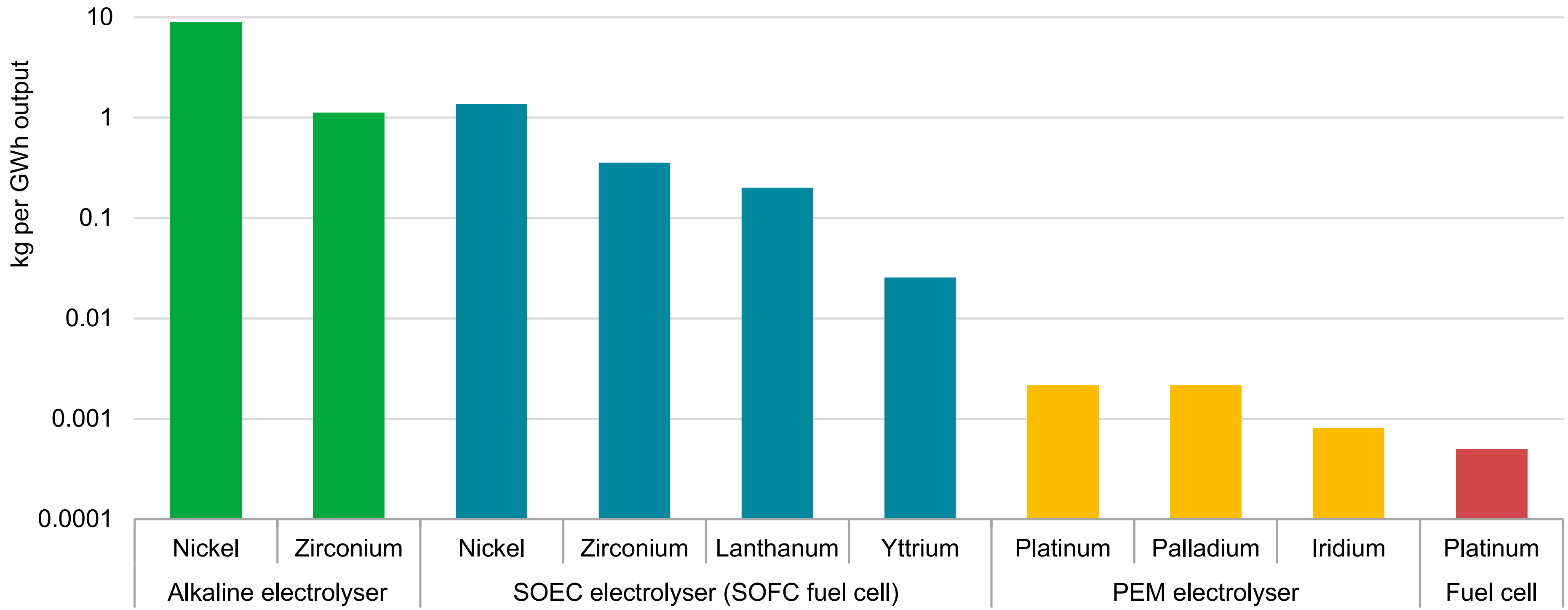
Hydrogen electrolysers and fuel cells could drive up demand for nickel, platinum and other minerals, but the market effects will depend on the shares of the different electrolyser types

Estimated levelised demand for selected minerals in electrolysers and fuel cells today



Notes: PEM = proton exchange membrane; SOEC = solid oxide electrolysis cells; SOFC = solid oxide fuel cell. Normalisation by output accounts for varying efficiencies of different electrolysis technologies. Full load hours of electrolysers assumed to be 5 000 hours per year.

Sources: Bareiß et al.(2019); Fuel Cells and Hydrogen Joint Undertaking (2018); James et al. (2018); Kiemel et al. (2021); Koj et al. (2017); Lundberg (2019); NEDO (2008); Smolinka et al. (2018); US Department of Energy (2014; 2015).

Alkaline and PEM, the two dominant types of electrolysers, have very different mineral requirements; solid oxide electrolysers present fewer mineral concerns, but are less developed

Hydrogen is a versatile energy carrier that can be produced from fossil fuels, biomass or electricity via electrolysis of water. Electrolysers are a promising means of expanding the uses of renewable and nuclear electricity to include applications that benefit from storing or using a gaseous source. However, there is uncertainty about which of the three main types of electrolyser might dominate the market.

Alkaline electrolysers

Alkaline electrolysis is a mature and commercial technology that has been used since the 1920s in both small and large plants. However, very large plants have not been built in recent decades because they were uncompetitive against hydrogen production from natural gas. The largest plants being built today are around 10 MW, with a single-stack demonstration project of this size entering operation in Japan in 2020. Compared with other electrolysis technologies, manufacturing capacity for alkaline electrolysers is much larger, with an estimated 2 GW per year available today. European manufacturers have published plans to expand existing plants to achieve a capacity of over 6 GW per year. In China, where the manufacturing base is being developed rapidly, the cheaper and more familiar alkaline technology is also dominant.

Alkaline electrolysers have low capital costs, partly because of their avoidance of precious metals. However, current designs do require nickel in quantities of more than one tonne per MW, or 1 000 tonnes for a 1 GW electrolyser plant, similar to some of the largest sizes currently proposed. Reductions in nickel demand for alkaline electrolysers are expected, but nickel is not expected to be eliminated from future designs. However, if today's state-of-the-art design that use around 800 kg per MW were representative of future requirements, and even if alkaline electrolysers dominate the market, then nickel demand for electrolysers would remain much lower than that for batteries in the SDS. Nonetheless, in such a case, if nickel prices rise strongly due to challenges in the battery supply chain, electrolyser costs would be affected. In addition to nickel, 1 MW of alkaline electrolyser could today require around 100 kg of zirconium, half a tonne of aluminium and more than 10 tonnes of steel, along with smaller amounts of cobalt and copper catalysts.

Proton exchange membrane (PEM) electrolysers

PEM electrolysers have the advantages of smaller size, more flexible operation and higher-pressure output than alkaline, but are less mature, more costly and currently have shorter lifetimes. However, PEM represents the majority of current hydrogen demonstration projects outside China, partly because there are incentives for electrolyser users to test the options and determine whether the operational benefits of PEM are worth the additional costs compared with alkaline electrolysers.

The largest PEM facility – 20 MW – began operation in Canada in 2021, and others near this scale are in development in Europe. Globally, PEM manufacturing capacity stands at less than 500 MW per year, but two sites in Europe are under development to raise this to more than 1 GW per year by 2023. As more experience is gained and manufacturing scales up, capital costs are expected to decline significantly.

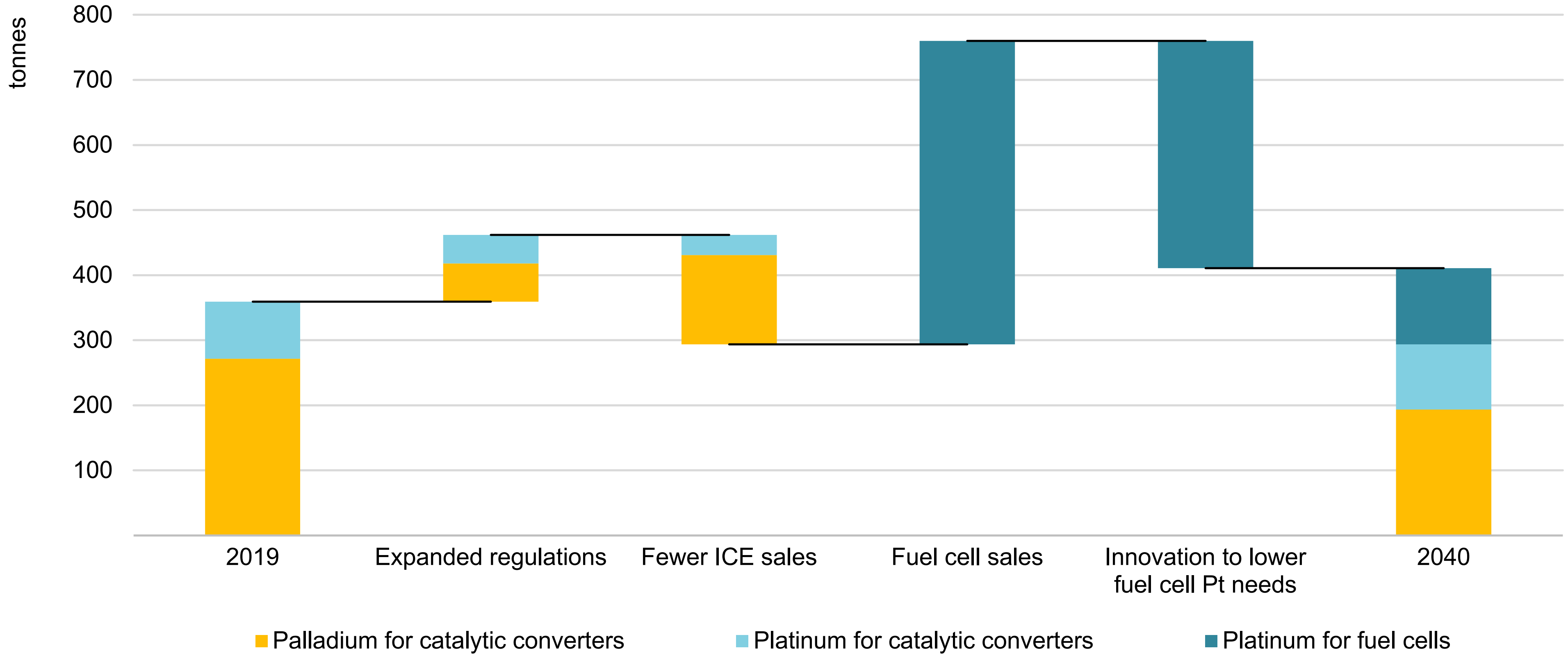
If PEM were to dominate the hydrogen market, it would increase energy-sector demand for platinum and iridium. PEM catalysts currently use around 0.3 kg of platinum and 0.7 kg of iridium per MW. Experts believe reductions to one-tenth of these amounts are possible in the next decade in order to minimise costs (Kiemel et al., 2021). A separate approach in development, using anion exchange membranes, could avoid the use of these metals altogether.

Solid oxide electrolysis cells (SOECs)

SOECs are currently being tested at smaller scales and have higher efficiencies and low material costs. It is not expected that they will come to dominate the market, but they have significant promise, especially because they can operate in reverse as fuel cells and can be integrated into other high-temperature processes or synthetic fuel production. The primary mineral demands of SOECs are nickel (150-200 kg per MW), zirconium (around 40 kg per MW), lanthanum (around 20 kg per MW) and yttrium (less than 5 kg per MW). It is expected that each of these quantities could be halved through better design in the next decade, with technical potential to drop nickel content to below 10 kg per MW. To enable comparison with other electrolysers, these quantities need to be adjusted downwards in line with the higher efficiencies of SOECs.

In the SDS, platinum demand for vehicles in 2040 remains dominated by catalytic converters and not fuel cells

Drivers of demand for platinum and palladium for vehicles in the SDS



Note: Pt = platinum.

Major improvements that reduce the platinum intensity of fuel cells have been made in the past decade, with the amount of platinum in fuel cell cars halving

In clean energy transitions, internal combustion engine vehicles might be largely replaced by EVs, including fuel cell electric vehicles (FCEVs), with other important roles for non-vehicular transport and biofuels. While the automotive sector is set to become a dominant source of global demand for lithium, nickel and cobalt for EV batteries, it already leads demand for platinum and palladium for use in catalytic converters. For these so-called platinum group metals, a key issue is whether new demand from fuel cells will offset declining demand from internal combustion engine vehicles.

Fuel cells

While fuel cells for converting hydrogen to electricity have been in production for many years, the introduction of commercial passenger FCEVs has spurred innovation to reduce the use of platinum to limit costs. In 2014 Toyota's first-generation Mirai car used around 40g of platinum, around three-quarters less platinum per kW of output than the 2008 prototype (James et al., 2018). The second-generation Mirai, released in 2020, reduced this by roughly a further third per kW and increased the maximum power output from 114 kW to 158 kW. Plans are in place in Japan to reach 5g per car in 2040. Similar targets for reduced platinum loading per kW have also been set by US DOE, including targets for trucks, which require three times more power than cars. If these targets are met, demand for FCEVs in the SDS would grow platinum demand to just over 100 tonnes by 2040.

Catalytic converters

Catalytic converters represent around 40% of global platinum demand today, and are also the major source of demand for two other platinum group metals: rhodium and palladium. Despite all early catalytic converters using mostly platinum, gasoline-based systems now have a palladium to platinum ratio of 5:1 or higher, partly because palladium has been cheaper historically. Catalytic converters for diesel engines use a more equal share of platinum and palladium, while all systems use smaller quantities of rhodium for controlling nitrogen oxides.

The higher prevalence of catalytic converters in gasoline vehicles means that palladium demand now outstrips platinum demand in the automotive sector by between 200% and 300%. Tightening regulations and responses to car emissions scandals have pushed up palladium prices to double those of platinum per tonne. While substitution between the metals is possible, it requires a redesign of the catalyst system and therefore needs more certainty about future relative prices than exists today. In the SDS, an increase in the coverage of emissions regulation to include all new cars by 2030, coupled with continued sales of internal combustion engine, especially hybrids, keeps demand for platinum group metals for use in catalytic converters above that for fuel cells by 2040.

Reliable supply of minerals

Introduction

In Chapter 2 we explored how the material-intensive nature of a clean energy system is set to drive a huge rise in demand for critical minerals. This naturally raises questions about whether this growth – in most cases well above the historical pace – can be supplied in a reliable manner, and whether the environmental and social consequences associated with mineral production can be managed properly.

For some minerals, demand and supply were delicately balanced before the pandemic, and there were expectations that supply imbalances might emerge in the coming years. While Covid-induced demand reductions alleviated some of these pressures, concerns about the adequacy and affordability of future supply are ever-present as the world emerges from the crisis and many countries put renewables and batteries at the heart of their economic stimulus packages. The price rallies in the latter part of 2020 and early 2021 may have provided a preview of what could happen when the world accelerates onto a decarbonisation pathway, although these price increases were not always linked to physical market balances.

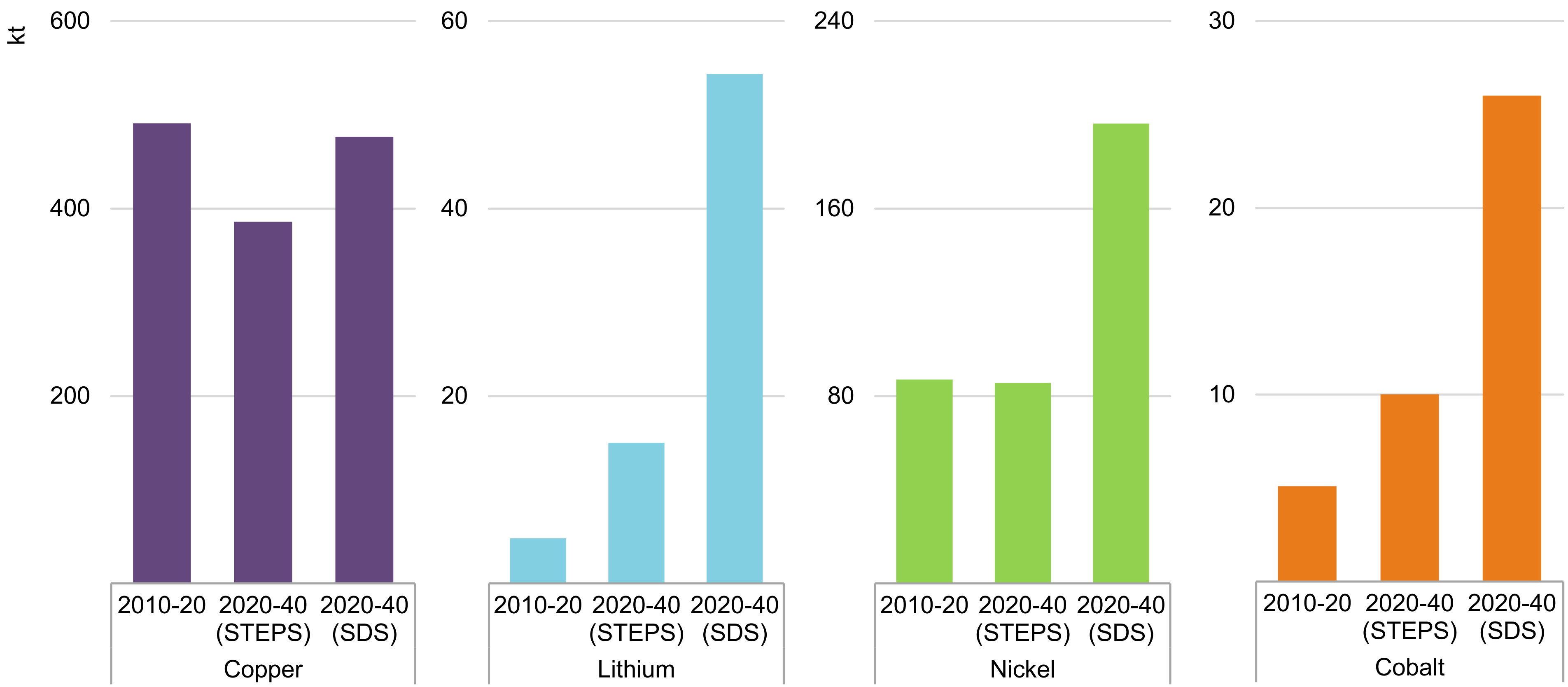
If history is any guide, the market responds to strains on supply by reducing demand, substitution or increasing supply. But this is typically accompanied by price volatility, considerable time lags or some loss of performance or efficiency. In the context of clean energy transitions, inadequate mineral supply could result in more expensive, delayed or less efficient transitions. Given the urgency of reducing emissions, this is a possibility that the world can ill afford.

In this chapter we examine some of the major vulnerabilities that may hinder adequate supply and lead to greater price volatility, focusing on the five focus minerals (copper, lithium, nickel, cobalt and rare earth elements [REEs]) that play a particularly important role in many clean energy technologies. We also consider the specific challenges that each mineral faces. We then discuss policy approaches to ensure reliable supply of minerals, drawing lessons from historical episodes of disruption as well as the IEA's long-standing experience in safeguarding oil market security. Finally, the chapter assesses the potential contributions from secondary supply, via recycling, and discusses what can be done to scale up recycling to reduce primary supply requirements and in turn security risks.

How policy makers and companies handle the challenges around reliable and sustainable supply will determine whether critical minerals are a vital enabler of clean energy transitions or a bottleneck in the process.

In the SDS, the required level of supply growth for most minerals is well above the levels seen in the past decade

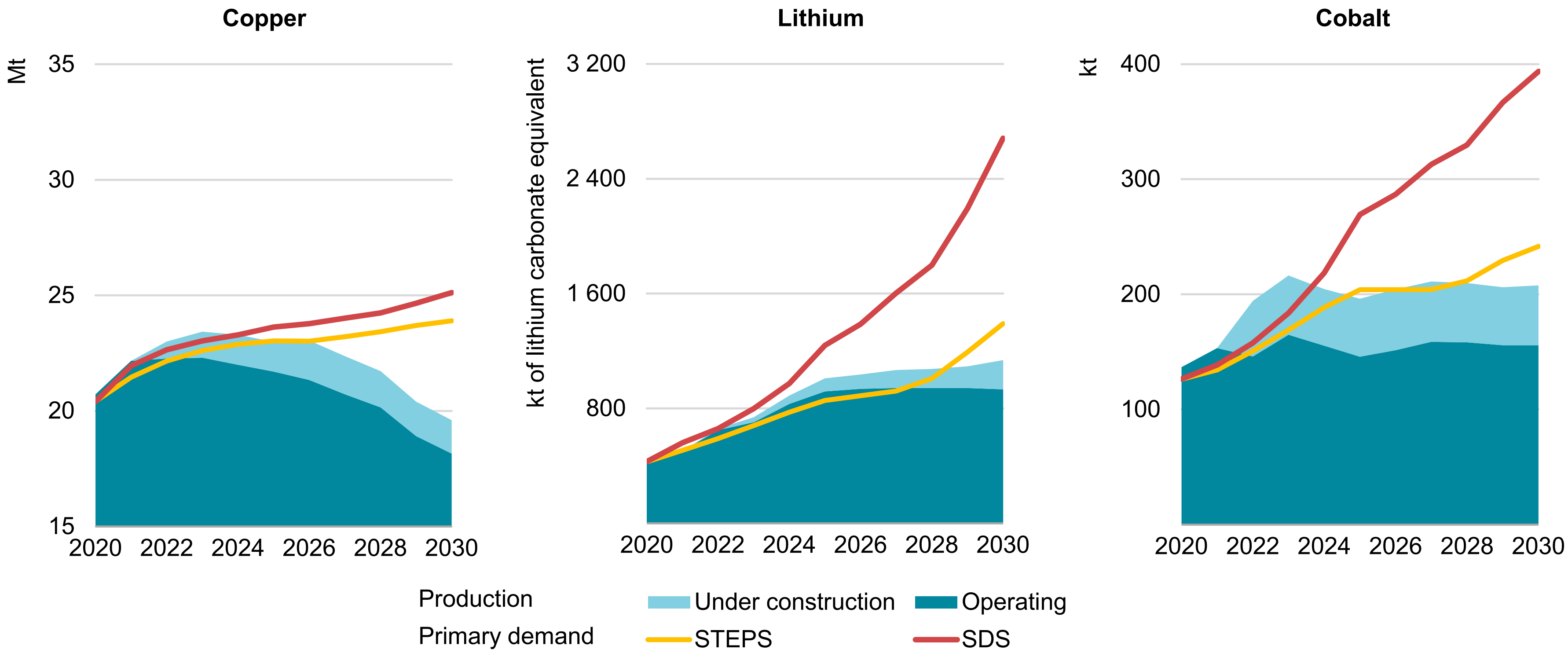
Annual average total demand growth for selected minerals by scenario



Notes: Total demand includes both demand from clean energy technologies and other consuming sectors. kt = thousand tonnes; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

Meeting primary demand in the SDS requires strong growth in investment to bring forward new supply sources over the next decade

Committed mine production and primary demand for selected minerals



Notes: Primary demand is total demand net of recycled volume (also called primary supply requirements). Projected production profiles are sourced from the S&P Global Market Intelligence database with adjustments to unspecified volumes. Operating projects include the expansion of existing mines. Under-construction projects include those for which the development stage is indicated as commissioning, construction planned, construction started or preproduction. Mt = million tonnes.

Source: IEA analysis based on S&P Global (2021).

Current supply and investment plans are not yet ready for accelerated energy transitions

In today's markets, most minerals that are vital to clean energy technologies are relatively well supplied. Prices for certain minerals have risen strongly since the second half of 2020, with some reaching multi-year highs. This was due to expectations of strong future growth, as well as demand recovery in the People's Republic of China ("China"). While it is too early to brace for the next price cycle, if we slightly extend the time horizon, we see ample reasons to be vigilant about the ability of supply to meet demand – especially as many governments redouble efforts to accelerate energy transitions.

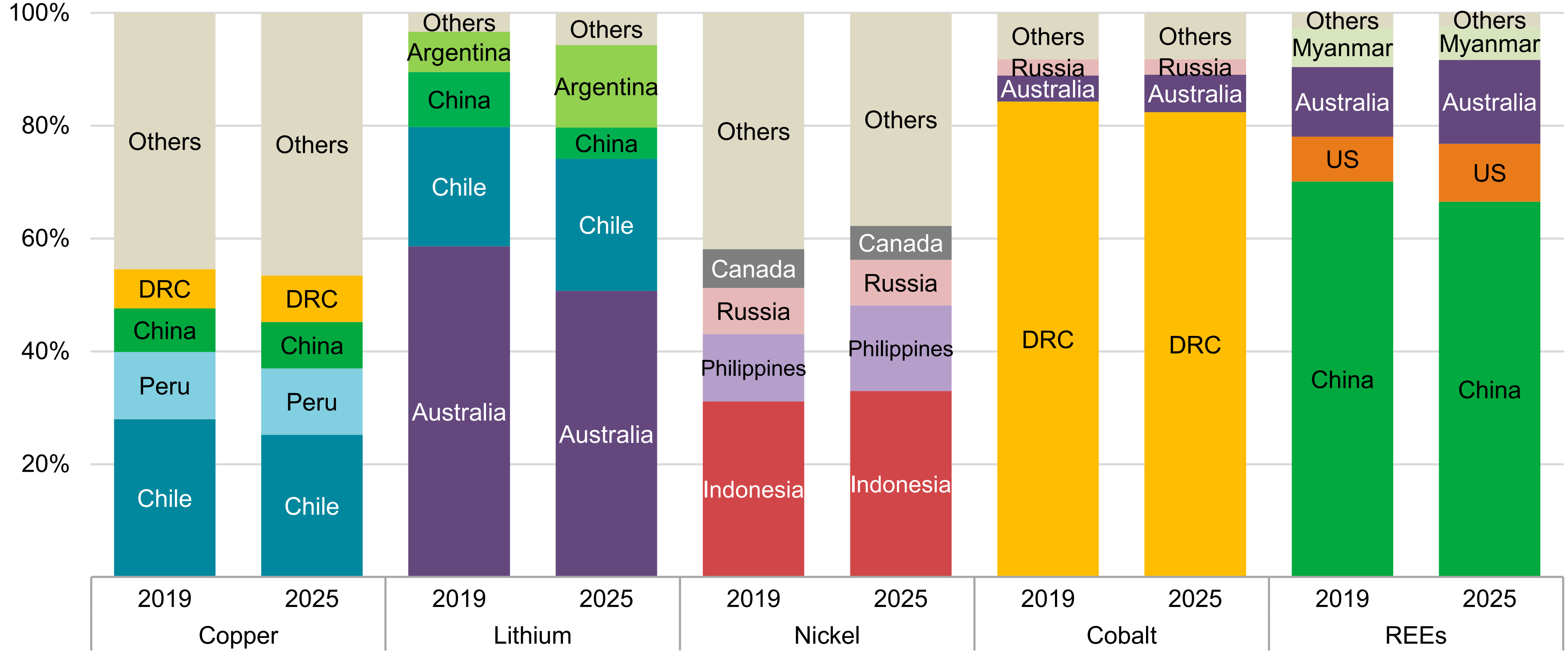
In the SDS, the scale of demand growth is well above the levels seen in recent decades. For example, in the period to 2040 annual average demand growth for nickel and cobalt is two and five times higher respectively than the levels seen in the 2010s. In the case of copper, the SDS sees a continuation of strong demand growth in the 2010s through the coming decades.

The picture for near-term supply is mixed. Some minerals such as lithium raw material and cobalt are expected to be in surplus in the near term, while lithium hydroxide, battery-grade nickel and certain REEs (e.g. neodymium and dysprosium) might face tight supply in the years ahead as demand rises. However, after the medium term, projected demand surpasses the expected supply from existing mines and projects under construction for most minerals, meaning that significant additional investment will be needed to support demand growth.

This is especially the case to meet requirements in the SDS. Current supply and investment plans are geared to a world of gradual, insufficient action on climate change (the STEPS trajectory), but not sufficient to support accelerated energy transitions. While there are a host of projects in the pipeline at varying stages of development, several risk factors may, if unchecked, increase the possibility of market tightness and new price cycles, slowing energy transitions. These include (i) higher geographical concentration of production, (ii) a mismatch between the pace of change in demand and the typical project development timeline, (iii) the effects of declining resource quality, (iv) growing scrutiny of environmental and social performance of production, and (v) higher exposure to climate risk such as water stress, among others (which are explored in more detail in the following pages).

Geographical concentration: Analysis of project pipelines indicates that, in most cases, the geographical concentration of production is unlikely to change in the near term

Major producing countries of selected minerals, 2019 and 2025

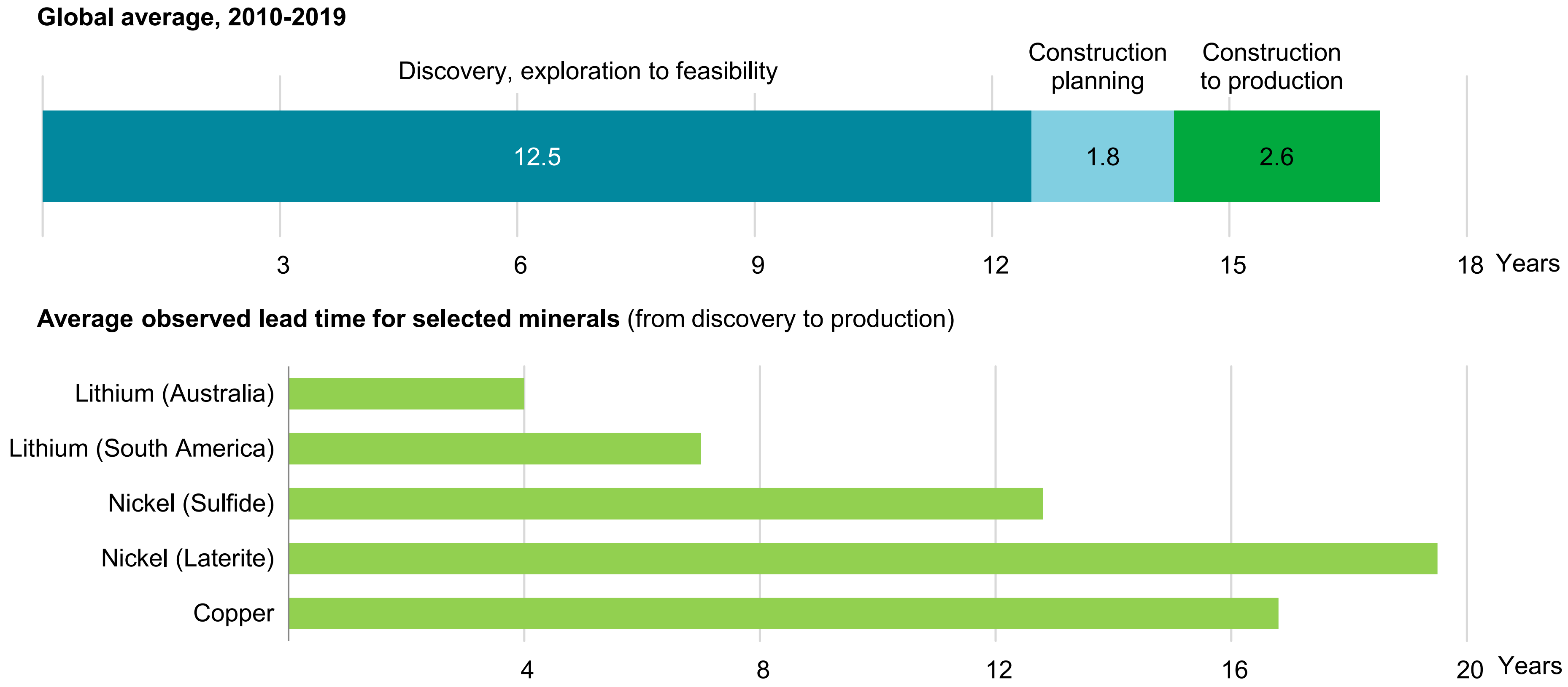


Note: Due to the availability of data on projections for future production, REEs here comprise neodymium, praseodymium, terbium and dysprosium only. DRC = Democratic Republic of the Congo; US = United States; Russia = Russian Federation.

Source: IEA analysis based on the project pipeline in S&P Global (2021) complemented by World Bureau of Metal Statistics (2020) and Adamas Intelligence (2020) (for REEs).

Project development lead times: Market tightness can appear much more quickly than new projects

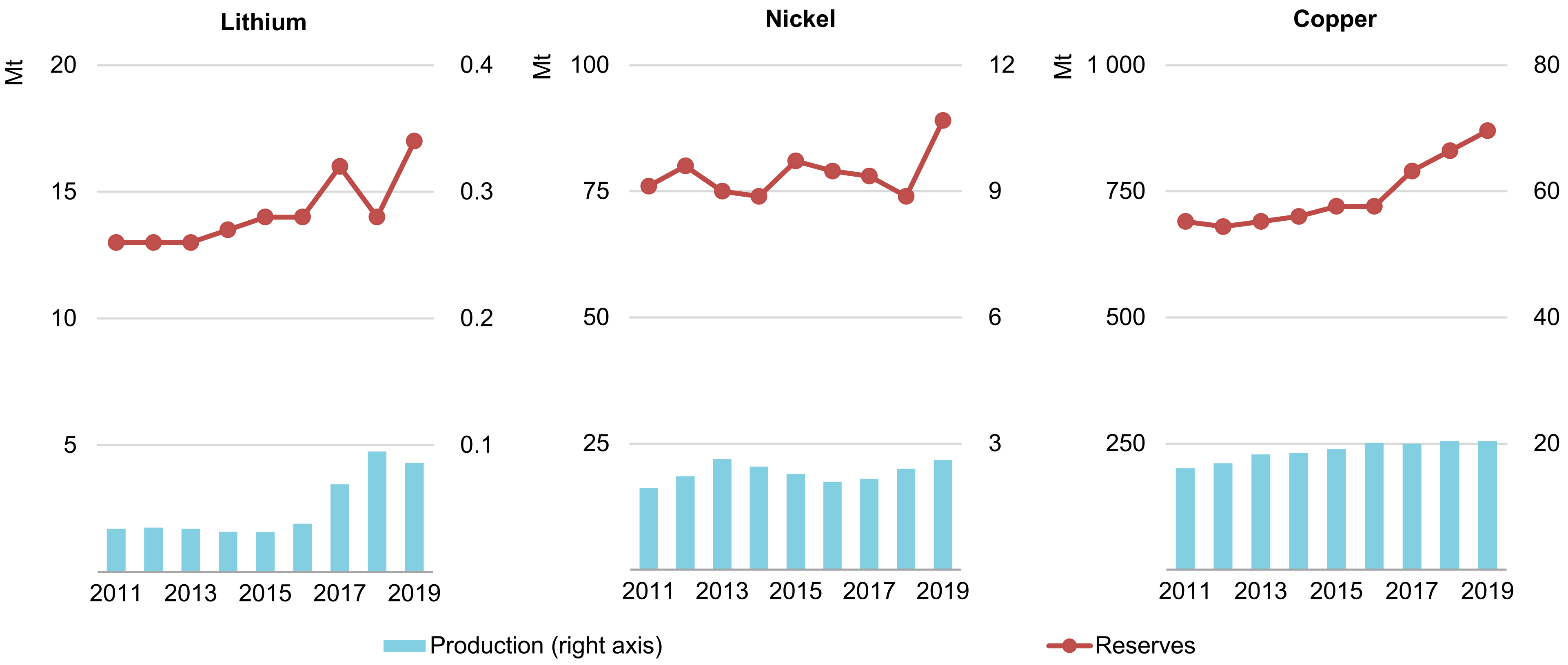
Global average lead times from discovery to production, 2010-2019



Note: Global average values are based on the top 35 mining projects that came online between 2010 and 2019.
Source: IEA analysis based on S&P Global (2020), S&P Global (2019a) and Schodde (2017).

Resources: There is no shortage of resources. Economically viable reserves have been growing despite continued production growth

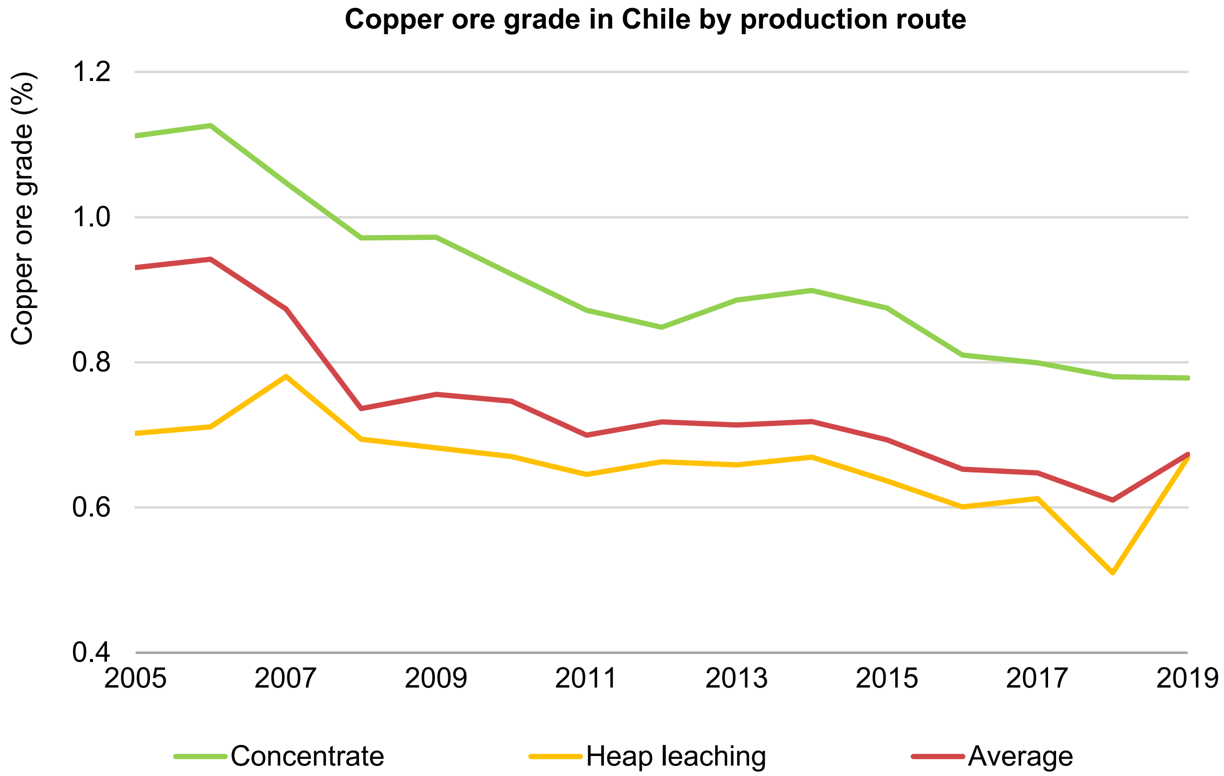
Reserves and production for selected mineral resources

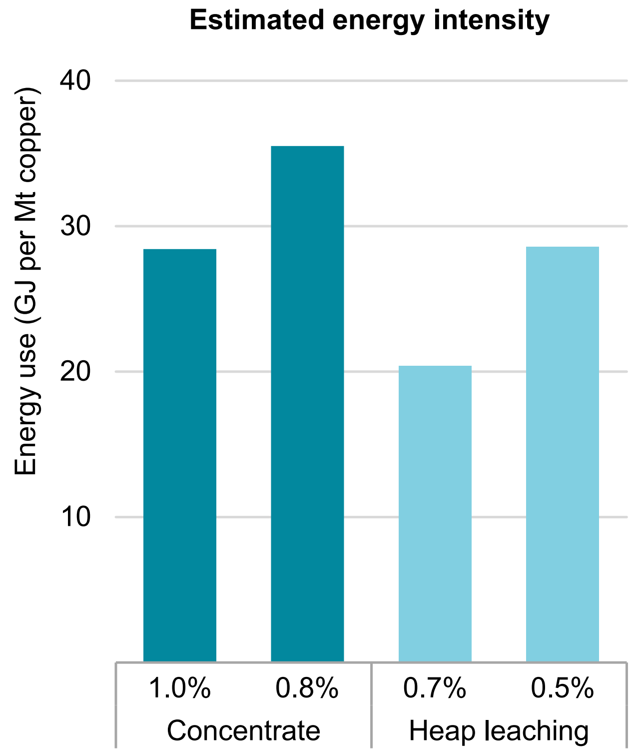


Sources: USGS (2021); USGS (2020).

Resources: However, declining ore quality poses multiple challenges for extraction and processing costs, emissions and waste volumes

Average ore grade in Chile and estimated energy intensity by quality

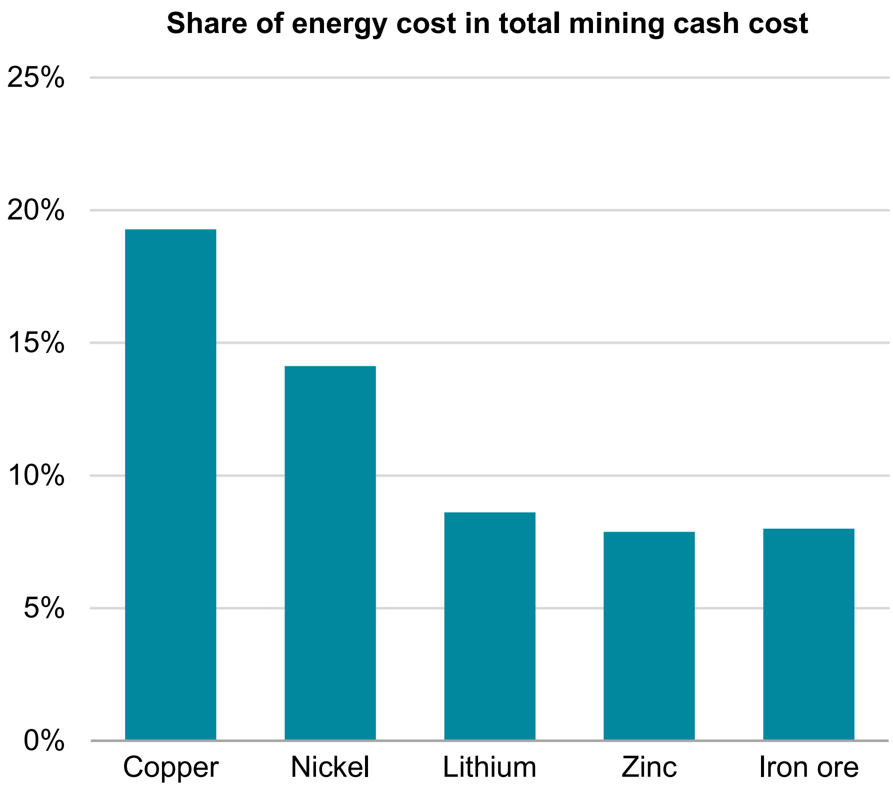


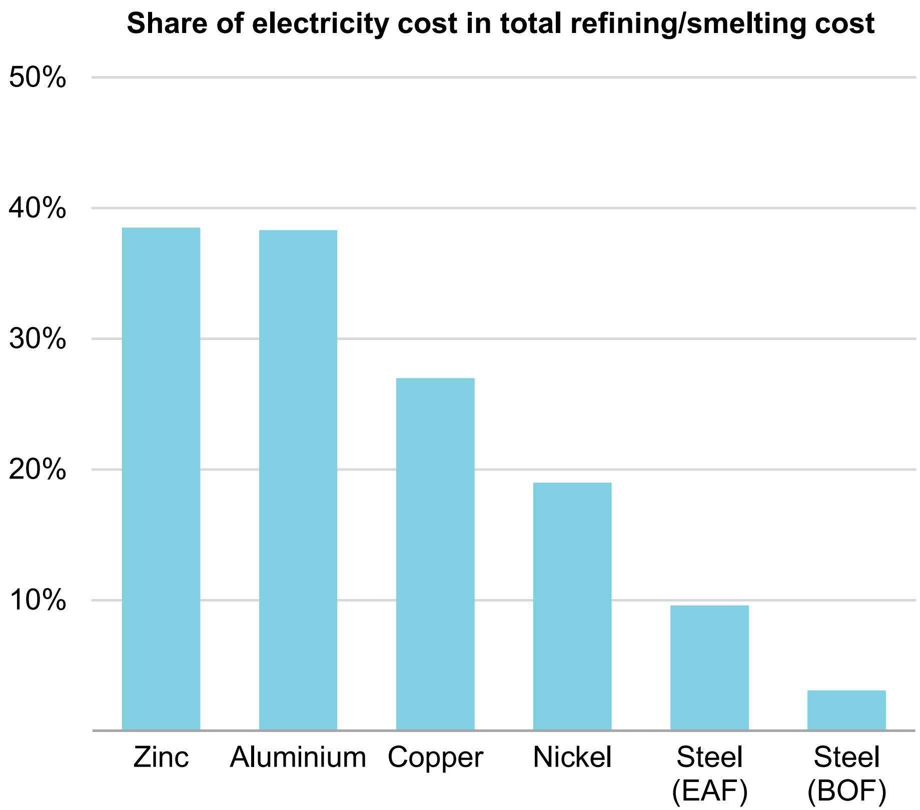


Notes: Energy use for concentrate covers mine, concentrating plant, smelter, refinery and services. For heap leaching, energy use covers mine, leaching, solvent extraction, electro-winning processes and services. GJ = gigajoule.
Source: IEA analysis based on COCHILCO (2019) and Rötzer and Schmidt (2020).

Scrutiny of ESG issues: Growing imperative to improve environmental performance could also put upward pressure on production costs of energy-intensive mining and processing activities

Share of energy cost in total mining cash cost and electricity intensity for selected materials



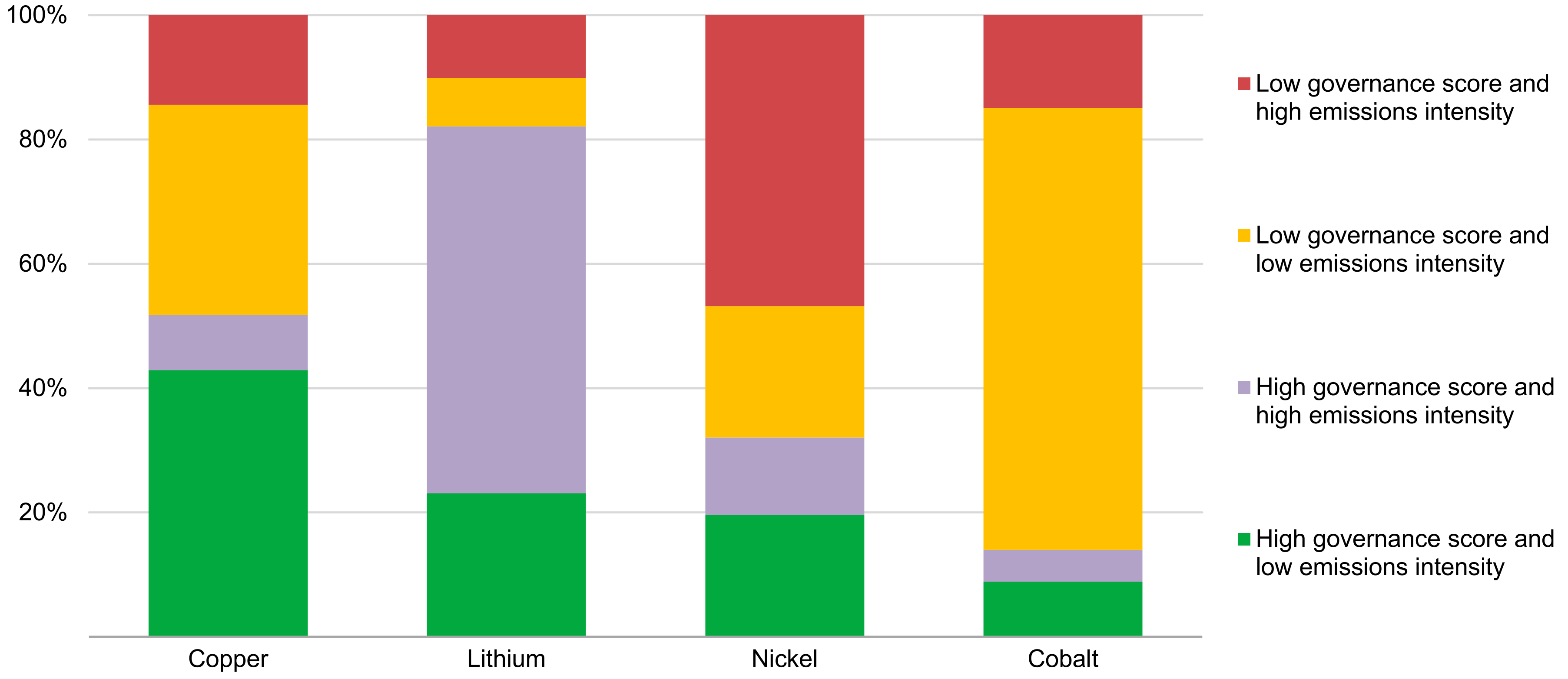


Notes: ESG = environmental, social and governance; EAF = electric arc furnace; BOF = basic oxygen furnace. Energy and electricity costs show global average values, and can vary by region and operational practice.

Source: IEA analysis based on S&P Global (2021) for mining, BHP (2011) for iron ore and Eurometaux (2020) for refining/smelting.

Scrutiny of ESG issues: The majority of current production volumes come from regions with low governance scores or high emissions intensity

Distribution of production of selected minerals by governance and emissions performance, 2019

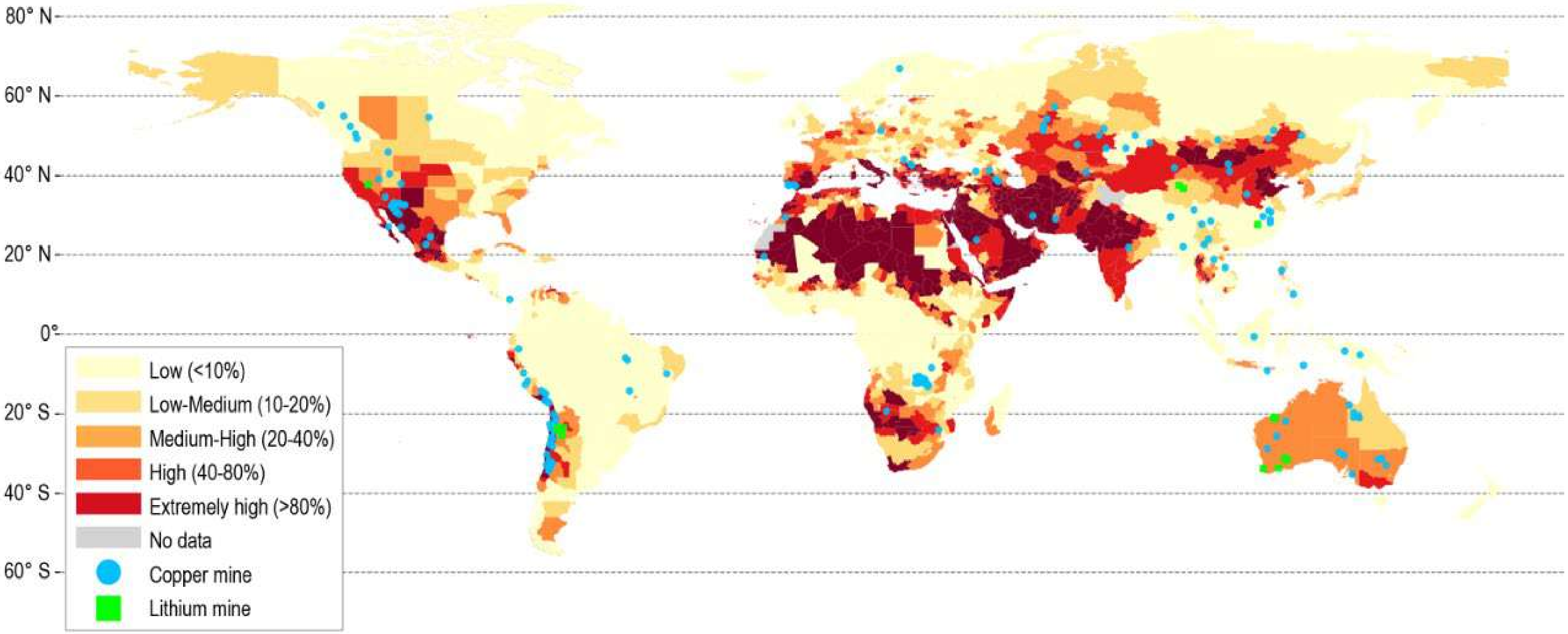


Notes: Analysis using the World Bank Worldwide Governance Indicator (as a proxy for governance) and electricity CO_2 intensity (as a proxy for emissions performance). Composite governance rank scores below 50 were classified as low governance; electricity CO_2 emissions intensity above 463 g CO_2/kWh (global average value in 2019) was classified as high emissions intensity.

Source: World Bank (2020), IEA (2020).

Climate risk: Mining assets are exposed to growing climate risks and water stress

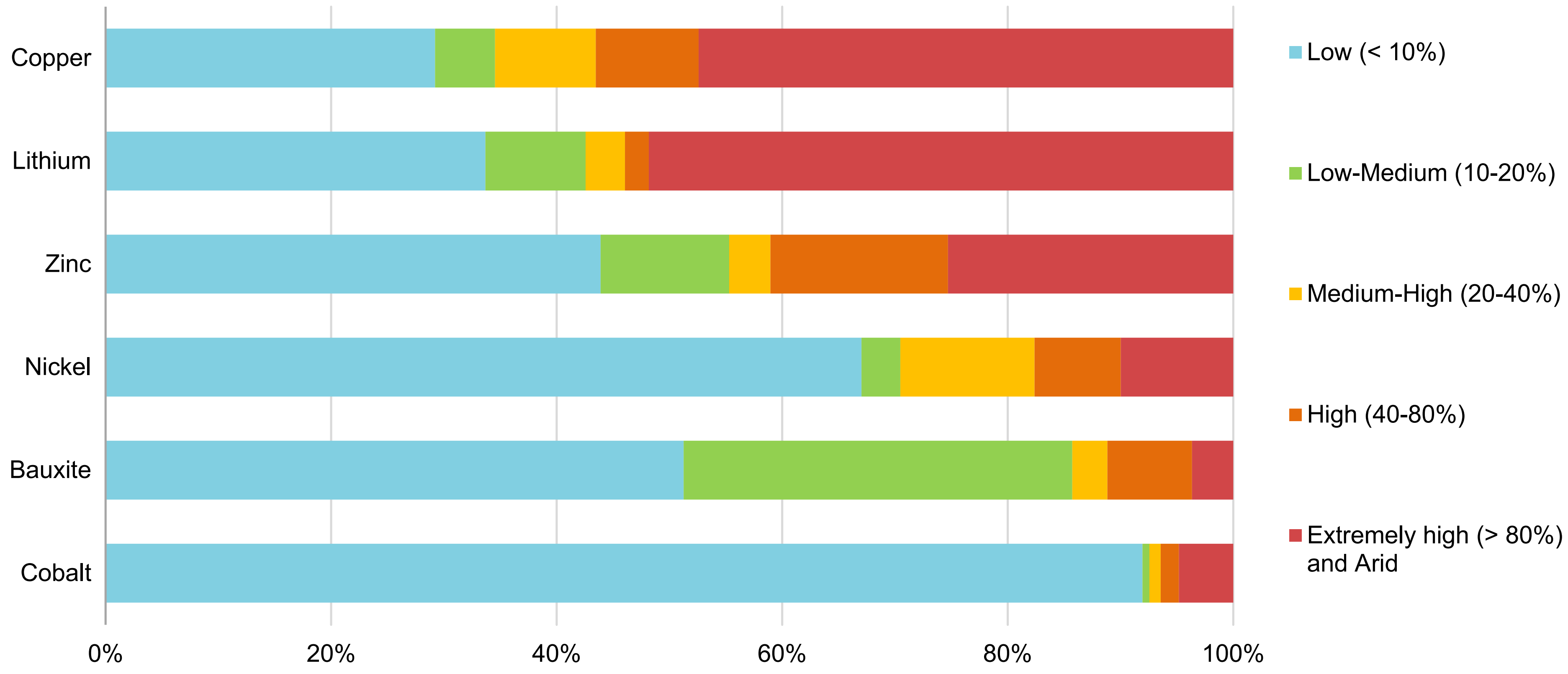
Location of copper and lithium mines and water stress levels, 2020



Note: The exact water stress levels vary by location. While we assessed the share of mines located in water stress areas according to granular regional representations (shown on the following page), we aggregated them at the sub-national level on the map for the sake of simplification. Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.
Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Climate risk: Around half of global lithium and copper production is concentrated in areas of high water stress

Share of production volume by water stress level for selected minerals, 2020



Note: Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.
Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Several vulnerabilities may hinder adequate mineral supply and lead to greater price volatility

As countries step up their climate ambitions, securing reliable supplies of critical minerals may have major impacts on the affordability of clean energy technologies and the prospects for countries to nurture a clean technology manufacturing industry. Several risk factors are in play.

Geographical concentration: Today's production and processing operations for many energy transition minerals are highly concentrated in a small number of countries, making the system vulnerable to political instability, geopolitical risks and possible export restrictions (see Chapter 1).

Our analysis of today's project pipeline indicates that this picture is unlikely to change in the near term. With the exception of copper, where planned production growth in the United States, DRC and Indonesia helps diversify the pool of supply, most of the output growth for lithium, nickel and cobalt are expected to come from today's major producers, implying a higher degree of concentration in the years ahead. Under these circumstances, physical disruptions (e.g. earthquakes, tsunamis and flooding) or regulatory and geopolitical events in major producing countries can have large impacts on the availability of minerals, and in turn on prices. Recent events, such as Indonesia's ban on nickel ore export and China's export ban on REEs, serve to highlight these concerns. More recently, the military coup in Myanmar has raised concerns over supply disruption of heavy REEs, fuelling a surge in prices (Reuters, 2021a). Natural disasters have also become one of the most frequent causes of mineral supply disruption, third only to accidents and labour strikes (Hatayama and Tahara, 2018).

Project development lead times: The recent pick-up in investment in many minerals offers some support for near-term supply, but additional investment will be required to satisfy rising demand, especially in the SDS. Despite growing momentum behind energy transitions, uncertainty over the trajectory of future demand may hold back company investment decisions needed to achieve orderly energy transitions. Long project lead times exacerbate the risk of a mismatch in timing between demand and the industry's ability to bring on new projects.

Analysis of major mines that came online between 2010 and 2019 shows that it took 16.5 years on average to develop projects from discovery to first production, although the exact duration varies by mineral, location and mine type (S&P Global, 2020). On average, It took more than 12 years to complete exploration and feasibility studies, and 4-5 years for the construction phase. These long lead times raise questions about the ability of supply to ramp up output if demand were to pick up rapidly (although some supply sources such as expansion from existing mines and artisanal small-scale mining have shorter lead times). If companies wait for deficits to emerge before commiting to new projects, this could lead to a prolonged period of market tightness and price volatility.

A further complication is that mining is only one part of the value chain. Whether investment occurs in a co-ordinated manner throughout the value chain is another significant issue, as price signals may not be passed efficiently along the value chain. The recent rise in lithium carbonate prices (and a possible tightening of lithium hydroxide supply) amid ample supply of lithium raw material is one indication of possible strains arising from different parts of the value chain. REE processing is another example of complication, where growth in mined output does not necessarily guarantee greater supply of certain rare earth oxides in high demand (see section on REEs).

Resource quality: Like other commodities, minerals are not free from concerns over the availability of resources. Resources are known metallic concentrations with reasonable prospects for eventual economic extraction, whereas reserves are the economically mineable part of resources under today's circumstances. There are generally no signs of shortages in these areas: despite continued production growth over the past decades, economically viable reserves have been increasing for many energy transition minerals. For example, lithium reserves increased by 30% between 2011 and 2019, while production expanded two-and-a-half times. The volume of copper reserves also rose by 30% in the last 10 years. This is because reserves have been replenished by exploration activities triggered by growing demand. In Australia lithium reserves increased by 70% in 2017 as price spikes in 2016-17 motivated the country to tap its under-explored resources.

Concerns about resources relate to quality rather than quantity. In recent years, ore quality has continued to decline across commodities as high-quality deposits (and higher-grade parts of the deposits) are exploited earlier. Technological improvement that allows the exploitation of lower-grade deposits has also played a role. For example, the average copper ore grade in Chile has decreased by 30% over the last 15 years. This brings about multiple challenges. Extracting metal content from lower-grade ores requires more energy, exerting upward pressure on extraction and processing costs and carbon dioxide (CO_2) emissions. Lower-grade ores also generate larger amounts of rock waste and tailings that require careful treatment. This means that, over time, strengthened efforts would be needed to offset underlying upward pressures on production costs.

Growing scrutiny of ESG issues: While minerals play a vital role in supporting clean energy transitions, energy is also crucial in the production of minerals. Due in part to declining resource quality, the production and processing of energy transition minerals are energy-intensive, involving higher emissions to produce the same quantity of product. In recent years, mining and processing companies have faced growing pressure to address these and other issues related to their social and environmental performance (see Chapter 4). A growing number of consumers and investors are requesting companies to disclose targets and action plans on these issues. Tightening scrutiny of ESG issues could have an impact on costs and supply prospects, especially in areas reliant on artisanal mines or where requirements are uneven across different jurisdictions or types of company. For example, around 10-15% of copper, lithium and cobalt production and almost half of nickel production in 2019 came from regions with low governance scores and high emissions intensity.

Exposure to climate risks: In recent years, a combination of more frequent drought events in major producing regions and higher water intensity in ore processing has brought the critical importance of sustainable water sourcing to attention. For example, in 2019 the worst drought in more than 60 years severely affected some operations in Chile, with similar events having occurred in Australia, Zambia and others. The El Teniente mine, the largest underground copper mine in Chile, implemented water rationing to deal with severe droughts (CRU, 2020a).

Among minerals, copper and lithium are particularly vulnerable to water stress given their high water requirements. Over 50% of today's lithium production is concentrated in areas with high water stress levels. Some 80% of copper output in Chile is produced in mines located in high water stress and arid areas. This has triggered companies to invest in desalination capacity to mitigate the risk. Moreover, the share of mines located in high water stress areas is set to increase over time. As climate change causes more frequent droughts and alters water flows, the availability of high-quality water resources will become a crucial factor affecting stable minerals supplies.

In addition to water shortage, several major producing regions such as Australia, China, and Africa are also subject to other forms of climate risk, including extreme heat or flooding, which pose challenges to ensuring reliable and sustainable supplies. For example, flooding can lead to spills of hazardous waste from mine sites or waste storage, and tailings dam failure, with extensive environmental damage (see Chapter 4; Rüttinger et al., 2020). This requires companies to assess physical risks from climate change in their operations and integrate climate resilience planning in their sustainability strategies. For example, BHP periodically reviews the potential vulnerabilities of their operating assets and investment portfolio to climate risks, and devises strategies to address them.

Supply prospects for the focus minerals

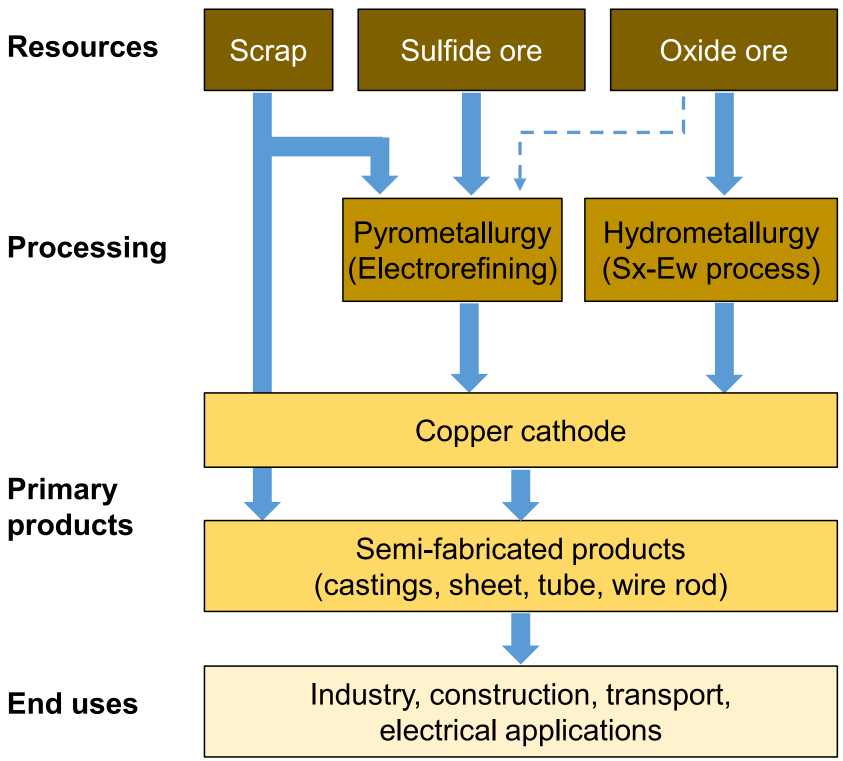
Each mineral faces a different set of challenges in ensuring adequate supply

Mineral	Key challenges
Copper	• Challenging to substitute due to its superior performance in electrical applications • Mines currently in operation are nearing their peak due to declining ore quality and reserves exhaustion • Declining ore quality exerts upward pressure on production costs, emissions and waste volumes • Mines in South America and Australia are exposed to high levels of climate and water stress
Lithium	• Possible bottleneck in lithium chemical production as many smaller producers are financially constrained after years of depressed prices • Lithium chemical production is highly concentrated in a small number of regions, with China accounting for 60% of global production (over 80% for lithium hydroxide) • Mines in South America and Australia are exposed to high levels of climate and water stress
Nickel	• Possible tightening of battery-grade Class 1 supply, with high reliance on the success of HPAL projects in Indonesia; HPAL projects have track records of delays and cost overruns • Alternative Class 1 supply options (e.g. conversion of NPI to nickel matte) are either cost-prohibitive or emissions-intensive • Growing environmental concerns around higher CO_2 emissions and tailings disposal
Cobalt	• High reliance on the DRC for production and China for refining (both around 70%) set to persist, as only a few projects are under development outside these countries • Significance on artisanal small-scale mining makes the supply vulnerable to social pressures • New supply is subject to developments in nickel and copper markets as some 90% of cobalt is produced as a by-product of these minerals
Rare earth elements	• Dominance of China across the value chain from mining to processing and magnet production • Negative environmental credentials of processing operations • Differences in demand outlooks for individual elements bring risk of price spikes for those in high demand (e.g. neodymium) and slumps for those in low demand (e.g. cerium)

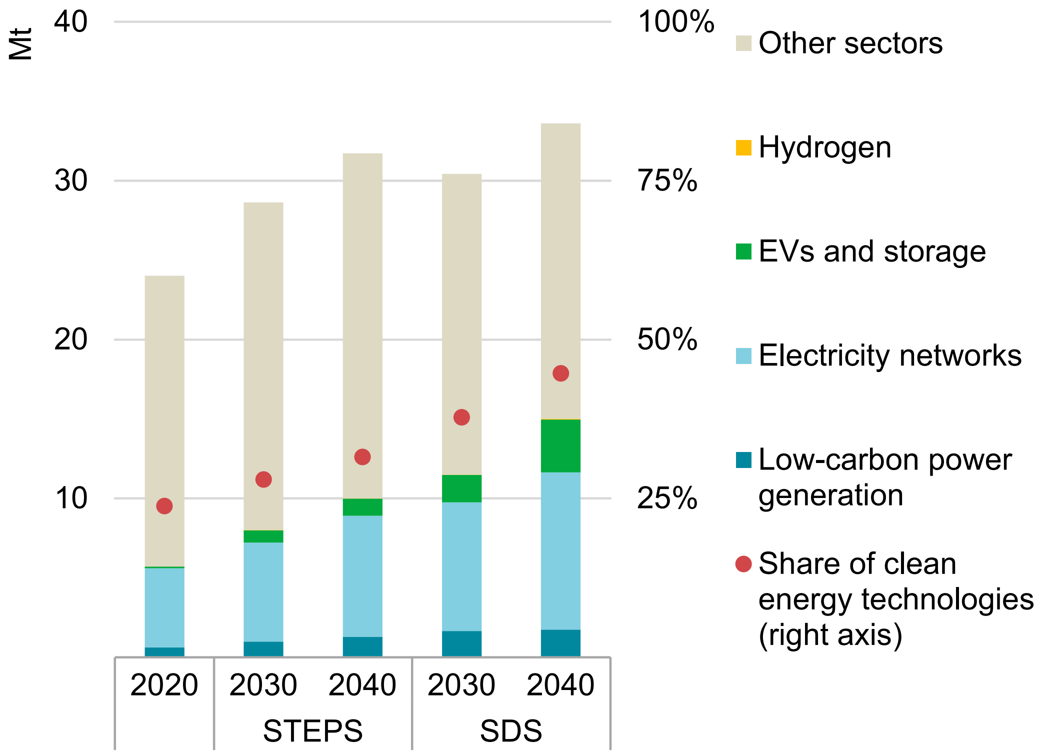
Notes: HPAL = high-pressure acid leaching; NPI = nickel pig iron.

Copper: From resource to consumer

Copper supply chain



Total copper demand by sector and scenario



Notes: EVs = electric vehicles. Sx-Ew = solvent extraction and electrowinning. High-grade oxide ore is processed in pyrometallurgy. Demand does not include the volume reused in a semi-fabricated form.

Copper: Copper is the most widely used mineral in clean energy technologies

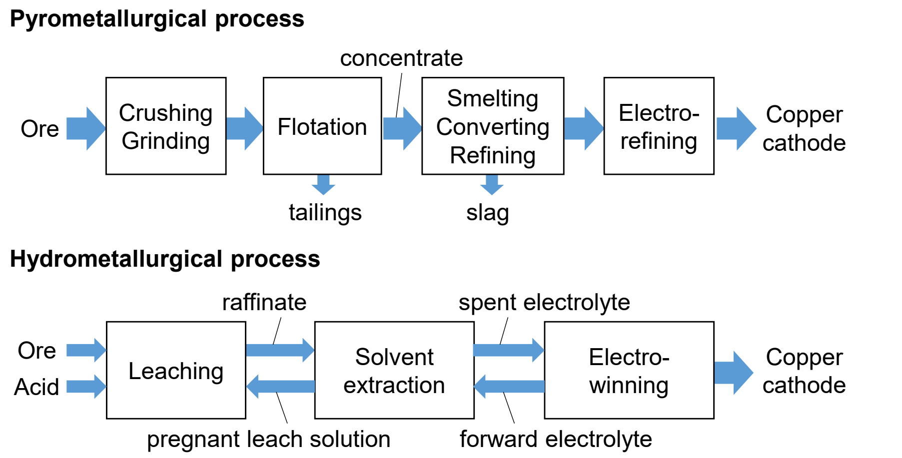
Thanks to its unmatched thermal and electrical conductivity, copper is widely used in a broad range of electronic and industrial applications. Its attributes make it challenging to substitute.

The western part of South America, notably Chile and Peru, is the largest producer of mined copper, responsible for 40% of global output. China, the DRC, the United States and Australia are the other major producing countries.

There are two main types of copper ore; copper sulfide (about 80% of production) and copper oxide (about 20%). Sulfide ore is processed via a pyrometallurgical process (known as smelting); the ore is crushed and ground, then transformed into concentrates, which are then exported to China and other countries to produce refined copper through electrorefining. Oxide ore is processed through a hydrometallurgical process known as Sx-Ew (solvent extraction and electrowinning), which extracts copper from the ore to the solvent and then separates copper cathode from the solvent by electrowining. Sx-Ew processes are usually conducted near mining sites. In addition to mining, recycled scrap also plays a role. Depending on the purity, some scrap (e.g. discarded metal in manufacturing processes) is easily remanufactured, whereas less pure scrap (e.g. post-consumer products) needs to go through a pyrometalliurgical process. China is the largest copper refining country, with around 40% market share, followed by Chile, Japan and Russia. However, as China accounts for 50% of global demand for refined copper, it also imports refined copper products from abroad.

Copper demand for clean energy technologies remains one of the largest both by weight and monetary value. Clean energy technologies are also the fastest growing segment for copper demand. Their share of total copper demand rises from 24% today to 30% by 2040 in the STEPS and 45% in the SDS.

Copper processing processes



Sources: Hawker et al. (2014); Forsén et al. (2017).

Copper: New projects under development could bring a sizeable boost to near-term supply, but more is needed to support rising demand

Copper supply has been expanding rapidly over the past decades to satisfy rising demand caused by strong economic growth in emerging and developing economies. More than 250 mines currently operate in nearly 40 countries, producing around 21 Mt of copper. This is 30% greater than 10 years ago.

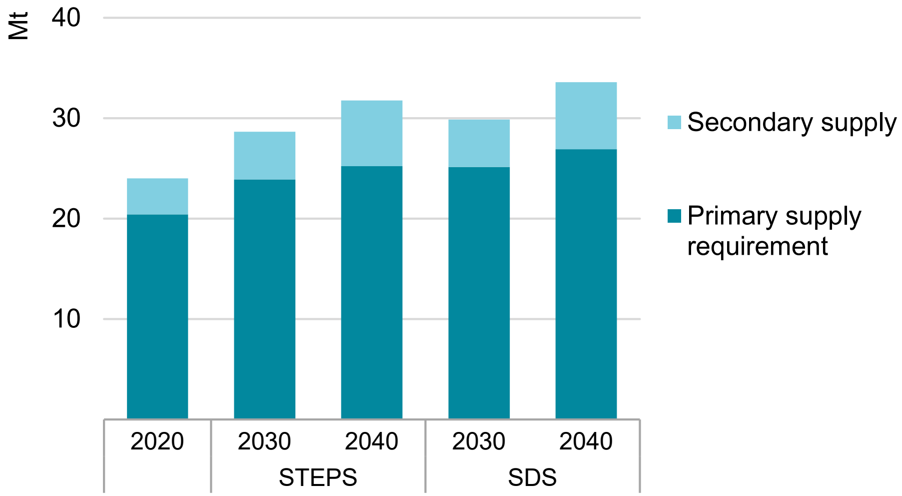
However, past trends may not be a good guide to what could happen in the coming decades. Production at today's major copper mines has already peaked or is expected to peak in the early 2020s due to declining ore quality and reserve exhaustion. For example, the world's largest copper mine, Escondida in Chile, appears to have reached a peak and its production in 2025 is expected to be at least 5% lower than today (S&P Global, 2021).

On the back of optimism for copper's role in the energy transition, investment has been picking up. A few large projects, such as Quellaveco in Peru and Kamoa-Kakula in the DRC are under construction. Several expansion projects such as Oyu Tolgoi in Mongolia are also in progress. These projects could deliver considerable near-term supply, if completed on schedule.

While Chile and Peru remain the largest producers through to 2025, the picture is set to become slightly more diverse, with the DRC and Indonesia increasing their production. As for processing, China is expected to continue its dominant position in the near term, with its capacity growth to 2025 accounting for nearly half of all planned additions to global capacity. As China's processing share increases (but not its mining share), the country is set to have more influence on the trade and pricing of intermediate products.

Beyond the near term, few projects are planned to start operations in the late 2020s, while output from exsting mines is expected to contract further. Meeting rising demand in the longer term would require continued new project development.

Primary supply requirements for copper by scenario



Copper: Declining ore quality exerts upward pressure on production costs and emissions, requiring additional efforts for technology innovation and efficiency improvement

While there is no shortage of resources (e.g. the size of copper reserves has increased by 30% over the last 10 years), developing new projects has become challenging due mainly to declining ore quality in major producing regions. As noted above, the average grades of concentrate in Chile have decreased by 30% since 2005. The feed for hydrometallurgical processes has also deteriorated in quality. Currently the copper content in Chilean ore is about 0.7% on average. The deposits in some major mines are depleting and developments are moving towards the fringes of exploited deposits.

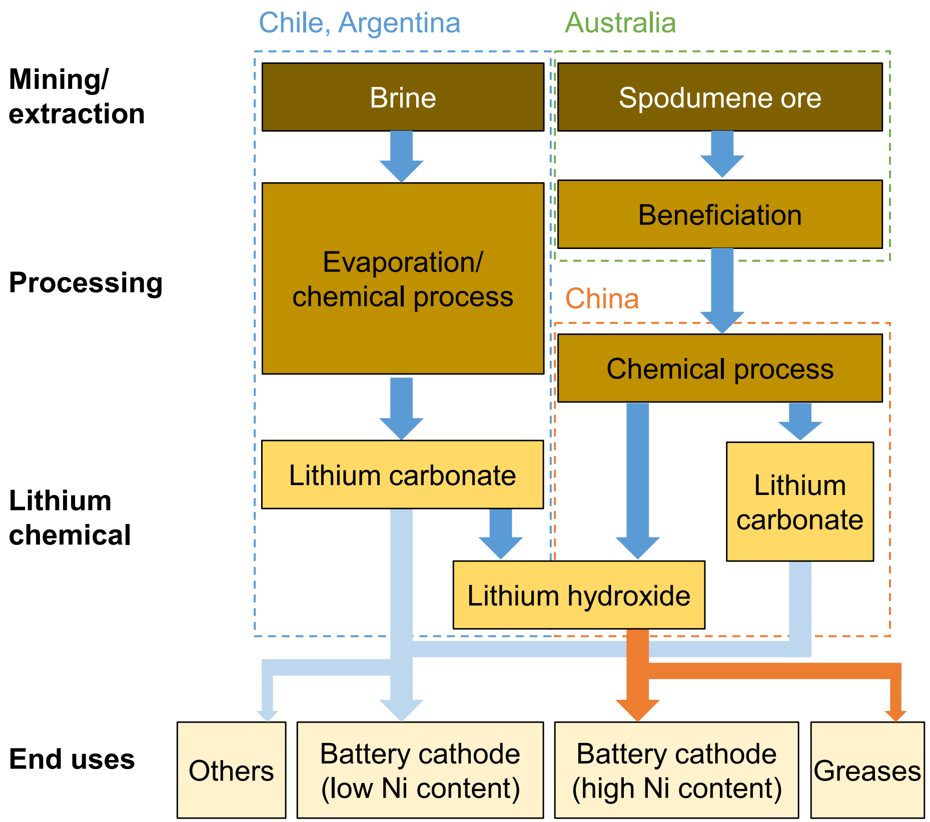
Extracting metal content from lower grade ores gives rise to additional cost and energy use, not just for on-site procesing, but also for operations along the value chain (e.g. dust suppression and reclamation). Moreover, the deeper the production site, the more cost and energy are required.

While cost escalations are a major challenge for the copper industry, the impacts of resource depletion can be offset by technology innovation. Until the late 19th century, average ore grades were 10-20%; then they decreased to 2-3% in the early part of 20th century (Henckens and Worrell, 2020). More recently, technologies such as aerial surveys, satellite imagery, geographic information systems and computer models have unlocked new supplies in a cost-effective manner, enabling a dramatic increase in output (Rötzer and Schmidt, 2018). In particular, the emergence of Sx-Ew processes since the 1970s has allowed greater efficiency in dealing with oxide resources. This process accounts for 20% of global copper production today. As with other minerals, continued technology innovation is pivotal to sustain affordable copper supply.

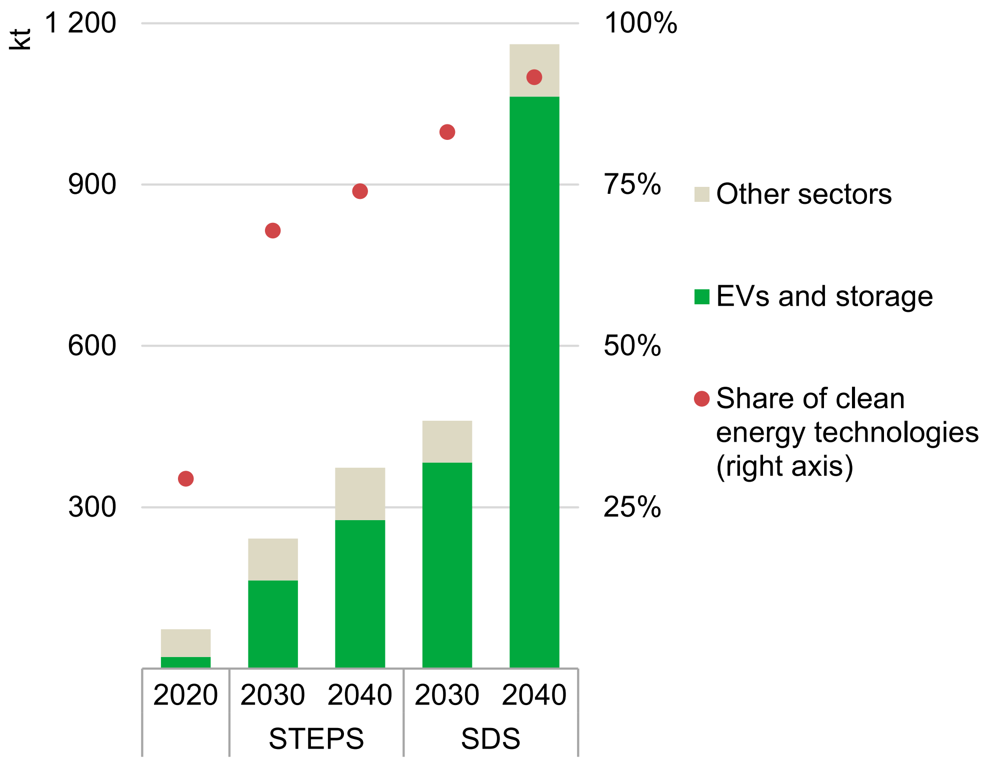
There are also environmental challenges. Major copper producing areas in South America face water scarcity, as discussed above. Moreover, hazardous elements such as arsenic are highly concerned in the copper industry. Deteriorating ore grades bring a problem of higher impurity including arsenic content, which can cause serious water and air pollution. The average arsenic content in Chilean concentrate has doubled since the beginning of 2000s, leading to higher costs to manage wastewater and mine tailings. Smelters also face challenges to remodel their processes to meet the environmental regulations related to arsenic. For example, new smelters in Chile are required to capture 99.97% of arsenic emissions (COCHILCO, 2018). Some smelters are planning to redesign their processes in response, and others are conducting R&D for copper-arsenic separation technologies.

Lithium: From resource to consumer

Lithium supply chain



Total lithium demand by sector and scenario



Note: Some spodumene ore is directly consumed for ceramic material.