Can deep-sea mining be an answer to the need for more critical minerals?

After decades of experience with deepwater oil and gas production, many countries and companies are increasingly eyeing resources beneath the sea as a response to declining high-grade deposits on land. Several exploration projects are progressing in the exclusive economic zones (EEZs) of Japan, Norway and Papua New Guinea. Following the discovery of large sulphide deposits, Norway plans to issue licences to kick-start deep-sea mining as early as 2023, which could place it among the first countries to harvest minerals on the seabed. Around 30 projects are waiting for the formulation of official rules outside the EEZ by the International Seabed Authority (ISA).

Deep-sea mining is the process of exploiting mineral resources from the area of the ocean below 200 metres. There are three main types of deposits: (i) cobalt-rich crust that contains manganese, iron, cobalt, copper, nickel and platinum; (ii) polymetallic nodules which are rich in manganese, nickel, copper, cobalt, molybdenum and REEs; and (iii) sea-floor massive sulphides which contain copper, gold, zinc, lead, barium and silver. In an area of 4.5 million square kilometres in the eastern Pacific Ocean, reserves of polymetallic nodules are estimated at 274 Mt for nickel and 44 Mt for cobalt, multiple times the global terrestrial reserves (Hefferman, 2019).

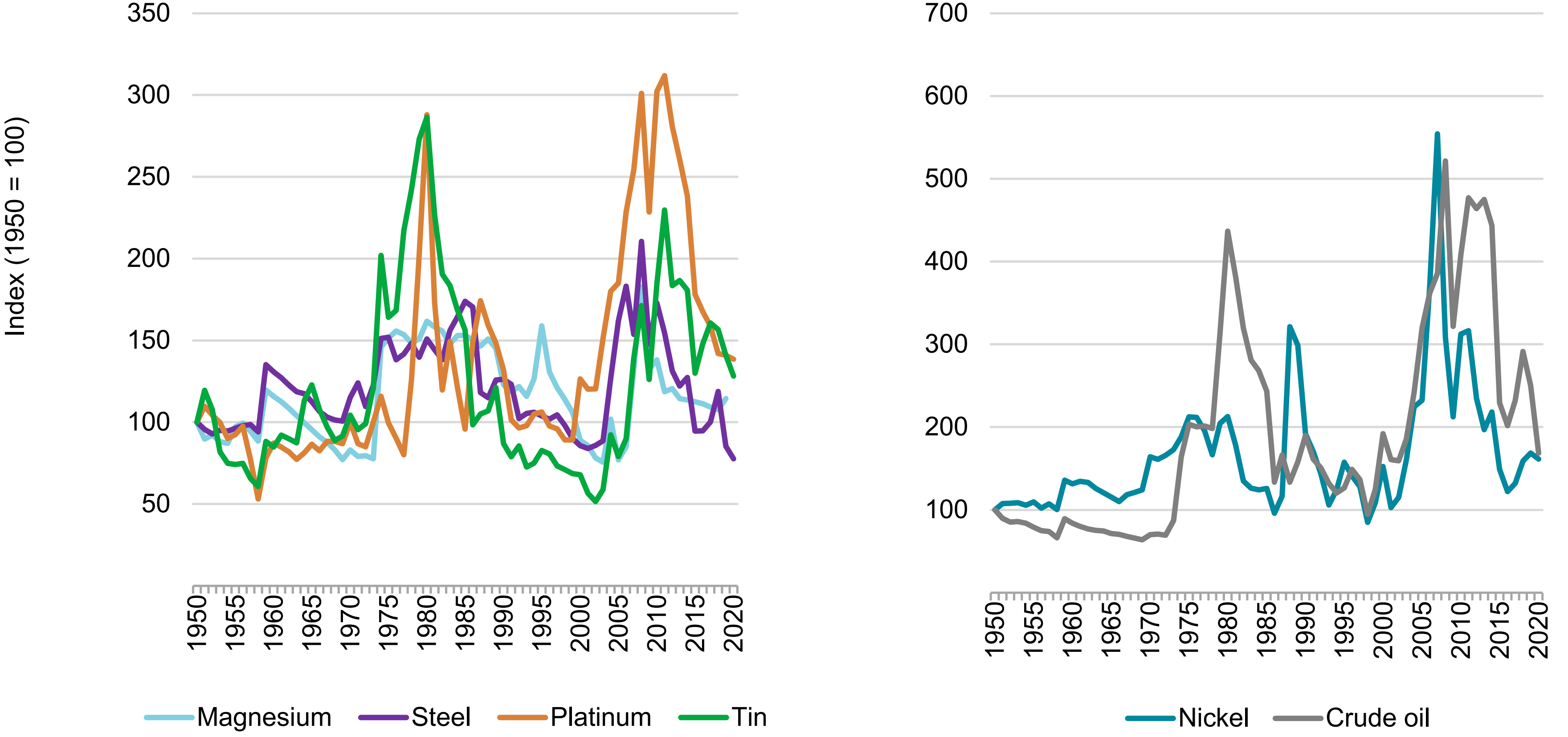
However, there are economic, technical and environmental hurdles. The technologies required are different from onshore mining or deepwater oil and gas extraction. Cutting machines and collecting vehicles need to work remotely under high water pressure, and pumping a mixture of ore and slurry requires different skills from the extraction of oil and gas. While a pilot ore lifting for massive sulfide succeeded in Japan in 2017, further technology development is needed to make the process commercially viable (METI, 2017).

Studies also suggest potentially significant environmental impacts. Machines often cause seafloor disturbance, which could alter deep-sea habitats and release pollutants. Sediment plumes, which arise from stirring up fine sediments, could also affect ecosystems, which take long time to recover. Ecosystems in some old test sites have not yet recovered after 30 years (Hefferman, 2019). The impacts on biodiversity are largely unknown. Despite the vast opportunities, rigorous assessments would be needed to understand the full extent of environmental damage and develop proper regulatory measures. BMW, Samsung SDI, Volvo and Google recently announced moratorium on materials from deep-sea mining until the risks are fully understood (WWF, 2021). The ISA is developing regulatory frameworks for the international seabed, aiming to promote deep-sea mining while minimising environmental risks.

Approaches to ensure reliable mineral supply

Periodic price spikes and volatility have characterised mineral resource markets, just as they have for crude oil

US price trends for several commodities in real terms, 1950-2020



Sources: IEA analysis based on USGS (2013) for historical prices to 2010 and S&P Global (2021) for recent prices.

Governments and industry responded to previous episodes of supply concern with substitution, innovation and supply responses, but with price increases and time lags

Analysis of historical episodes of tight mineral supply provides useful insight into the factors that could help to mitigate future risks from price spikes. Mitigating activity includes mineral substitution or innovation in supply and demand technologies, although not all price spikes can be avoided entirely. As mineral extraction and processing are often energy-intensive, mineral prices are influenced by trends in energy prices in addition to factors such as geological concentration, production capacity and supply chain bottlenecks.

Lower-grade US iron ore: Time lags limit substitution

When the production of natural iron ore peaked in Minnesota in 1953, research into the extraction of iron from taconite was ramped up in the state (Manuel, 2017). Producing iron from abundant taconite requires processing of over three times more rock than natural ore. Although the quality of iron from taconite had been rejected by the Ford Motor Company in the 1920s, its viability improved as prices of steel rose. A mine was opened in 1955, but this could not prevent the share of Minnesota iron ore in the United States slipping from 68% in 1946 to less than half by 1960. A tax incentive for taconite producers was added to Minnesota's constitution in 1964, but by that time iron ore trade had become more globalised and the problem that taconite mines had sought to address was not as pressing. Most taconite mines had closed by the 1980s, by which time their favourable tax treatment had also put the natural ore mines out of business.

Trade rules drove (and cooled) magnesium price spikes

Magnesium's military importance has shaped its production since the early 20th century, with all major countries seeking to host a domestic industry. However, not all countries have equal magnesium resources, which has periodically driven intensive research into thermal processes that extract magnesium from ore-bearing rocks and electrolytic processes to extract magnesium from brine. Since 1950 US magnesium prices have surged four times: in response to inflation in 1973; in response to a jump in aluminium demand in 1987; in response to the barring of Candian imports in 1995; and in response to the closure of plants in Canada and Russia, combined with anti-dumping duties on Chinese imports, in 2007 (USGS, 2013).

Price spikes have largely been resolved by relaxing import constraints, while innovation has not enabled local production despite high prices. The price jolt in 1987 was resolved by new capacity coming online in Canada (though this was itself subject to US anti-dumping measures by 1992). Trade policy-induced volatility continues to affect incentives to invest in new capacity in several major economies.

Aluminium substituted for copper, but with time lags

In electrical cabling, aluminium performs similarly to more expensive copper but has some technical downsides. It became a serious competitor for copper in electrical conductors after World War II, when copper demand could not be met by producer countries. In Germany copper prices rose sixfold in the 20 years to 1966, while aluminium prices were more constant. Aluminium has enjoyed a price advantage ever since, but has not penetrated the market accordingly.

One reason is the time it took for innovation to overcome safety concerns and match the cumulative experience of engineers using copper. Research launched in the United Kingdom in the 1950s took around a decade to resolve key issues, by which time the relative prices had converged and certain applications were using underground cables where the weight advantage was nullified. In the second half of the 20th century, aluminium demand for electrical cabling was seen to respond to copper price spikes, but with a lag of years or decades (Messner, 2002). Its impact was muted by the cyclicality of relative prices and the dominant foothold that copper had already gained.

Aluminium also substituted for tin, notably in packaging. This was initially in response to high tin prices resulting from international cartelisation that was intended to benefit tin producers and user countries. It provides a lesson in the unanticipated effects of such measures.

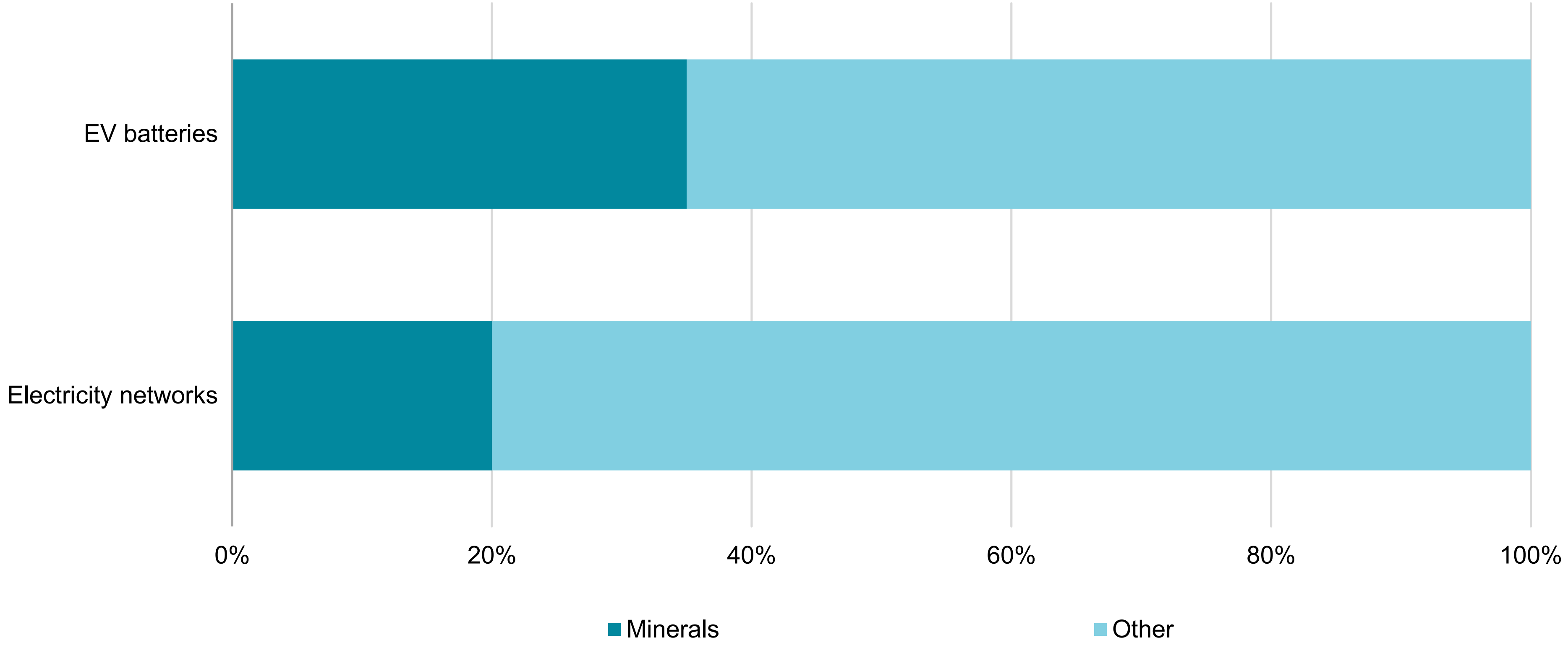
As total aluminium demand has risen, technological advances have made it possible to use lower-grade resources – the maximum allowable silica content of bauxite has doubled in 30 years – without prices ever reaching more than 40% above their 1950 level in real terms. Due to price advantages, major consumers such as the United States continue to rely on imports rather than exploit advances in the use of bauxite-containing clays and non-bauxite sources.

Platinum prices spurred innovation in substitution

Since 1979 the automotive sector has been the principal platinum consumer for catalytic converters. Initial platinum purchases by car companies fuelled speculation that pushed up prices. One response to higher prices was more commodity trading and fewer bilateral trades with South African producers. However, volatile platinum prices remained an issue for the automotive sector in the 1980s, spurring research into substitution (USGS, 2013). In 1988 Ford announced a platinum-free catalyst, and by the late 1990s catalytic converters for gasoline cars contained more palladium than platinum. However, a subsequent spike in the palladium price caused producers to return to platinum briefly, before platinum prices outpaced those of palladium again when catalytic converters for diesel engines were introduced. While today's relative prices would suggest a return to platinum in gasoline catalytic converters, this is not widely expected for reasons of well-established designs and supply chains, and past experiences of cyclical prices.

The biggest risk from inadequate mineral supply could be less affordable and delayed clean energy transitions

Current share of mineral cost in total investment in selected clean energy technologies



Note: Mineral cost for EV batteries (based on 40 kWh NMC622) covers copper, lithium, cobalt, manganese, nickel, graphite and aluminium, and that for electricity networks covers copper and aluminium.

Source: IEA analysis based on Argonne National Laboratory (2020), BatPac 4.0.

Countries and regions are stepping up efforts to ensure reliable supplies, although their policy approaches differ

While policy makers have been concerned about critical minerals since the 1950s, export restrictions on REEs introduced by China in 2010 triggered many countries to adopt formal strategies and implement measures to ensure reliable supplies of minerals. Over the past decade, the European Union, the United States, Japan, Canada and Australia have all introduced critical material strategies. The issue of critical minerals has risen further up the policy agenda due to growing momentum behind clean energy transitions. Although ensuring undisrupted supplies is a common feature of the strategies, specific directions and policy priorities vary depending on national or regional circumstances.

Meanwhile, China has emerged as a major force in global supply chains for critical minerals and clean energy technologies over recent decades. The country's rise to becoming the kingpin of clean energy supply chains has largely been underpinned by its long-term industrial policies, such as five-year plans for economic development, the Made in China initiative and the Belt and Road Initiatives. In this section, we examine major policy directions and approaches to ensuring mineral security across global regions.

The European Union: Diversified and sustainable supplies to support clean energy transitions

In September 2020 the European Commission published a set of policy documents to make Europe's raw materials supply more secure and sustainable. It updated its policy directions from previous studies to align with new 2030 and 2050 climate ambitions. The policy package extended the list of critical minerals to 30, compared to 14 in 2011. Together with bauxite, titanium and strontium, lithium was added to the list for the first time in 2020, reflecting the region's ambition to nurture a battery and EV manufacturing industry. Some EU member states have a strong metal refining and manufacturing base. Finland refines around 10% of global refined cobalt output. There are major manufacturers of solar PV components, wind turbines and EVs in the region. However, the region is almost entirely reliant on external mining supplies for many energy transition minerals such as lithium, cobalt and REEs.

The European Union plans to seek opportunities for sourcing critical minerals domestically, for example by tapping opportunities for enhanced metal extraction in post-mining regions. The EU Action Plan estimates that this could lead to 80% of Europe's lithium demand being supplied from European sources by 2025 (European

Commission, 2020a). Other measures include encouraging circular uses of resources, including establishing advanced recycling capacity, strengthening efforts for sustainable product sourcing, and promoting technology innovation for material substitution. Europe holds a leading position in recycling critical minerals, with over 50% of its base metals coming from recycled sources (Eurometaux, 2019). To implement the plan, the European Union established the European Raw Materials Alliance, which involves industrial actors along the value chain, member states and regions, trade unions, civil society, research organisations, investors and non-governmental organisations. The alliance aims to diversify supply chains, attract investment into the raw material value chain, foster technology innovation and create an enabling framework for the circular economy.

The United States: Revitalising domestic production and building resilient supply chains

From the 1960s until the late 1980s, the Mountain Pass mine in California was the largest source of rare earth oxides in the world. In 1992 China surpassed the United States as the world's largest producer. Since then, China has dominated the global supply of REEs. After the Chinese export embargo in 2010, the US Department of Energy issued its first Critical Materials Strategy that year. The strategy identified 14 critical minerals, which were extended to 35 in later years. Since then, critical minerals have become a prominent feature in US national security and defence strategies, highlighting the interdependence of economic security with national security.

The 2019 Federal Strategy to Ensure Secure and Reliable Supply of Critical Minerals highlighted that the country is reliant on imports for 31 of the 35 critical minerals, and has no domestic production for 14 of them. The strategy included 24 policy goals under the six major "calls to action" categories, alongside over 60 recommendations aiming to revitalise production and processing operations in the country and alleviate vulnerability against supply disruption. In addition to rebuilding domestic production, the strategy acknowledged the important role of strategic partnerships with other regions such as Canada, the European Union, Australia and Japan.

The Energy Resource Governance Initiative (ERGI), launched by the Bureau of Energy Resources of the US Department of State in June 2019, expanded the scope further to engage other major producers across the globe. Its aim is to promote sound mining sector governance and resilient global supply chains for critical minerals. This initiative brings countries together to engage in advancing governance principles, sharing best practices and encouraging a level playing field for investment. The founding partners – Australia, Botswana, Canada, Peru and the United States – released the ERGI Toolkit to share and reinforce best practices.

Japan: Securing critical mineral deposits overseas and investing in demand-side innovation

Due to its natural circumstances and highly industrialised economy, Japan realised early on that it had to meet its demand for natural resources through active foreign engagement and emergency preparedness. This has been the case both for oil and natural gas and also for critical minerals. In accordance with Ministry of Economy, Trade and Industry policy, it defined over 30 minerals as "rare metals" to ensure security of supply. Although Japan has no domestic resources, it does have a significant REE processing and refining industry, including 15% of global permanent magnet production (CSIS, 2021). Japan's official target is to raise the self-sufficiency rate of mineral resources (base metals) to more than 80% by 2030. For this, the country has been taking action on both demand and supply sides. For example, in the aftermath of the Chinese export ban in 2010, Japan introduced a comprehensive policy package ("ABCD+R" initiative) that encompasses both supply and demand to reduce the risk of REE supply disruption.

On the supply side, Japan has been operating a strategic stockpiling programme since 1983, through Japan Oil, Gas and Metals National Corporation (JOGMEC). The government also provides financial support (loans, guarantees and equity) to Japanese companies working to develop overseas critical mineral resources, through JOGMEC. JOGMEC also directly conducts exploration activities in co-operation with foreign companies. These activities tend to be linked to direct supply guarantees for Japanese manufacturers. Japan is also eyeing the potential of mineral resources on the seabed and conducted the first probe exploration in 2017.

The government also supports R&D for recycling, material efficiency and substitution technologies to reduce the primary supply requirements. These have been among the most active areas of Japan's co-operation with the United States and the European Union.

Canada: Aiming to be a supplier of sustainable and responsible minerals for global markets

Canada holds some of the world's most substantial reserves of many minerals, including some 15 million tonnes of rare earth oxides (NRCAN, 2020). The Canadian Minerals and Metals Plan released in 2019 sets a policy vision for establishing Canada as the leading mining nation of sustainable and responsible minerals. In response to growing momentum for clean energy transitions, it aims to bolster Canada's standing as an exploration and mining powerhouse, increase foreign direct investment, promote the competitive mining service industry, and therefore boost the local economy. An additional task identified in the plan is to assess Canada's recycling capacity to determine how it can support sustainability and competitiveness.

In January 2020 Canada and the United States signed a Joint Action Plan on Critical Minerals Collaboration to advance mutual co-operation. Additionally, Canada joined the US-led ERGI to advance its goals of securing sustainable supply chains for critical minerals. The country also has strong bilateral relations on critical minerals with both the European Union and Japan through regular policy dialogue. It is also working with the Global Battery Alliance to develop a circular and sustainable EV battery value chain.

The country is putting a strong focus on sustainable development of minerals. It implemented a range of initiatives aiming to accelerate R&D for green mining technologies and promote sustainable development practices under the umbrella of the Green Mining Innovation initiative by the Department of Natural Reources. In 2016 CanmetMINING, a research branch of the department, initiated an internal programme called Mining Value from Waste to examine opportunities to reprocess mine waste to recover minerals and repurpose other inert materials. The Mining Association of Canada *Toward Sustainable Mining Initiative* is a widely recognised sustainability programme that supports mining companies' efforts to manage environmental and social risks. It was among the first to set a sustainability standard requiring site-level assessments.

Australia: Strengthening the critical minerals sector to support its economy through foreign investment, infrastructure and innovation

Australia is a major producer of many critical minerals: it is the world's largest producer of lithium and zirconium concentrate, and the fourth largest producer of REEs. The country is well placed to support global clean energy transitions as a reliable and responsible supplier of many minerals that are vital to clean energy technologies. Australia's Critical Minerals Strategy 2019 outlines the government's ambition to expand this potential by promoting investment into its minerals sector. The focus includes downstream processing and refining, boosting innovation to lower production costs, and connecting mineral development projects with infrastructure development. At the beginning of 2020 the government established the Critical Minerals Facilitation Office within the Department of Industry, Science, Energy and Resources. The office's main goals include: (i) enabling and attracting investment; (ii) partnering internationally on global supply chains; (iii) helping finance prospective domestic critical minerals projects; and (iv) facilitating critical minerals research.

In March 2021 Australia launched the Resources Technology and Critical Minerals Processing road map and allocated funds under the government's AUD 1.5 billion Modern Manufacturing Strategy. The intention is to help manufacturers increase their competitiveness and build scale in the global market in the areas of resources technology and critical mineral processing. The road map aims to enhance the country's critical mineral processing capabilities, develop processing and refining industries, and maximise the value of country's resources.

China: A major force in the global supply chain for critical minerals through decades of industrial policies

China's recognition of the strategic value of minerals dates back to the seventh National Five-Year Plan for Rare Earth Industry (1986–

1990), which highlighted the need for research and production of advanced rare earth applications and new materials (CSIS, 2021). During the 1990-2010 period the focus was to secure resources to serve the country's burgeoning appetite for infrastructure build-out. Where domestic resources were lacking, China pursued a "going out" strategy and invested in overseas mining projects. A combination of state-directed investment and financing support based on long-term strategic plays saw Chinese firms take major positions in supplies of minerals from other countries, often in higher-risk jurisdictions. It is estimated that China today owns or has influence over half of the DRC's cobalt production through large stakes in its mining industry (FP, 2019).

At the same time, the country has been active in nurturing downstream capacity through supportive regulation, state-backed financing and subsidies. In some cases (e.g. REE), export and production quotas were used to favour companies that create additional value through processing, although export restrictions were lifted following the decision by World Trade Organization. The country currently accounts for some 40-70% of global copper, lithium and cobalt refining and almost 90% of REE processing.

While these approaches enabled China's rise in the critical mineral supply chain, in some cases they were accompanied by side effects such as financial losses, overcapacity and weakened environmental performance. As such, approaches in the 2010s shifted gear from large investment in bulk materials to focused investment in strategic "new materials", reflecting the changing pattern of consumption and the evolving ambition in the clean energy space (STRADE, 2018).

In 2015 the government announced the Made in China 2025 initiative, which identified the "new materials" industry as one of ten important areas for government support. The new materials included permanent magnets (made from REE) that are central to many clean energy applications such as EV motors and wind turbines. While recent investment in overseas mineral assets does not appear to be as large as before, strategic investment continues. Examples include Tianqi Lithium's equity acquisitions in Chilean company SQM (23.8%) and Australia's Greenbushes lithium mine (51%).

Due to the strong foothold of its downstream industries, China's consumption of mined material has been increasing, often at a faster pace than domestic production growth (e.g. copper, REE). This triggered the country to introduce policies to mitigate risks from potential supply disruption. China's National Mineral Resource Plan for 2016–2020 called for a warning mechanism to safeguard its REE supply chains against potential disruption, and a more systematic demand and supply analysis of mineral products. More recently China passed a law to allow export controls on items considered to be critical to the state's interest and security. The country also announced draft legislation to strengthen the approval process for REE development projects (CSIS, 2021).