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The Role of Critical Minerals in Clean Energy Transitions



World Energy Outlook Special Report

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

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Foreword

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Foreword

Ever since the International Energy Agency (IEA) was founded in 1974 in the wake of severe disruptions to global oil markets that shook the world economy, its core mission has been to foster secure and affordable energy supplies.

Today, the global energy system is in the midst of a major transition to clean energy. The efforts of an ever-expanding number of countries and companies to reduce their greenhouse gas emissions to net zero call for the massive deployment of a wide range of clean energy technologies, many of which in turn rely on critical minerals such as copper, lithium, nickel, cobalt and rare earth elements.

An evolving energy system calls for an evolving approach to energy security. As clean energy transitions accelerate globally and solar panels, wind turbines and electric cars are deployed on a growing scale, these rapidly growing markets for key minerals could be subject to price volatility, geopolitical influence and even disruptions to supply.

This *World Energy Outlook* special report on *The Role of Critical Minerals in Clean Energy Transitions* identifies risks to key minerals and metals that – left unaddressed – could make global progress towards a clean energy future slower or more costly, and therefore hamper international efforts to tackle climate change. The IEA is determined to play a leading role in enabling governments around the world to anticipate and navigate possible disruptions and avoid damaging outcomes for our economies and our planet.

This special report is the most comprehensive global study of this subject to date, underscoring the IEA's commitment to ensuring energy systems remain as resilient, secure and sustainable as possible. Building on the IEA's detailed, technology-rich energy modelling tools, we have established a unique and extensive database that underpins our projections of the world's future mineral requirements under different climate and technology scenarios.

This is what energy security looks like in the 21st century. We must pay close attention to all potential vulnerabilities, as the IEA did in our recent series on electricity security for power systems, which covered challenges such as growing shares of variable renewables, climate resilience and cyber security.

Today's supply and investment plans for many critical minerals fall well short of what is needed to support an accelerated deployment of solar panels, wind turbines and electric vehicles. Many minerals come from a small number of producers. For example, in the cases of lithium, cobalt and rare earth elements, the world's top three producers control well over three-quarters of global output. This high geographical concentration, the long lead times to bring new mineral production on stream, the declining resource quality in some areas,

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and various environmental and social impacts all raise concerns around reliable and sustainable supplies of minerals to support the energy transition.

These hazards are real, but they are surmountable. The response from policy makers and companies will determine whether critical minerals remain a vital enabler for clean energy transitions or become a bottleneck in the process.

Based on this special report, we identify the IEA's six key recommendations to ensure mineral security. An essential step is for policy makers to provide clear signals about their climate ambitions and how their targets will be turned into action. Long-term visibility is essential to provide the confidence investors need to commit to new projects. Efforts to scale up investment should go hand-in-hand with a broad strategy that encompasses technology innovation, recycling, supply chain resilience and sustainability standards.

There is no shortage of resources worldwide, and there are sizeable opportunities for those who can produce minerals in a sustainable and responsible manner. Because no single country will be able to solve these issues alone, strengthened international cooperation is essential. Leveraging the IEA's long-standing leadership in safeguarding energy security, we remain committed to helping governments, producers and consumers tackle these critical challenges.

Finally, I would like to thank the excellent team behind this ground-breaking report, led by Tae-Yoon Kim under the direction of Tim Gould, for their work in producing analysis of such high quality, and many other colleagues from across the Agency who brought their expertise to bear on this crucial topic.

Dr. Fatih Birol
Executive Director
International Energy Agency

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Executive summary

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In the transition to clean energy, critical minerals bring new challenges to energy security

An energy system powered by clean energy technologies differs profoundly from one fuelled by traditional hydrocarbon resources. Building solar photovoltaic (PV) plants and wind farms and electric vehicles (EVs) generally requires more minerals than their fossil fuel-based counterparts. A typical electric car requires six times the mineral inputs of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables has risen.

The types of mineral resources used vary by technology. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies.

The shift to a clean energy system is set to drive a huge increase in the requirement for these minerals, meaning that the energy sector is emerging as a major force in mineral markets. Until the mid-2010s, the enegy sector represented a small part of total demand for most minerals. However, as energy transitions gather pace, clean energy technologies are becoming the fastest-growing segment of demand.

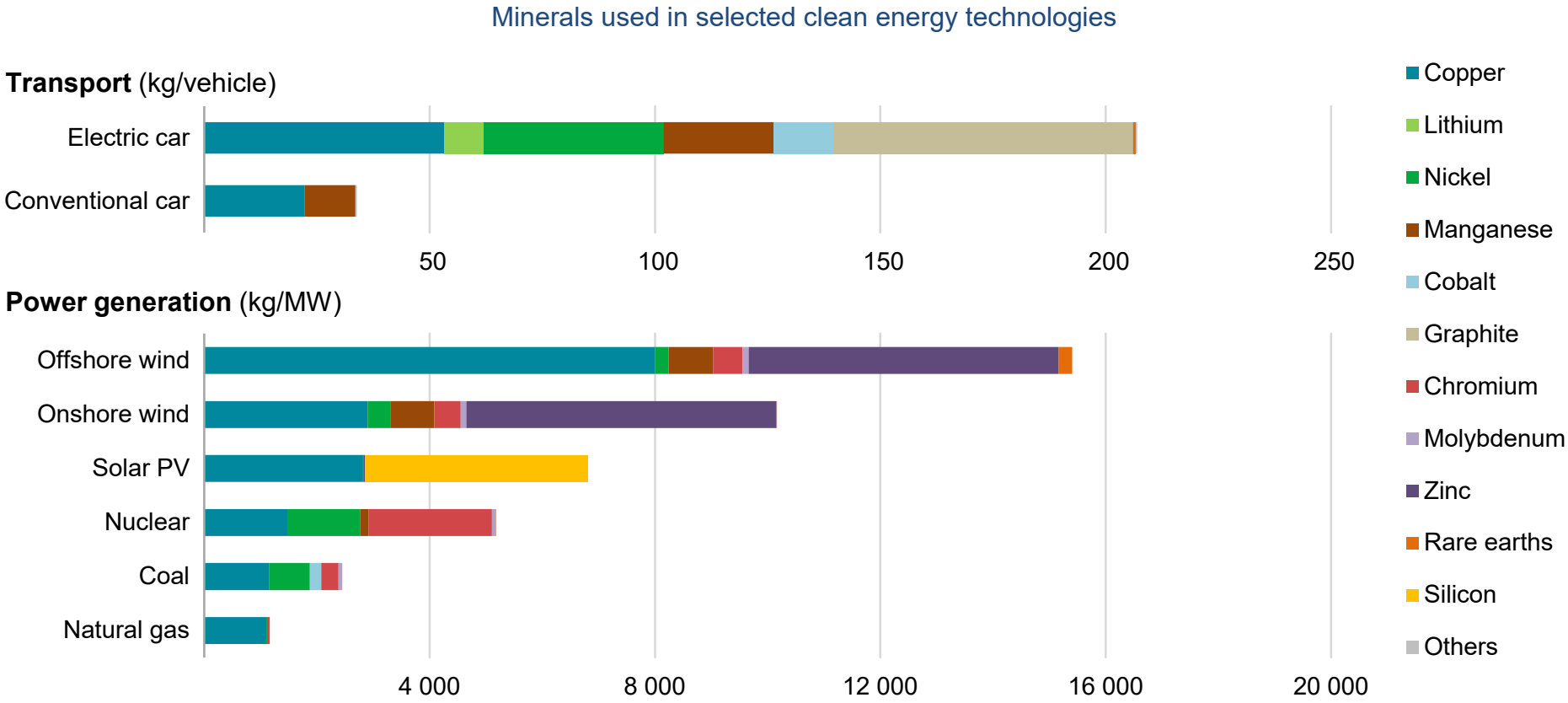
In a scenario that meets the Paris Agreement goals, clean energy technologies' share of total demand rises significantly over the next two decades to over 40% for copper and rare earth elements, 60-70% for nickel and cobalt, and almost 90% for lithium. EVs and battery storage have already displaced consumer electronics to become the largest consumer of lithium and are set to take over from stainless steel as the largest end user of nickel by 2040.

As countries accelerate their efforts to reduce emissions, they also need to make sure their energy systems remain resilient and secure. Today's international energy security mechanisms are designed to provide insurance against the risks of disruptions or price spikes in supplies of hydrocarbons, particularly oil. Minerals offer a different and distinct set of challenges, but their rising importance in a decarbonising energy system requires energy policy makers to expand their horizons and consider potential new vulnerabilities. Concerns about price volatility and security of supply do not disappear in an electrified, renewables-rich energy system.

This is why the IEA is paying close attention to the issue of critical minerals and their role in clean energy transitions. This report reflects the IEA's determination to stay ahead of the curve on all aspects of energy security in a fast-evolving energy world.

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The rapid deployment of clean energy technologies as part of energy transitions implies a significant increase in demand for minerals

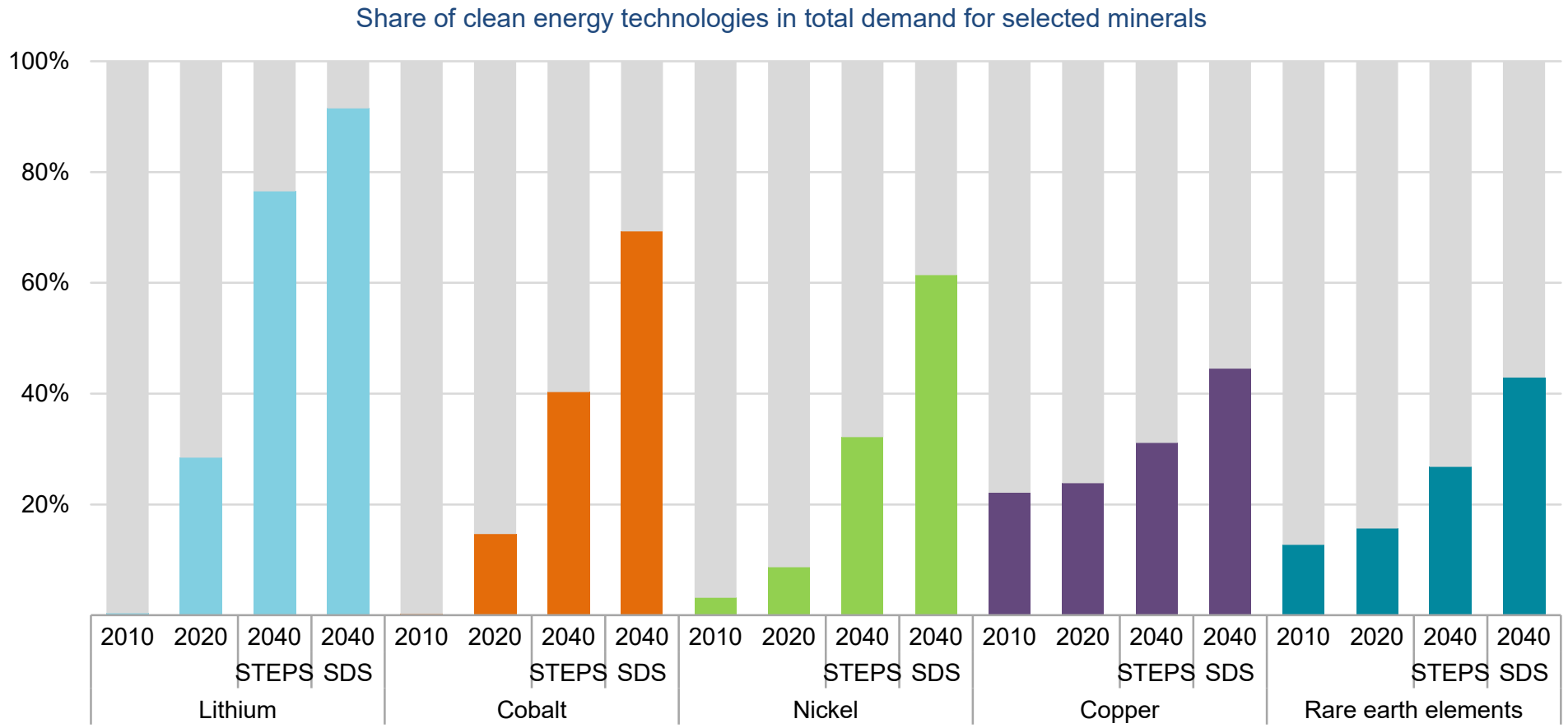


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Notes: kg = kilogramme; MW = megawatt. Steel and aluminium not included. See Chapter 1 and Annex for details on the assumptions and methodologies.

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The energy sector becomes a leading consumer of minerals as energy transitions accelerate



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Notes: Demand from other sectors was assessed using historical consumption, relevant activity drivers and the derived material intensity. Neodymium demand is used as indicative for rare earth elements. STEPS = Stated Policies Scenario, an indication of where the energy system is heading based on a sector-by-sector analysis of today's policies and policy announcements; SDS = Sustainable Development Scenario, indicating what would be required in a trajectory consistent with meeting the Paris Agreement goals.

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Clean energy transitions will have far-reaching consequences for metals and mining

Our bottom-up assessment suggests that a concerted effort to reach the goals of the Paris Agreement (climate stabilisation at "well below 2°C global temperature rise", as in the IEA Sustainable Development Scenario [SDS]) would mean a quadrupling of mineral requirements for clean energy technologies by 2040. An even faster transition, to hit net-zero *globally* by 2050, would require six times more mineral inputs in 2040 than today.

Which sectors do these increases come from? In climate-driven scenarios, mineral demand for use in EVs and battery storage is a major force, growing at least thirty times to 2040. Lithium sees the fastest growth, with demand growing by over 40 times in the SDS by 2040, followed by graphite, cobalt and nickel (around 20-25 times). The expansion of electricity networks means that copper demand for power lines more than doubles over the same period.

The rise of low-carbon power generation to meet climate goals also means a tripling of mineral demand from this sector by 2040. Wind takes the lead, bolstered by material-intensive offshore wind. Solar PV follows closely, due to the sheer volume of capacity that is added. Hydropower, biomass and nuclear make only minor contributions given their comparatively low mineral requirements. In other sectors, the rapid growth of hydrogen as an energy carrier underpins major growth in demand for nickel and zirconium for electrolysers, and for platinum-group metals for fuel cells.

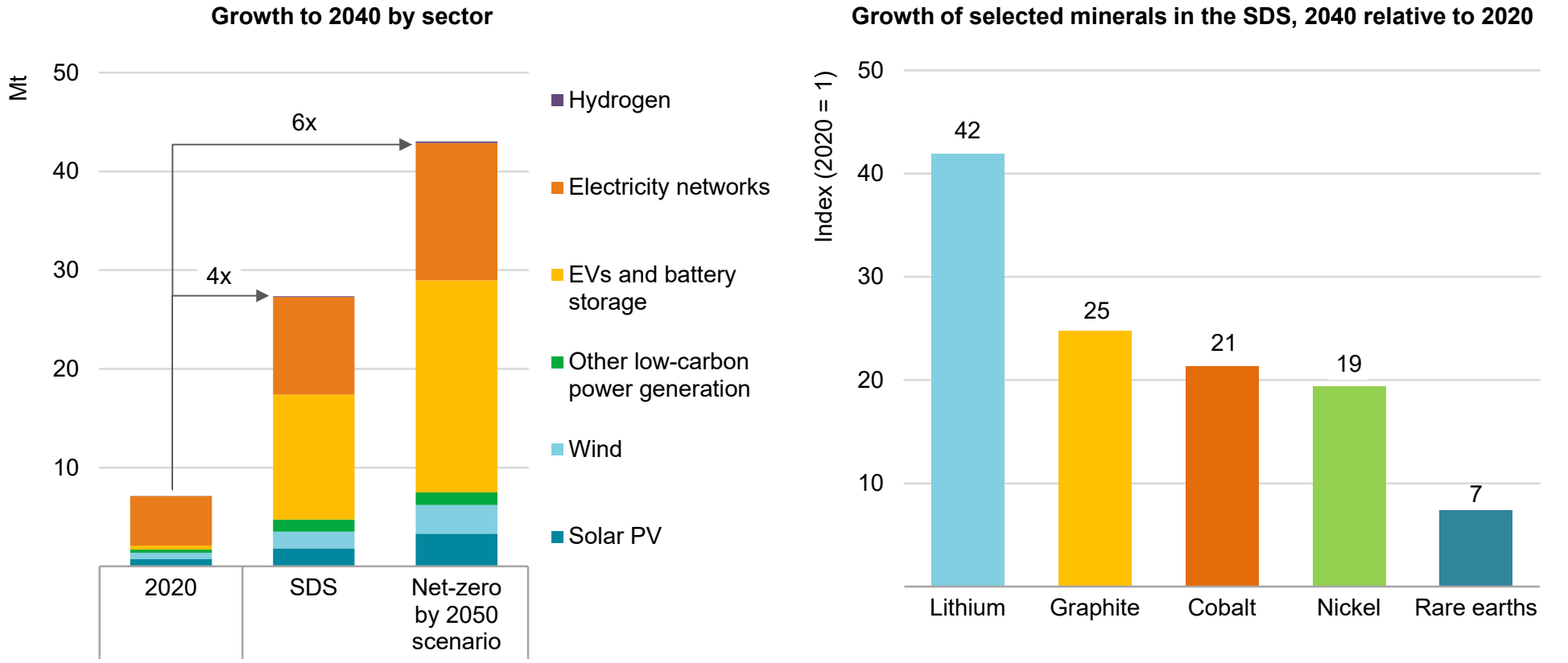
Demand trajectories are subject to large technology and policy uncertainties. We analysed 11 alternative cases to understand the impacts. For example, cobalt demand could be anything from 6 to 30 times higher than today's levels depending on assumptions about the evolution of battery chemistry and climate policies. Likewise rare earth elements may see three to seven times higher demand in 2040 than today, depending on the choice of wind turbines and the strength of policy support. The largest source of demand variability comes from uncertainty around the stringency of climate policies. The big question for suppliers is whether the world is really heading for a scenario consistent with the Paris Agreement. Policy makers have a crucial role in narrowing this uncertainty by making clear their ambitions and turning targets into actions. This will be vital to reduce investment risks and ensure adequate flow of capital to new projects.

Clean energy transitions offer opportunities and challenges for companies that produce minerals. Today revenue from coal production is ten times larger than those from energy transition minerals. However, there is a rapid reversal of fortunes in a climate-driven scenario, as the combined revenues from energy transition minerals overtake those from coal well before 2040.

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Mineral demand for clean energy technologies would rise by at least four times by 2040 to meet climate goals, with particularly high growth for EV-related minerals

Mineral demand for clean energy technologies by scenario

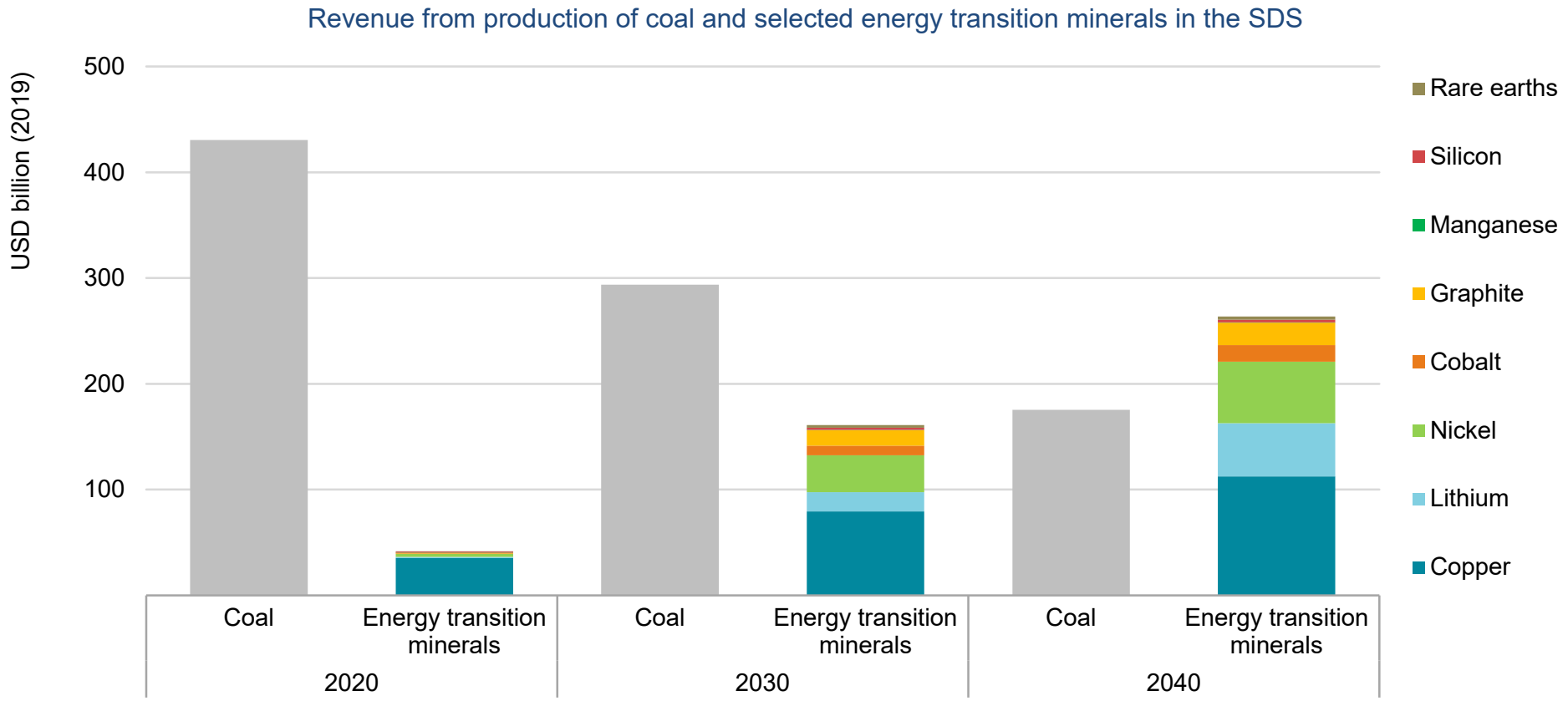


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Notes: Mt = million tonnes. Includes all minerals in the scope of this report, but does not include steel and aluminium. See Annex for a full list of minerals.

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Changing fortunes: Coal vs energy transition minerals



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Notes: Revenue for energy transition minerals includes only the volume required in clean energy technologies, not total demand. Future prices for coal are projected equilibrium prices in *WEO 2020* SDS. Prices for energy transition minerals are based on conservative assumptions about future price trends (moderate growth of around 10-20% from today's levels).

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Today's mineral supply and investment plans fall short of what is needed to transform the energy sector, raising the risk of delayed or more expensive energy transitions

The prospect of a rapid increase in demand for critical minerals – well above anything seen previously in most cases – raises huge questions about the availability and reliability of supply. In the past, strains on the supply-demand balance for different minerals have prompted additional investment and measures to moderate or substitute demand. But these responses have come with time lags and have been accompanied by considerable price volatility. Similar episodes in the future could delay clean energy transitions and push up their cost. Given the urgency of reducing emissions, this is a possibility that the world can ill afford.

Raw materials are a significant element in the cost structure of many technologies required in energy transitions. In the case of lithium-ion batteries, technology learning and economies of scale have pushed down overall costs by 90% over the past decade. However, this also means that raw material costs now loom larger, accounting for some 50-70% of total battery costs, up from 40-50% five years ago. Higher mineral prices could therefore have a significant effect: a doubling of lithium or nickel prices would induce a 6% increase in battery costs. If both lithium and nickel prices were to double at the same time, this would offset all the anticipated unit cost reductions associated with a doubling of battery production capacity. In the case of electricity networks, copper and aluminium currently represent around 20% of total grid investment costs. Higher prices as a result of tight supply could have a major impact on the level of grid investment.

Our analysis of the near-term outlook for supply presents a mixed picture. Some minerals such as mined lithium and cobalt are expected to be in surplus in the near term, while lithium chemical products, battery-grade nickel and key rare earth elements (e.g. neodymium and dysprosium) might face tight supply in the years ahead. However, looking further ahead in a scenario consistent with climate goals, expected supply from existing mines and projects under construction is estimated to meet only half of projected lithium and cobalt requirements and 80% of copper needs by 2030.

Today's supply and investment plans are geared to a world of more gradual, insufficient action on climate change (the STEPS trajectory). They are not ready to support accelerated energy transitions. While there is a host of projects at varying stages of development, there are many vulnerabilities that may increase the possibility of market tightness and greater price volatility:

- **High geographical concentration of production:** Production of many energy transition minerals is more concentrated than that of oil or natural gas. For lithium, cobalt and rare earth elements, the world's top three producing nations control well over three-

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quarters of global output. In some cases, a single country is responsible for around half of worldwide production. The Democratic Republic of the Congo (DRC) and China were responsible for some 70% and 60% of global production of cobalt and rare earth elements respectively in 2019. The level of concentration is even higher for processing operations, where China has a strong presence across the board. China's share of refining is around 35% for nickel, 50-70% for lithium and cobalt, and nearly 90% for rare earth elements. Chinese companies have also made substantial investment in overseas assets in Australia, Chile, the DRC and Indonesia. High levels of concentration, compounded by complex supply chains, increase the risks that could arise from physical disruption, trade restrictions or other developments in major producing countries.

- **Long project development lead times:** Our analysis suggests that it has taken on average over 16 years to move mining projects from discovery to first production. These long lead times raise questions about the ability of suppliers to ramp up output if demand were to pick up rapidly. If companies wait for deficits to emerge before committing to new projects, this could lead to a prolonged period of market tightness and price volatility.

- **Declining resource quality:** Concerns about resources relate to quality rather than quantity. In recent years, ore quality has continued to fall across a range of commodities. For example, the average copper ore grade in Chile declined by 30% over the past 15 years. Extracting metal content from lower-grade ores requires more energy, exerting upward pressure on production costs, greenhouse gas emissions and waste volumes.

- **Growing scrutiny of environmental and social performance:** Production and processing of mineral resources gives rise to a variety of environmental and social issues that, if poorly managed, can harm local communities and disrupt supply. Consumers and investors are increasingly calling for companies to source minerals that are sustainably and responsibly produced. Without broad and sustained efforts to improve environmental and social performance, it may be challenging for consumers to exclude minerals produced with poor standards as higher-performing supply chains may not be sufficient to meet demand.

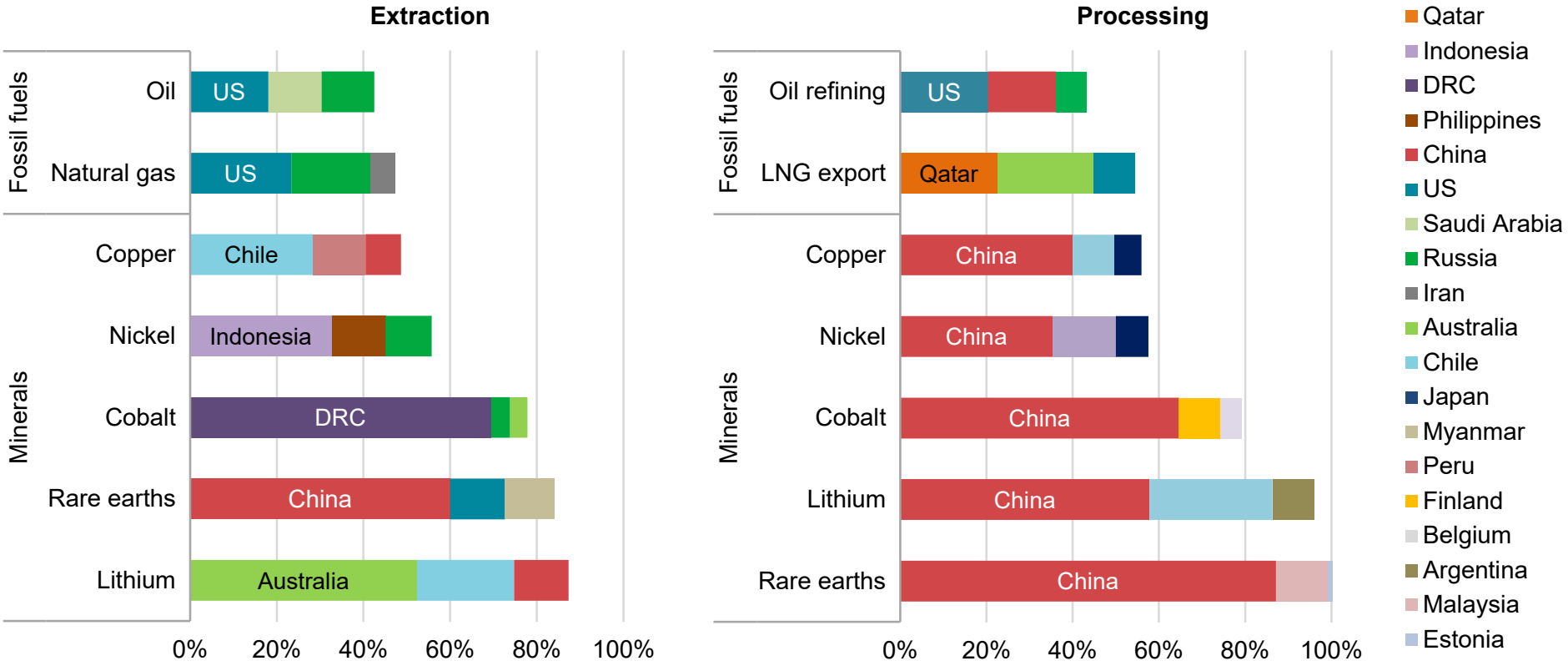
- **Higher exposure to climate risks:** Mining assets are exposed to growing climate risks. Copper and lithium are particularly vulnerable to water stress given their high water requirements. Over 50% of today's lithium and copper production is concentrated in areas with high water stress levels. Several major producing regions such as Australia, China, and Africa are also subject to extreme heat or flooding, which pose greater challenges in ensuring reliable and sustainable supplies.

These risks to the reliability, affordability and sustainability of mineral supply are manageable, but they are real. How policy makers and companies respond will determine whether critical minerals are a vital enabler for clean energy transitions, or a bottleneck in the process.

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Production of many energy transition minerals today is more geographically concentrated than that of oil or natural gas

Share of top three producing countries in production of selected minerals and fossil fuels, 2019



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Notes: LNG = liquefied natural gas; US = United States. The values for copper processing are for refining operations.
Sources: IEA (2020a); USGS (2021), World Bureau of Metal Statistics (2020); Adamas Intelligence (2020).

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New and more diversified supply sources will be vital to pave the way to a clean energy future

As energy transitions gather pace, security of mineral supply is gaining prominence in the energy security debate, a realm where oil has traditionally occupied a central role.

There are significant differences between oil security and mineral security, notably in the impacts that any disruption may have. In the event of an oil supply crisis, all consumers driving gasoline cars or diesel trucks are affected by higher prices. By contrast, a shortage or spike in the price of a mineral affects only the supply of *new* EVs or solar plants. Consumers driving existing EVs or using solar-powered electricity are not affected. In addition, the combustion of oil means that new supply is essential to the continuous operation of oil-using assets. However, minerals are a component of infrastructure, with the potential to be recovered and recycled.

Nonetheless, experience from oil markets may offer some valuable lessons for an approach to mineral security, in particular to underscore that supply-side measures need to be accompanied by wide-ranging efforts encompassing demand, technology, supply chain resilience and sustainability.

Rapid, orderly energy transitions require strong growth in investment in mineral supplies to keep up with the pace of demand growth. Policy makers can take a variety of actions to encourage new supply projects: the most important is to provide clear and strong signals about energy transitions. If companies do not have confidence in countries' energy and climate policies, they are likely to make investment decisions based on much more conservative expectations. Given the long lead times for new project developments, this could create bottlenecks when deployment of clean energy technologies starts to grow rapidly. Diversification of supply is also crucial; resource-owning governments can support new project development by reinforcing national geological surveys, streamlining permitting procedures to shorten lead times, providing financing support to de-risk projects, and raising public awareness of the contribution that such projects play in the transformation of the energy sector.

Reducing material intensity and encouraging material substitution via technology innovation can also play major roles in alleviating strains on supply, while also reducing costs. For example, 40-50% reductions in the use of silver and silicon in solar cells over the past decade have enabled a spectacular rise in solar PV deployment. Innovation in production technologies can also unlock sizeable new supplies. Emerging technologies, such as direct lithium extraction or enhanced metal recovery from waste streams or low-grade ores, offer the potential for a step change in future supply volumes.

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A strong focus on recycling, supply chain resilience and sustainability will be essential

Recycling relieves the pressure on primary supply. For bulk metals, recycling practices are well established, but this is not yet the case for many energy transition metals such as lithium and rare earth elements. Emerging waste streams from clean energy technologies (e.g. batteries and wind turbines) can change this picture. The amount of spent EV batteries reaching the end of their first life is expected to surge after 2030, at a time when mineral demand is set to still be growing rapidly. Recycling would not eliminate the need for continued investment in new supplies. But we estimate that by 2040, recycled quantities of copper, lithium, nickel and cobalt from spent batteries could reduce combined primary supply requirements for these minerals by around 10%. The security benefits of recycling can be far greater for regions with wider deployment of clean energy technologies due to greater economies of scale.

Regular market assessments and periodic stress tests, coupled with emergency response exercises (along the lines of the IEA's existing emergency response programmes), can help policy makers identify possible weak points, evaluate potential impacts and devise necessary actions. Voluntary strategic stockpiling can in some cases help countries weather short-term supply disruptions. Such programmes need to be carefully designed, and based on a detailed review of potential vulnerabilities. Some minerals with smaller markets have low pricing transparency and liquidity, making it difficult to manage price risks and affecting investment decisions. Establishing reliable price benchmarks will be a crucial step towards enhancing transparency and supporting market development.

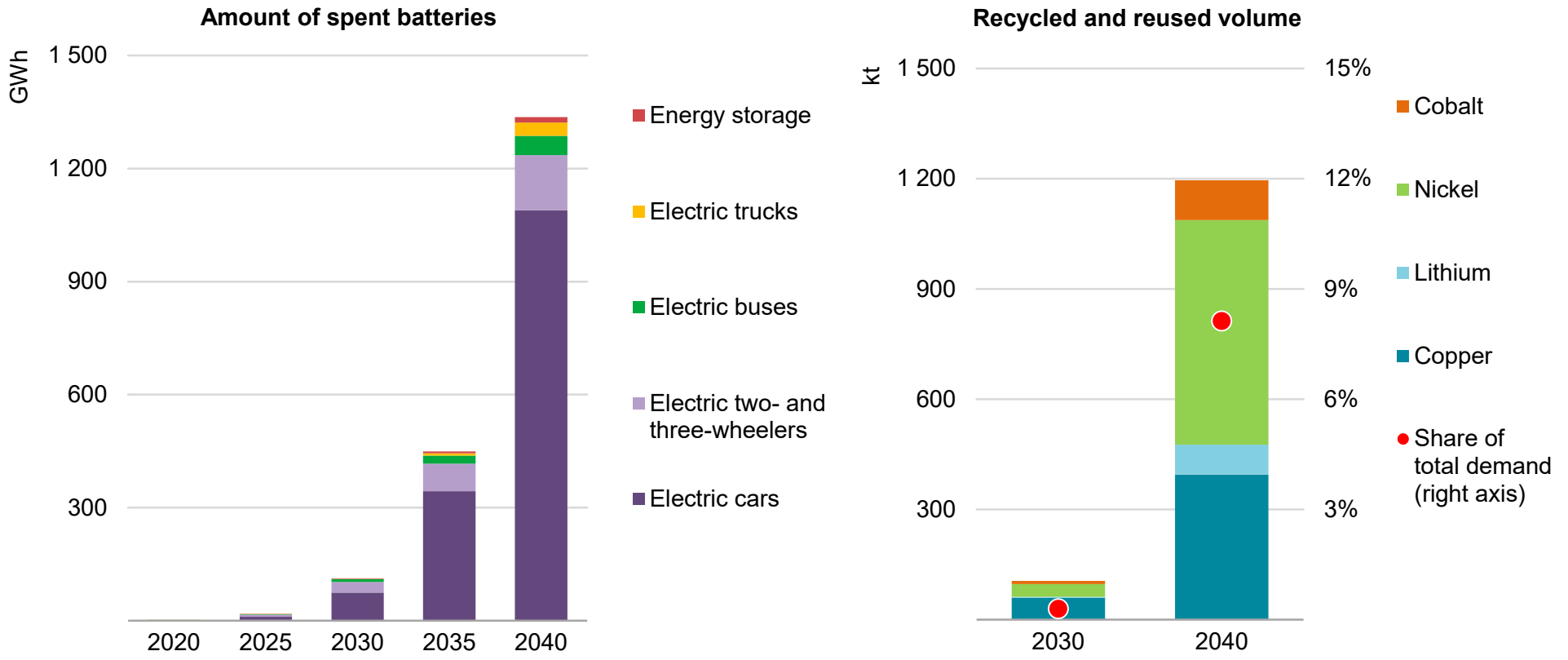
Tackling the environmental and social impacts of mineral developments will be essential, including the emissions associated with mining and processing, risks arising from inadequate waste and water management, and impacts from inadequate worker safety, human rights abuses (such as child labour) and corruption. Ensuring that mineral wealth brings real gains to local communities is a broad and multi-faceted challenge, particularly in countries where artisanal and small-scale mines are common. Supply chain due diligence, with effective regulatory enforcement, can be a critical tool to identify, assess and mitigate risks, increasing traceability and transparency.

Emissions along the mineral supply chain do not negate the clear climate advantages of clean energy technologies. Total lifecycle greenhouse gas emissions of EVs are around half those of internal combustion engine cars on average, with the potential for a further 25% reduction with low-carbon electricity. While energy transition minerals have relatively high emission intensities, a large variation in the emissions footprint of different producers suggests that there are ways to minimise these emissions through fuel switching, low-carbon electricity and efficiency improvements. Integrating environmental concerns in the early stages of project planning can help ensure sustainable practices throughout the project life cycle.

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The projected surge in spent battery volumes suggests immense scope for recycling

Amount of spent lithium-ion batteries from EVs and storage and recycled and reused minerals from batteries in the SDS

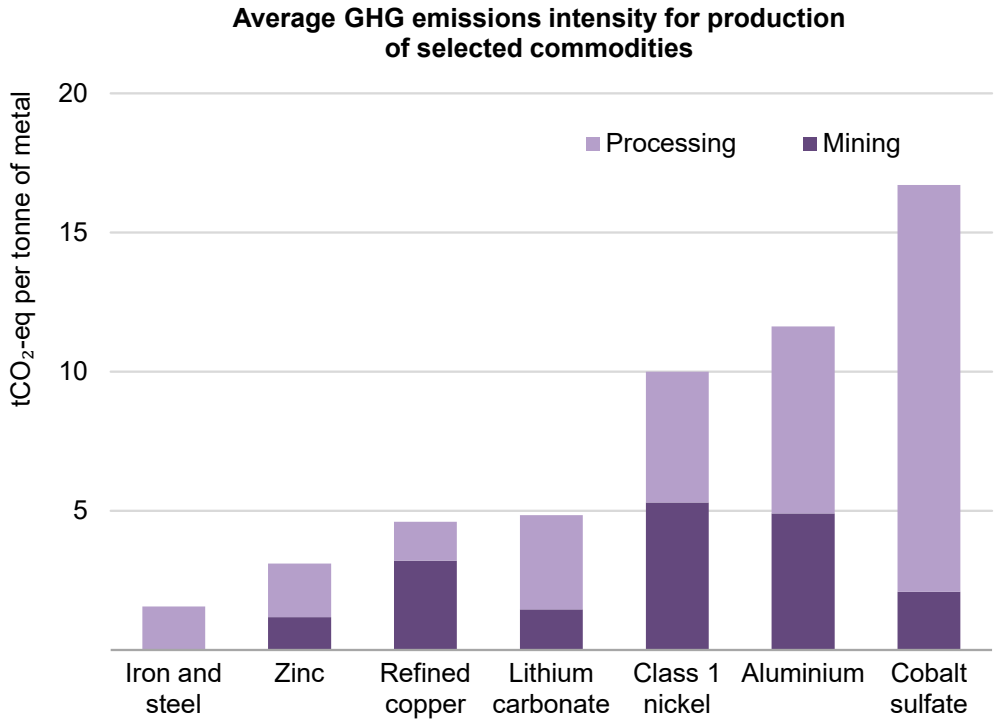


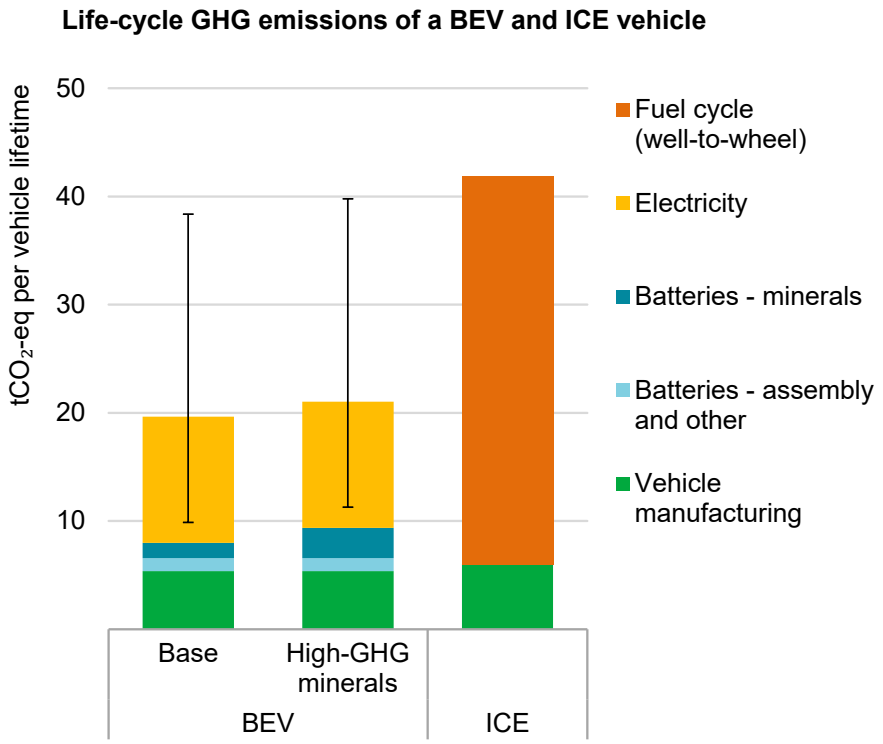
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Note: GWh = gigawatt hour.

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Stronger actions are required to counter the upward pressure on emissions from mineral production, but the climate advantages of clean energy technologies remain clear





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Notes: BEV = battery electric vehicle; ICE = internal combustion engine. The "High-GHG minerals" case assumes double the GHG emissions intensity for battery minerals. Includes both Scope 1 and 2 emissions of all GHG from primary production. See Chapter 4 for more detailed assumptions.

Source: IEA analysis based on IEA (2020a); IEA (2020b); Kelly et al. (2020); Argonne National Laborator (2020); Argonne National Laboratory (2019); Rio Tinto (2020); S&P Global (2021); Skarn Associates (2021); Marx et al. (2018).

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IEA's six key recommendations for a new, comprehensive approach to mineral security

1. **Ensure adequate investment in diversified sources of new supply.** Strong signals from policy makers about the speed of energy transitions and the growth trajectories of key clean energy technologies are critical to bring forward timely investment in new supply. Governments can play a major role in creating conditions conducive to diversifed investment in the mineral supply chain.

2. **Promote technology innovation at all points along the value chain.** Stepping up R&D efforts for technology innovation on both the demand and production sides can enable more efficient use of materials, allow material substitution and unlock sizeable new supplies, thereby bringing substantial environmental and security benefits.

3. **Scale up recycling.** Policies can play a pivotal role in preparing for rapid growth of waste volumes by incentivising recycling for products reaching the end of their operating lives, supporting efficient collection and sorting activities and funding R&D into new recycling technologies.

4. **Enhance supply chain resilience and market transparency.** Policy makers need to explore a range of measures to improve the resilience of supply chains for different minerals, develop response capabilities to potential supply disruptions and enhance market transparency. Measures can include regular market assessments and stress tests, as well as voluntary strategic stockpiles in some instances.

5. **Mainstream higher environmental, social and governance standards.** Efforts to incentivise higher environmental and social performance can increase sustainably and responsibly produced volumes and lower the cost of sourcing them. If industry players with strong environmental and social standards are rewarded in the marketplace, this can also bring new suppliers to a more diversified market.

6. **Strengthen international collaboration between producers and consumers**. An overarching international framework for dialogue and policy co-ordination among producers and consumers can play a vital role, an area where the IEA's energy security framework could usefully be leveraged. Such an initiative could include actions to (i) provide reliable and transparent data; (ii) conduct regular assessments of potential vulnerabilities of supply chains and potential collective responses; (iii) promote knowledge transfer and capacity building to spread sustainable and responsible development practices; and (iv) strengthen environmental and social performance standards to ensure a level playing field.

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Introduction

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Introduction

Clean energy transitions gained momentum in 2020, despite the major economic and social disruptions caused by the pandemic. Renewable electricity defied the Covid-19 crisis with record growth, and capacity additions are on course to reach fresh heights in the coming years (IEA, 2020). Electric car sales also charged ahead, with a remarkable 40% increase in 2020 amid a sluggish global market (IEA, 2021). Dozens of countries and many leading companies have announced plans to bring their emissions down to net zero by around the middle of this century.

The growing momentum behind clean energy transitions focuses attention on the importance of clean energy supply chains, and the adequate supply of minerals in particular. Minerals have played a vital role in the rise of many of the clean energy technologies that are widely used today – from solar panels and wind turbines to electricity networks and electric vehicles. But ensuring that these and other technologies can continue to draw on sufficient mineral supplies, and therefore support the acceleration of energy transitions, is a major challenge. Debates around energy security have traditionally been associated with oil and natural gas supplies, and more recently also with electricity, but as energy transitions gather pace policy makers need to expand their horizons to include new potential hazards.

With this *World Energy Outlook (WEO)* special report, we aim to: explain the complex links between clean energy technologies and minerals; assess the mineral requirements under varying energy and technology scenarios; and identify the security, environmental and social implications of minerals supply for the energy transition. The report reflects the IEA's determination to ensure it stays ahead of the curve on all aspects of energy security in a decarbonising world.

Our analysis is based on two main IEA scenarios, drawn from *WEO-2020*. The **Sustainable Development Scenario (SDS)** charts a pathway that meets in full the world's goals to tackle climate change in line with the Paris Agreement, improve air quality and provide access to modern energy. The SDS relies on countries and companies hitting their announced net-zero emissions targets (mostly by 2050) on time and in full, which spurs the world as a whole to reach it before 2070. The range of technologies that are required in the SDS provides an essential benchmark for our discussion throughout the report. Reaching net-zero emissions globally by 2050 would demand a dramatic extra push for the deployment of various clean energy technologies.

The other scenario we refer to in the analysis is the **Stated Policies Scenario (STEPS)**, which provides an indication of where today's policy measures and plans might lead the energy sector. These outcomes fall far short of the world's shared sustainability goals. Comparison between the outcomes in these two scenarios provides an indication of the range of possible futures.

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Scope

This report assesses the mineral requirements for a range of clean energy technologies, including renewable power (solar photovoltaic [PV], onshore and offshore wind, concentrating solar power, hydro, geothermal and biomass), nuclear power, electricity networks (transmission and distribution), electric vehicles, battery storage and hydrogen (electrolysers and fuel cells). Although this is not an exhaustive list of clean energy technologies, the technologies we cover represent the majority deployed in the SDS. We plan to expand the analysis to other technologies in future publications.

All these technologies require metals and alloys, which are produced by processing mineral-containing ores. Ores – the raw, economically viable rocks that are mined – are beneficiated to liberate and concentrate the minerals of interest. Those minerals are further processed to extract the metals or alloys of interest. Processed metals and alloys are then used in end-use applications. While this report covers the entire mineral and metal value chain from mining to processing operations, we use “minerals” as a representative term for the sake of simplicity.

Minerals are not only used in the clean energy sector, but are also used widely across the entire energy system, in technologies that improve efficiency and reduce emissions. For example, the most efficient coal-fired power plants require a lot more nickel than the least efficient ones in order to allow for higher combustion temperatures. Catalytic converters use platinum or palladium to help reduce harmful emissions from engines using petroleum. However, here we focus specifically on the use of minerals in clean energy technologies, given that they generally require considerably more minerals than fossil fuel counterparts. Our analysis also focuses on the requirements for building a plant (or making equipment) and not on operational requirements (e.g. uranium consumption in nuclear plants).

Our report considers a wide range of minerals used in clean energy technologies, as indicated in the Annex. They include chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, rare earth elements and others. Steel is widely used across a broad range of technologies, but we have excluded it from the scope given that it does not have substantial security implications and the energy sector is not a major driver of growth in steel demand.

Aluminium also plays a crucial role in clean energy transitions, being widely used in applications such as solar cells, wind turbines and vehicle lightweighting. We have excluded it from demand projections as it is regularly assessed as part of the *WEO* and *Energy Technology Perspectives* series. However, we have assessed its use in electricity networks as the outlook for copper is inherently linked with aluminium use in grid lines.

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Structure

We have structured this report in four chapters, as follows:

In **Chapter 1 (The State of Play)** we set out the linkages between critical minerals and energy transitions, and the reasons why they are rising up the policy agenda. We provide an overview of today's supply chains and examines their geographical concentration and other potential bottlenecks. We also describe the industry landscape, and recent investment and price dynamics.

In **Chapter 2 (Mineral Requirements for Clean Energy Technologies)** we analyse a range of possible trajectories for mineral requirements in various clean energy technologies. They include low-carbon power generation, batteries for electric vehicles and grid storage, electricity networks and hydrogen. We conducted the assessments using the detailed technology projections in IEA scenarios. We also address how and to what extent demand trajectories could evolve in different directions under a number of alternative technology evolution pathways.

In **Chapter 3 (Reliable Supply of Minerals)** we assess the prospects for supply of the main focus minerals – copper, lithium, nickel, cobalt and rare earth elements – that play a particularly important role in many clean energy technologies. We examine the contributions from existing mines and those under construction, and shed light on specific vulnerabilities that could create pressures on future supply.

In this chapter we also discuss the potential contribution of secondary supply, especially via recycling. We assess how recycling could contribute to reducing requirements for primary supply, taking into account both conventional sources and emerging waste streams such as spent batteries from electric vehicles.

Using our analysis and lessons from historical episodes of disruption, we identify policy approaches to ensure reliable supply of minerals in an evolving market environment.

In **Chapter 4 (Sustainable and Responsible Development of Minerals)** we examine the environmental, social and governance implications of minerals development which, if improperly managed, could offset or negate their positive contributions to clean energy technologies. We assess potential hazards, spanning from emissions during production and processing, to inadequate waste and water management and extending to local community impacts such as corruption, human rights abuses and worker safety. We finally discuss potential policy approaches to mitigate these risks.

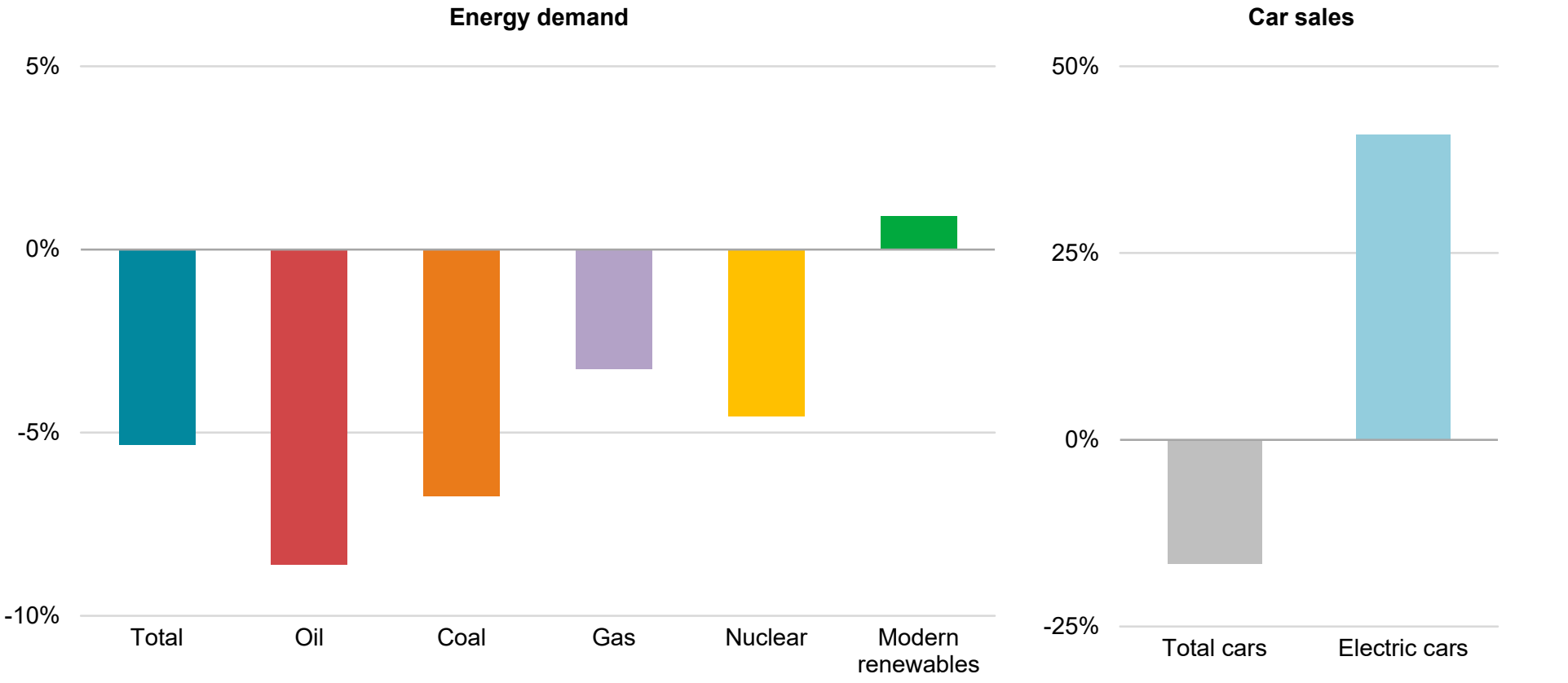
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The state of play

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Clean energy technologies defied the Covid-19 crisis with strong growth, making 2020 a pivotal year for clean energy transitions

Change in energy demand and car sales by type in 2020 relative to 2019



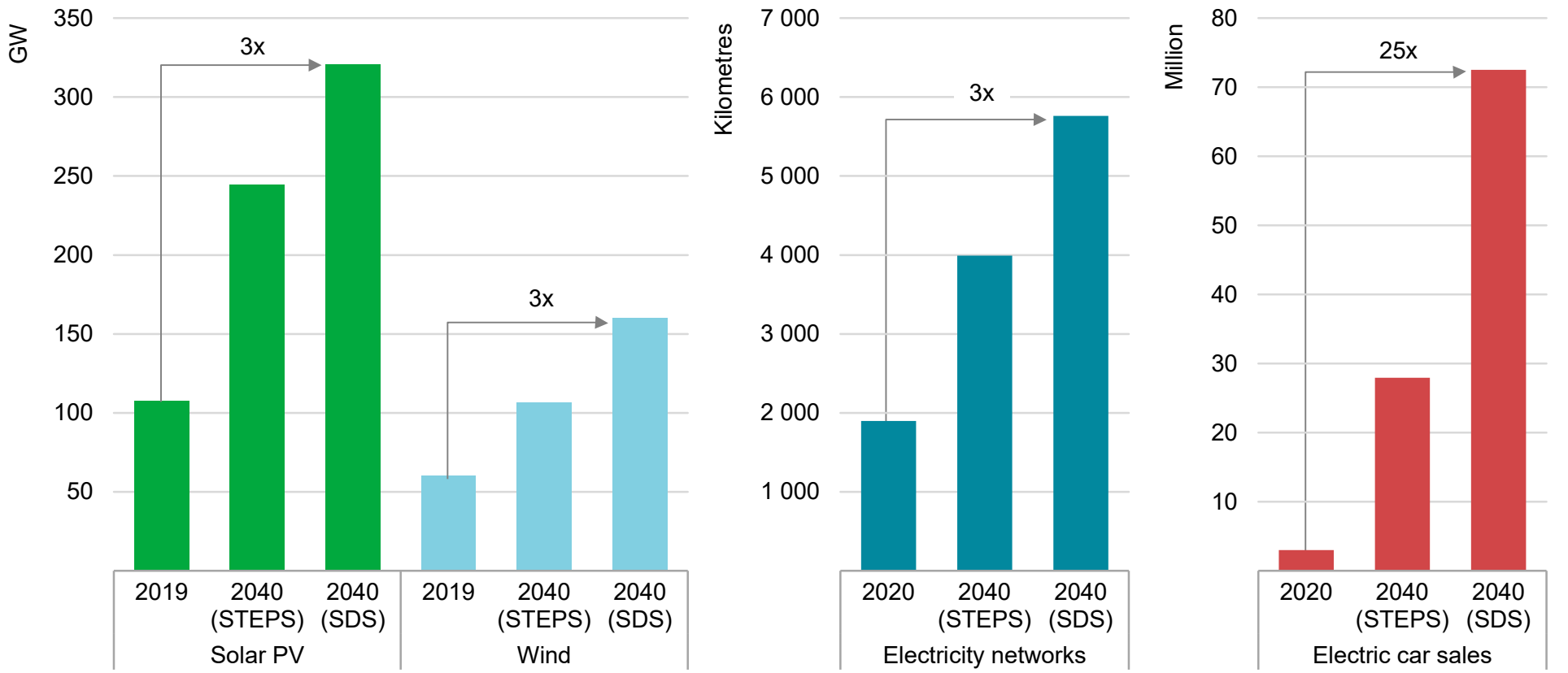
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Sources: IEA (2020a) for energy demand; IEA (2021a) for car sales.

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But achieving climate goals requires a further rapid acceleration in clean energy deployment

Annual deployment of clean energy technologies by scenario

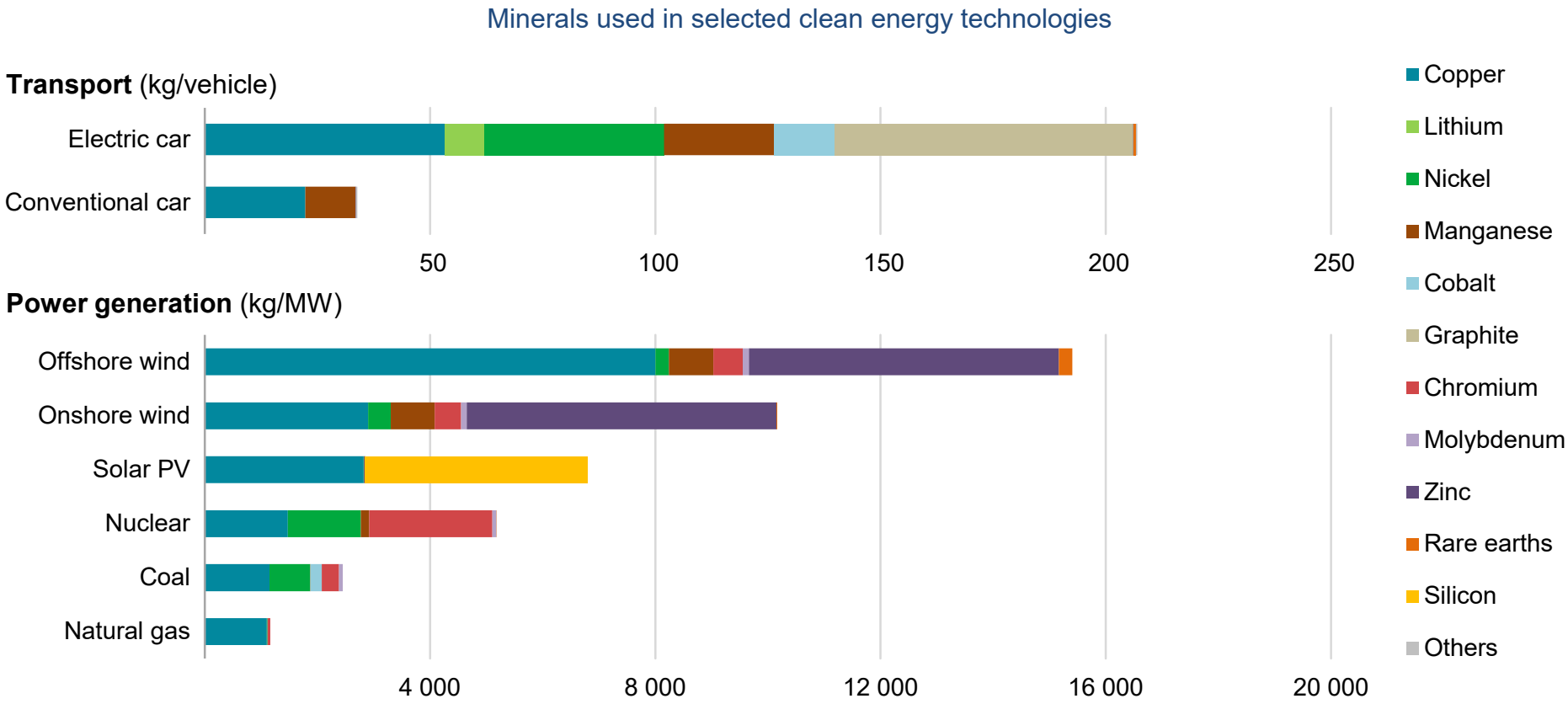


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Notes: PV = Photovoltaic; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.
Sources: IEA (2021a); IEA (2020a).

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The rapid deployment of these technologies as part of energy transitions implies a significant increase in demand for minerals

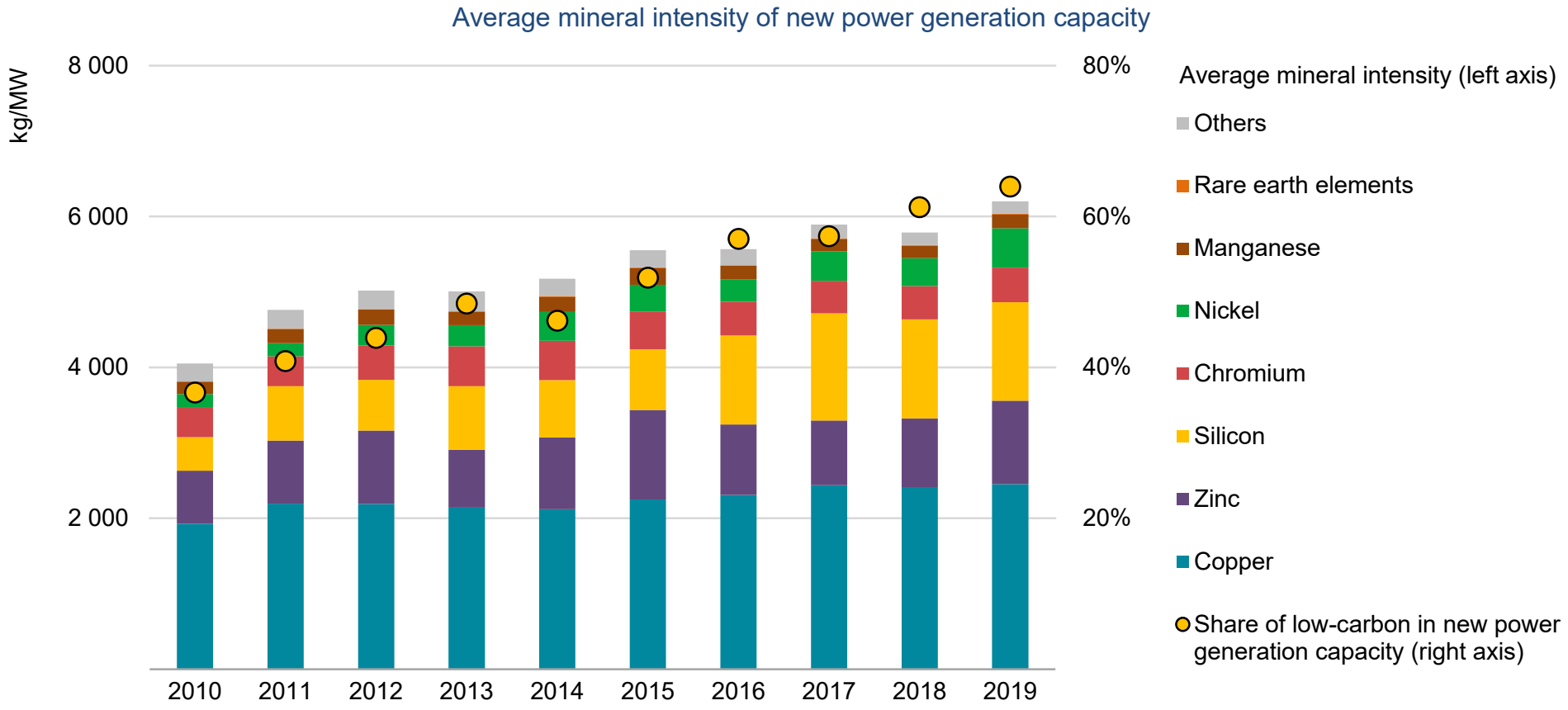


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Notes: kg = kilogramme; MW = megawatt. The values for vehicles are for the entire vehicle including batteries, motors and glider. The intensities for an electric car are based on a 75 kWh NMC (nickel manganese cobalt) 622 cathode and graphite-based anode. The values for offshore wind and onshore wind are based on the direct-drive permanent magnet synchronous generator system (including array cables) and the doubly-fed induction generator system respectively. The values for coal and natural gas are based on ultra-supercritical plants and combined-cycle gas turbines. Actual consumption can vary by project depending on technology choice, project size and installation environment.

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The mineral requirement for new power generation capacity has increased by 50% since 2010 as low-carbon technologies take a growing share of investment



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Note: Low-carbon technologies include renewables and nuclear.

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The shift from a fuel-intensive to a material-intensive energy system

The Covid-19 pandemic and resulting economic crisis have had an impact on almost every aspect of the global energy system. However, while fossil fuel consumption was hit hard in 2020, clean energy technologies – most notably renewables and electric vehicles (EVs) – remained relatively resilient. As a result, our latest estimates suggest that global energy-related CO_2 emissions fell by 6% in 2020, more than the 4% fall in energy demand (IEA, 2021b).

Nonetheless, as things stand, the world is far from seeing a decisive downturn in emissions – CO_2 emissions in December 2020 were already higher than their pre-crisis level one year earlier. Putting emissions on a trajectory consistent with the Paris Agreement, as analysed in the *World Energy Outlook* Sustainable Development Scenario (SDS), requires a significant scale-up of clean energy deployment across the board. In the SDS, the annual installation of solar PV cells, wind turbines and electricity networks needs to expand threefold by 2040 from today's levels, and sales of electric cars need to grow 25-fold over the same period. Reaching net-zero emissions globally by 2050 would demand an even more dramatic increase in the deployment of clean energy technologies over the same timeframe.

An energy system powered by clean energy technologies differs profoundly from one fuelled by traditional hydrocarbon resources. While solar PV plants and wind farms do not require fuels to operate, they generally require more materials than fossil fuel-based counterparts for construction. Minerals are a case in point. A typical electric car requires six times the mineral inputs of a conventional car and an onshore wind plant requires nine times more mineral resources than a gas-fired plant of the same capacity. Since 2010 the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as renewables increase their share of total capacity additions. The transition to clean energy means a shift from a fuel-intensive to a material-intensive system.

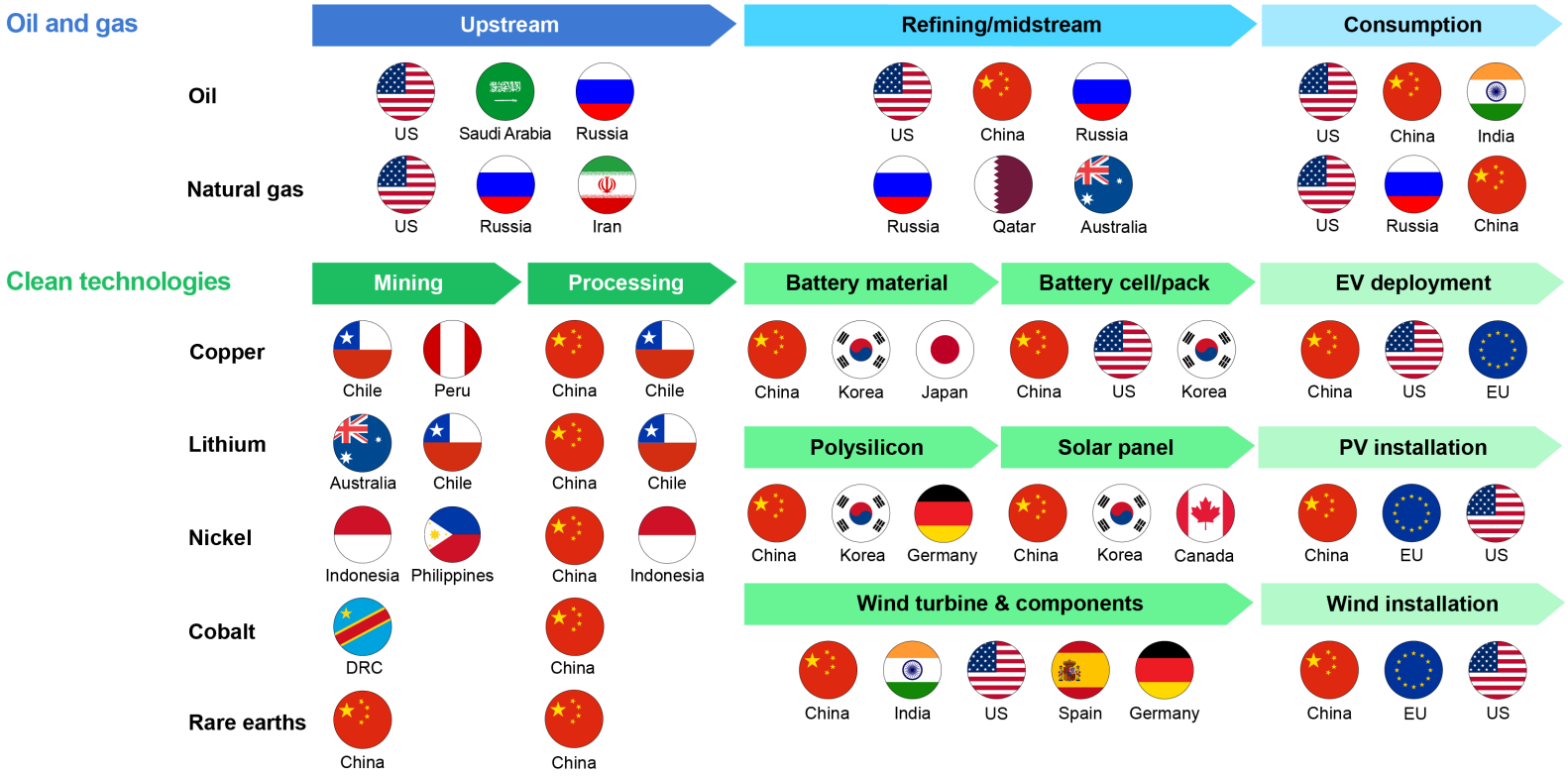
The types of mineral resources used vary by technology. Lithium, cobalt and nickel play a central role in giving batteries greater performance, longevity and higher energy density. Rare earth elements are used to make powerful magnets that are vital for wind turbines and EVs. Electricity networks need a huge amount of copper and aluminium. Hydrogen electrolysers and fuel cells require nickel or platinum group metals depending on the technology type. Copper is an essential element for almost all electricity-related technologies.

These characteristics of a clean energy system imply a significant increase in demand for minerals as more batteries, solar panels, wind turbines and networks are deployed. It also means that the energy sector is set to emerge as a major force in driving demand growth for many minerals, highlighting the strengthening linkages between minerals and clean energy technologies.

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The transition to a clean energy system brings new energy trade patterns, countries and geopolitical considerations into play

Indicative supply chains of oil and gas and selected clean energy technologies



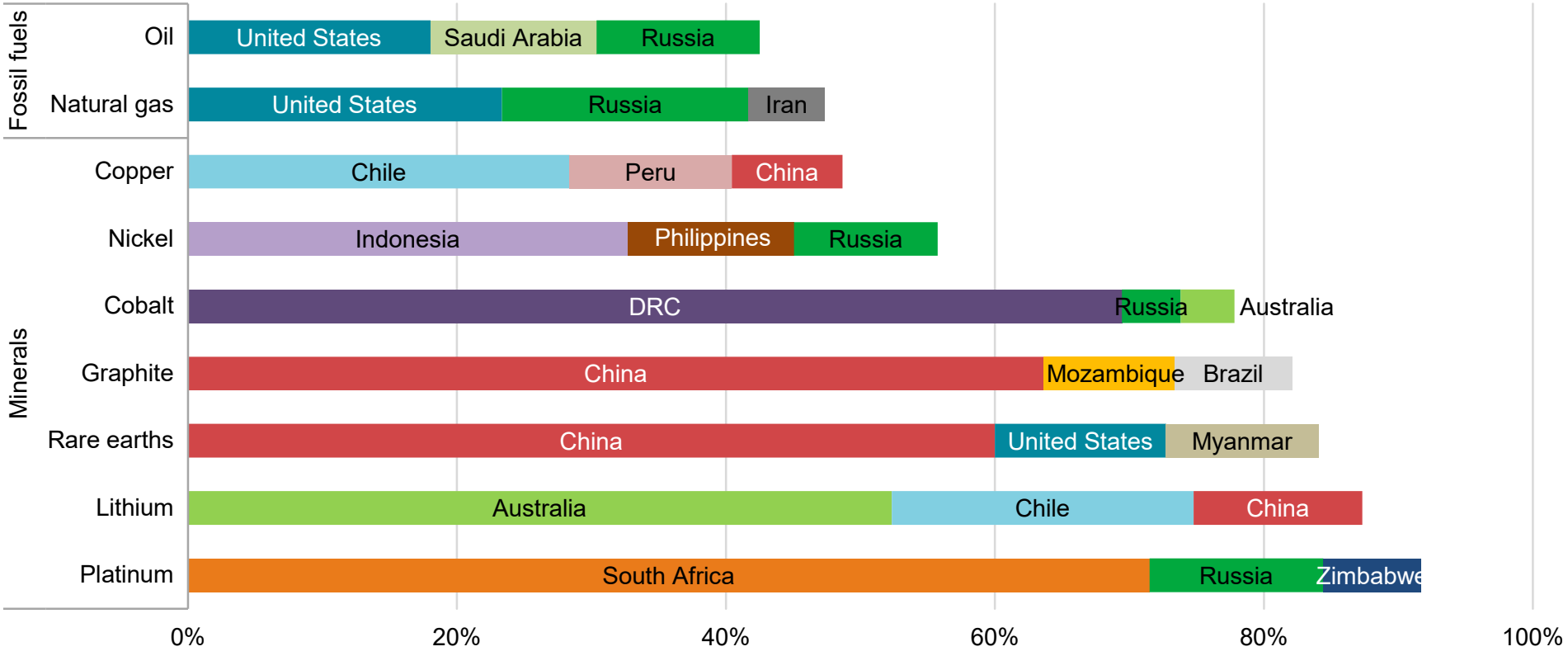
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Notes: DRC = Democratic Republic of the Congo; EU = European Union; US = United States; Russia = Russian Federation; China = People's Republic of China. Largest producers and consumers are noted in each case to provide an indication, rather than a complete account.

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Current production of many energy transition minerals is more geographically concentrated than that of oil or natural gas

Share of top three producing countries in total production for selected minerals and fossil fuels, 2019



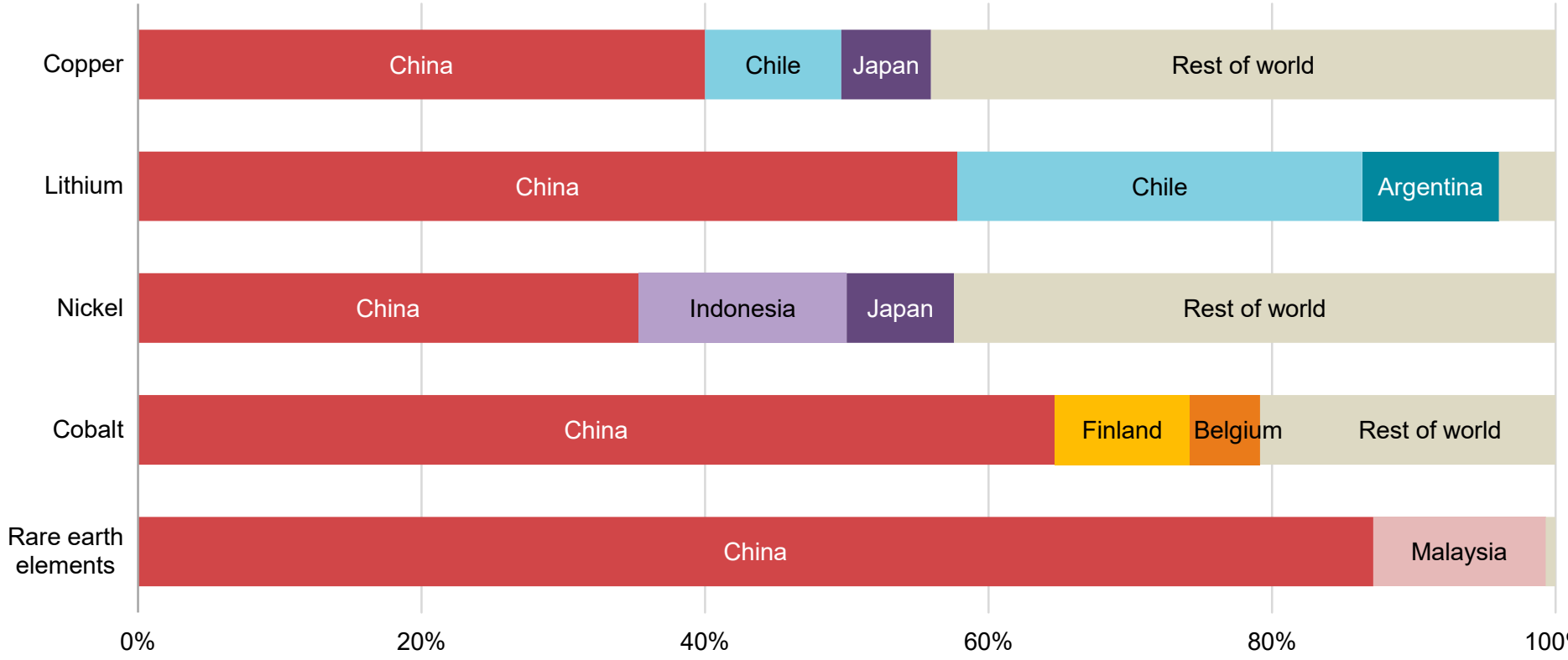
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Sources: IEA (2020b); USGS (2021).

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The level of concentration is similarly high for processing operations, with China's significant presence across the board

Share of processing volume by country for selected minerals, 2019



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Note: The values for copper are for refining operations.

Sources: World Bureau of Metal Statistics (2020); Adamas Intelligence (2020) for rare earth elements.

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Robust and resilient clean energy supply chains are essential, especially for critical minerals

Today's international energy security mechanisms are designed to provide some insurance against the risks of disruption, price spikes and geopolitical events in the supply of hydrocarbons, oil in particular. These concerns do not disappear during energy transitions as more solar panels, wind turbines and electric cars are deployed. However, alongside the many benefits of clean energy transitions, they also raise additional questions about the security and resilience of clean energy supply chains, which policy makers need to address.

Compared with fossil fuel supply, the supply chains for clean energy technologies can be even more complex (and in many instances, less transparent). In addition, the supply chain for many clean energy technologies and their raw materials is more geographically concentrated than that of oil or natural gas. This is especially the case for many of the minerals that are central to manufacturing clean energy technology equipment and infrastructure.

For lithium, cobalt and rare earth elements (REEs), the top three producing nations control well over three-quarters of global output. In some cases, a single country is responsible for around half of worldwide production. South Africa and the Democratic Republic of the Congo are responsible for some 70% of global production of platinum and cobalt respectively, and China accounted for 60% of global REE production in 2019 (albeit down from over 80% in the mid-2010s). The picture for copper and nickel is slightly more diverse, but still around half of global supply is concentrated in the top three producing countries.

The level of concentration is even higher for processing and refining operations. China has gained a strong presence across the board. China's share of refining is around 35% for nickel (the figure becomes higher when including the involvement of Chinese companies in Indonesian operations), 50-70% for lithium and cobalt, and as high as 90% for REE processing that converts mined output into oxides, metals and magnets.

This creates sources of concern for companies that produce solar panels, wind turbines, electric motors and batteries using imported minerals, as their supply chains can quickly be affected by regulatory changes, trade restrictions or political instability in a small number of countries. The Covid-19 pandemic already demonstrated the ripple effects that disruptions in one part of the supply chain can have on the supply of components and the completion of projects.

The implications of any potential supply disruptions are not as widespread as those for oil and gas (see Box 1.1). Nonetheless, trade patterns, producer country policies and geopolitical considerations remain crucial even in an electrified, renewables-rich energy system.

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Box 1.1. Oil security vs mineral security

Minerals are increasingly recognised as essential to the good functioning of an evolving energy system, moving into a realm where oil has traditionally occupied a central role. There are similarities, in that threats to reliable supply can have far-reaching consequences throughout the energy system. So traditional concerns over oil security (e.g. unplanned supply disruption or price spikes) are relevant for minerals as well.

However, fundamental differences exist in the impacts that disruption may have. An oil supply crisis, when it happens, has broad repercussions for all vehicles that run on it. Consumers driving gasoline cars or diesel trucks are immediately affected by higher prices.

By contrast, a shortage or spike in the price of a mineral required for producing batteries and solar panels affects only the supply of new EVs or solar plants. Consumers driving existing EVs or using solar-powered electricity are not affected. The main threats from supply disruptions are delayed and more expensive energy transitions, rather than disturbed daily lives.

Notably, oil burns up when it is used, requiring continuous inputs to run assets. However, minerals are a component of infrastructure, with the potential to be recovered and recycled at the end of the infrastructure lifetime (Hastings-Simon and Bazilian, 2020).

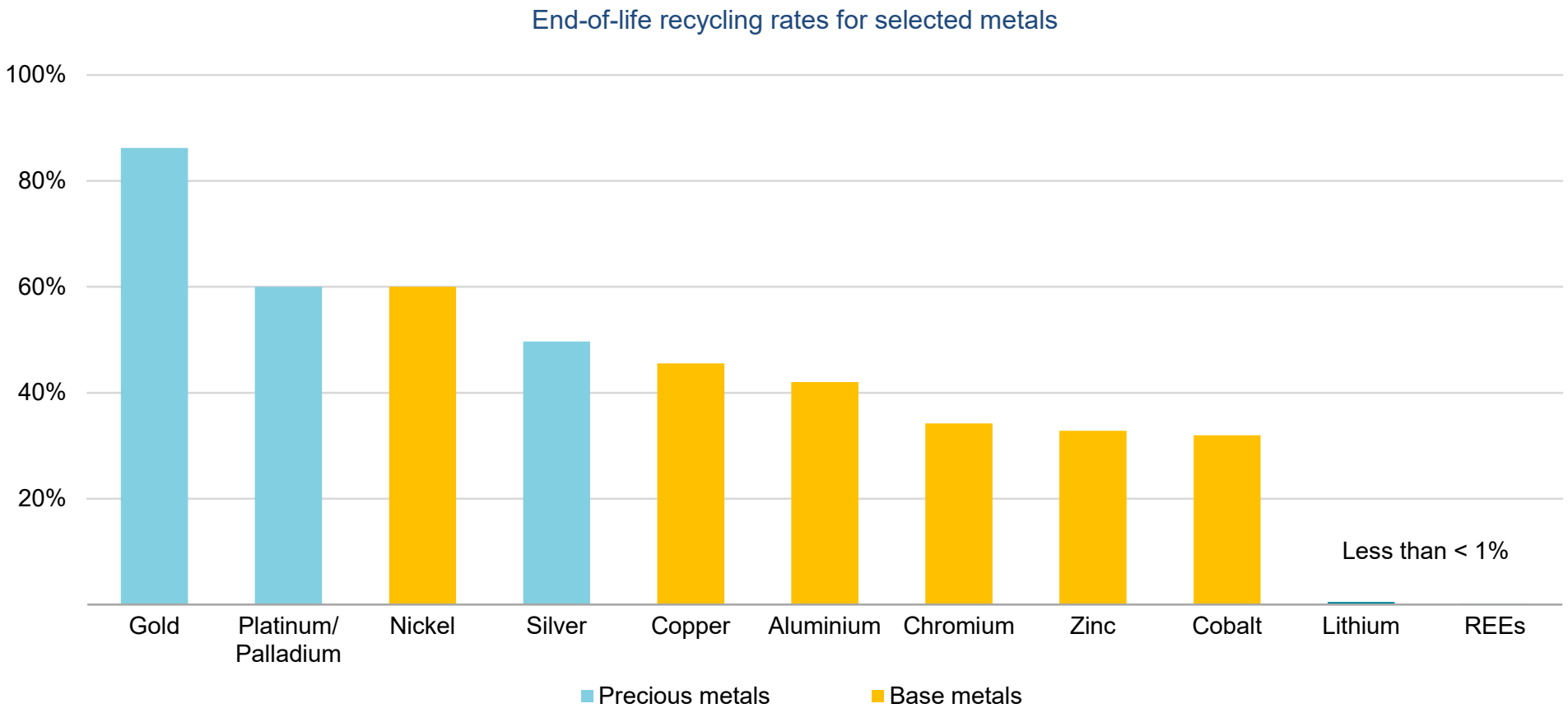
Moreover, while oil is a single commodity with a large, liquid global market, there are multiple minerals now in play for the energy sector, each with its own complexities and supply dynamics. Individual countries may have very different positions in the value chain for each of the minerals that are now rising in prominence in the global energy debate.

Despite these differences, the experience of oil markets may offer a number of lessons for an approach to mineral security. The approach to safeguarding oil security tended to focus on supply-side measures. Strategic stockholding has long been at the centre of the IEA's efforts to ensure oil market security. However, the framework for oil security has evolved over time to encompass demand and resilience aspects, including efforts to identify immediate areas of demand restraint, improve fuel efficiency and review countries' preparedness against potential disruption.

This range of responses and measures provides valuable context for the discussion on minerals security. While supply-side measures (e.g. ensuring adequate investment in production) remain crucial, these need to be accompanied by efforts to promote more efficient use of minerals, assess the resilience of supply chains, and encourage wider use of recycled materials, to be more effective.

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Today's recycling rates vary by metal depending on the ease of collection, price levels and market maturity



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Sources: Henckens (2021); UNEP (2011) for aluminium; Sverdrup and Ragnarsdottir (2016) for platinum and palladium; OECD (2019) for nickel and cobalt.

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Scaling up recycling can bring significant security benefits, although the need for continued investment in primary supply remains

One of the major differences between oil and minerals lies in the way that they are used and recovered in the energy system. Unlike oil, which is combusted on an ongoing basis, minerals and metals are permanent materials that can be reused and recycled continuously with the right infrastructure and technologies in place. Compared with oil, this offers an additional lever to ensure reliable supplies of minerals by keeping them in circulation as long as possible.

The level of recycling is typically measured by two indicators. End-of-life (EOL) recycling rates measure the share of material in waste flows that is actually recycled. Recycling input rates (also called recycled content rates) assess the share of secondary sources in total supply. EOL recycling rates differ substantially by metal. Base metals used in large volumes such as copper, nickel and aluminium have achieved high EOL recycling rates (Henckens, 2021). Precious metals such as platinum, palladium and gold have also achieved higher rates of recycling due to very high global prices encouraging both collection and product recycling. Lithium, however, has almost no global recycling capabilities due in part to limited collection and technical constraints (e.g. lithium reactivity in thermodynamic and metallurgic recycling), with a similar picture for REEs. There are also regional variances: around 50% of total base metal production in the European Union is supplied via secondary production, using recycled metals, as opposed to 18% in the rest of the world (Eurometaux, 2019).

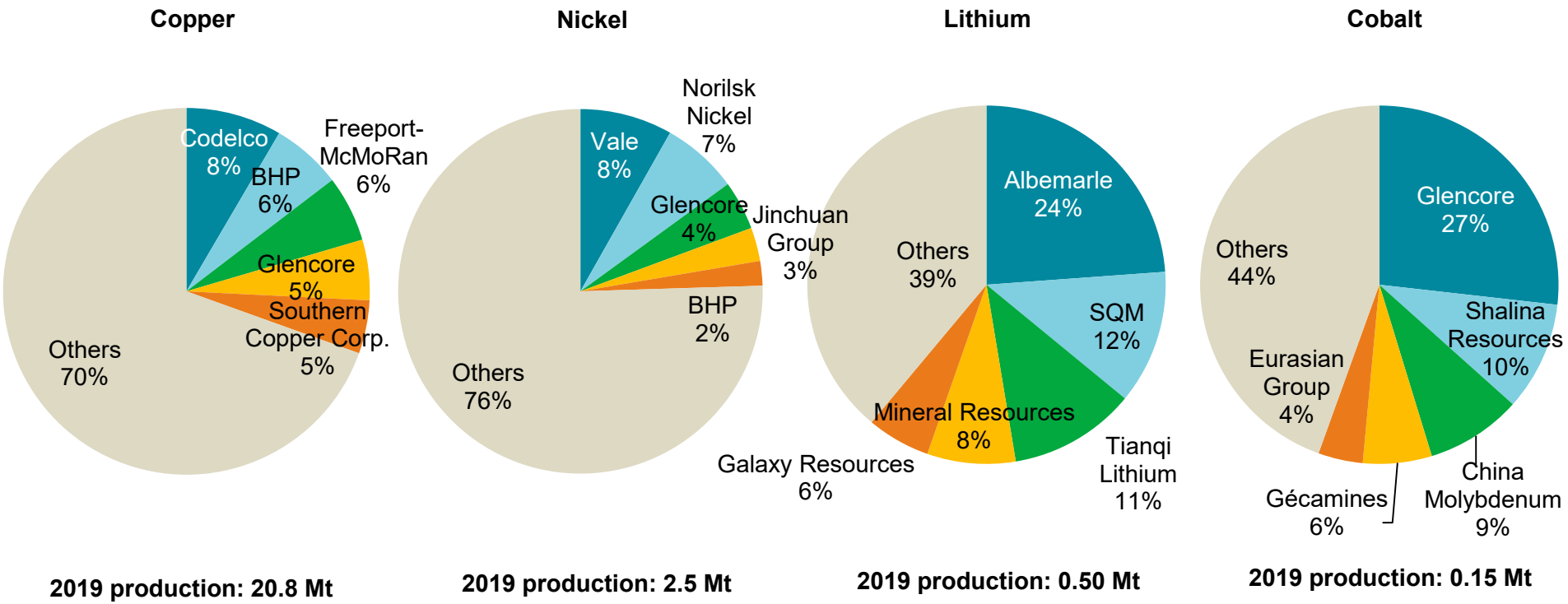
Recycling does not eliminate the need for continued investment in primary supply of minerals. A World Bank study suggests that new investment in primary supply will still be needed even in the case that EOL recycling rates were to reach 100% by 2050. (World Bank, 2020). However, recycling can play an important role in relieving the burden on primary supply from virgin materials at a time when demand starts to surge. For example, the amount of spent EV batteries reaching the end of their first life is expected to grow exponentially after 2030 in the SDS, offering the potential to reduce the pressure on investment for primary supply (see Chapter 3).

Although various commercial and environmental challenges exist, the competitiveness of the recycling industry is set to improve over time with economies of scale and technology improvement as more players enter the field. Their relative advantages are likely to be further supported by potential upward pressure on production costs for virgin resources. Also, regions with greater deployment of clean energy technology stand to benefit from far greater economies of scale. This highlights the sizeable security benefit that recycling can bring to importing regions and underscores the need to incorporate a circular approach in the mineral security framework.

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Companies that mine and process minerals have a major role to play in clean energy transitions

Major mining companies that produce selected energy transition minerals, 2019



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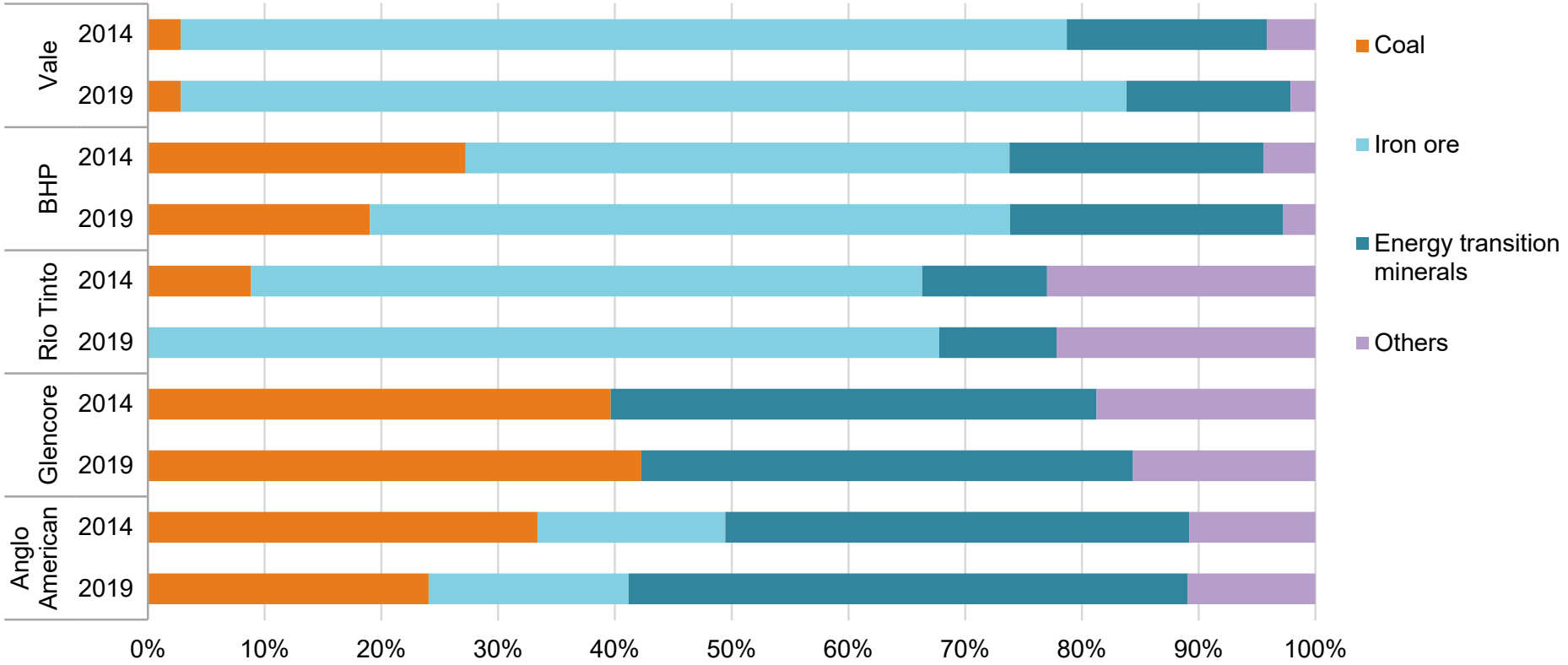
Notes: Mt = million tonnes. Glencore's cobalt production volume includes output from Katanga Mining Ltd. Shalina Resources' cobalt production volume includes output of Chemaf. Lithium production volumes are denoted on a lithium carbonate-equivalent basis.

Source: S&P Global (2021).

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Some mining majors have reduced coal exposure in recent years, although a decisive shift towards the minerals required for energy transitions is not yet visible

Production portfolio value of selected diversifed major mining companies, 2014 and 2019



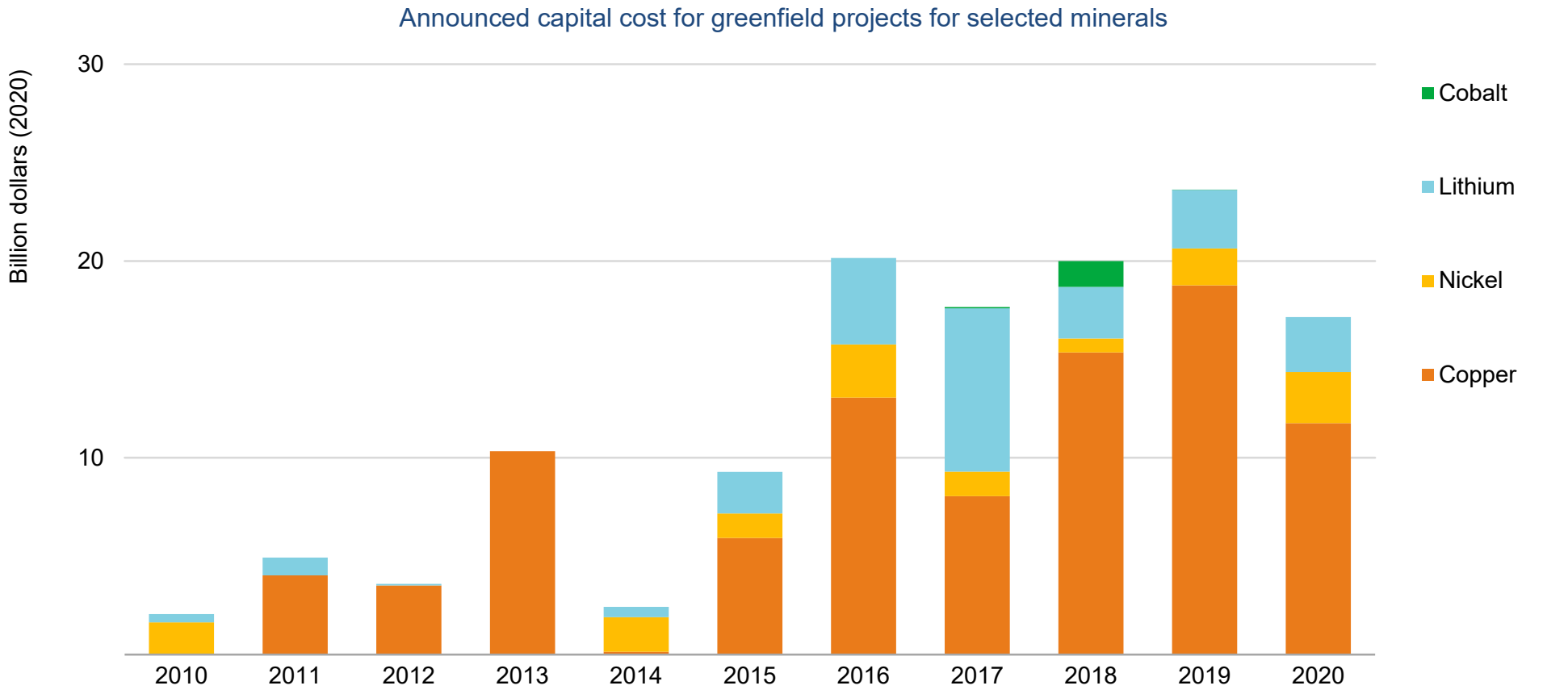
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Notes: Energy transition minerals include copper, lithium, nickel, cobalt, manganese, molybdenum and platinum-group metals. The value of the 2014 production portfolio was estimated using 2019 prices to remove price effects.

Source: IEA analysis based on companies' annual reports and S&P Global (2021).

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Investment in new mineral supply projects has been on an upward path…



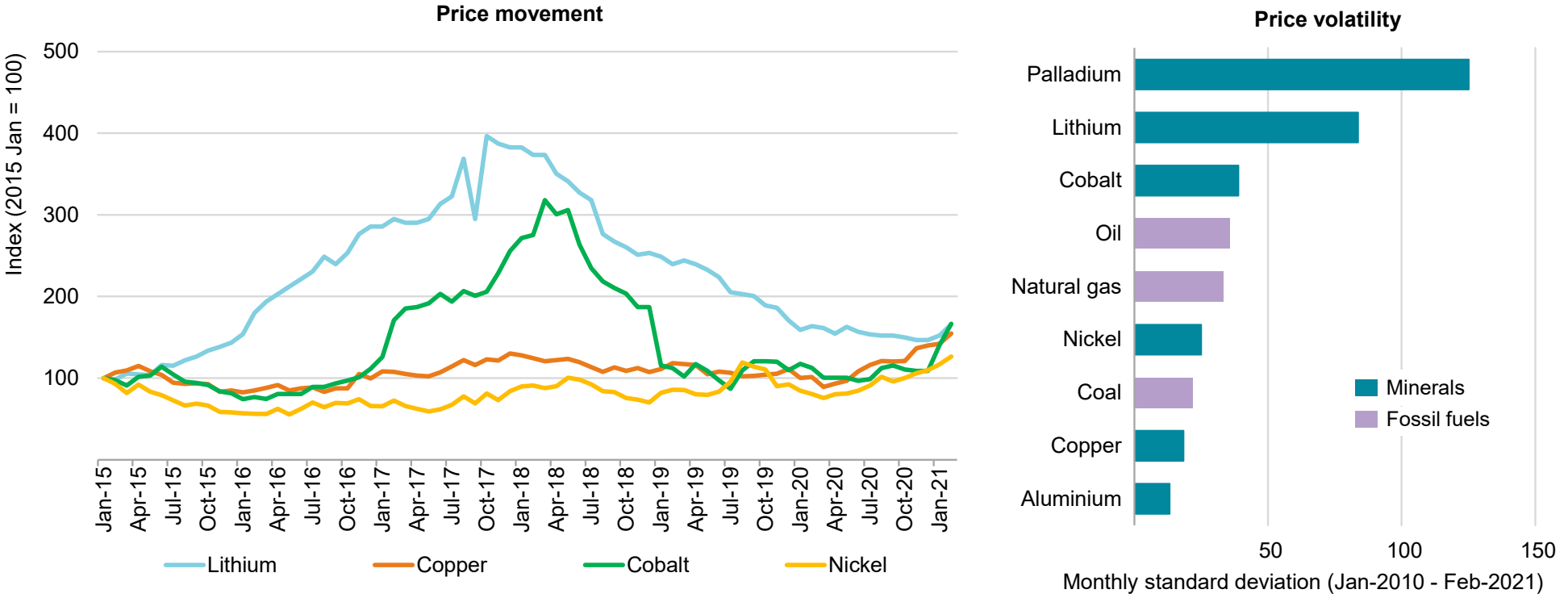
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Notes: Capital cost for cobalt includes only those projects whose primary commodity is cobalt. The figures do not include sustaining capital expenditure.
Source: S&P Global (2021).

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…but continued investment is needed to manage new price cycles and volatility

Price movement and volatility of selected minerals



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Notes: Assessment based on Lithium Carbonate CIF Asia, LME Copper Grade A Cash, LME Cobalt Cash and LME Nickel Cash prices.
Source: IEA (2020a), S&P Global (2021).

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Exploitation of mineral resources gives rise to a variety of environmental and social implications that must be carefully managed to ensure reliable supplies

Selected environmental and social challenges related to energy transition minerals

Areas of risks		Description
Environment	Climate change	• With higher greenhouse gas emission intensities than bulk metals, production of energy transition minerals can be a significant source of emissions as demand rises • Changing patterns of demand and types of resource targeted for development pose upward pressure
	Land use	• Mining brings major changes in land cover that can have adverse impacts on biodiversity • Changes in land use can result in the displacement of communities and the loss of habitats that are home to endangered species
	Water management	• Mining and mineral processing require large volumes of water for their operations and pose contamination risks through acid mine drainage, wastewater discharge and the disposal of tailings • Water scarcity is a major barrier to the development of mineral resources: around half of global lithium and copper production are concentrated in areas of high water stress
	Waste	• Declining ore quality can lead to a major increase in mining waste (e.g. tailings, waste rocks); tailings dam failure can cause large-scale environmental disasters (e.g. Brumadinho dam collapse in Brazil) • Mining and mineral processing generate hazardous waste (e.g. heavy metals, radioactive material)
Social	Governance	• Mineral revenues in resource-rich countries have not always been used to support economic and industrial growth and are often diverted to finance armed conflict or for private gain • Corruption and bribery pose major liability risks for companies
	Health and safety	• Workers face poor working conditions and workplace hazards (e.g. accidents, exposure to toxic chemicals) • Workers at artisanal and small-scale mine (ASM) sites often work in unstable underground mines without access to safety equipment
	Human rights	• Mineral exploitation may lead to adverse impacts on the local population such as child or forced labour (e.g. children have been found to be present at about 30% of cobalt ASM sites in the DRC) • Changes in the community associated with mining may also have an unequal impact on women

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Clean energy transitions offer opportunities and challenges for companies

As the world moves from fuel-intensive systems to more material-intensive systems, companies that produce minerals and metals provide an essential bridge between resources in the ground and the energy technologies that consumers need. As such, there is large scope for mining and refining companies to contribute to orderly clean energy transitions by ensuring adequate supply of minerals. These projects will inevitably be subject to strong scrutiny of their social and environmental performance.

Many of the large mining companies are already involved in the energy sector, as producers of coal. Energy transitions therefore present a challenge, as well as an opportunity, as companies respond to rising stakeholder pressure to clarify the implications of energy transitions for their operations and business models. Some of these companies are already moving away from coal. Rio Tinto entirely exited the coal business in recent years and other companies are heading in a similar direction, largely through reducing thermal coal production. Although there has been growing participation in copper production in recent years, they have yet to make a concerted move into energy transition minerals.

Despite the prospects offered by energy transitions, until recently companies were quite cautious about committing significant capital to new projects; this is largely because of uncertainties over the timing and extent of demand growth (linked to questions about the real commitment of countries to their climate ambitions) as well as the complexities involved in developing high-quality projects.

The picture is starting to change, as countries have sent stronger signals about their net-zero ambitions, and price signals for some minerals in 2017-2018 offered greater encouragement. Investment in new projects picked up in the latter part of the 2010s (although there was a Covid-induced fall in 2020). This trend would need to be sustained in order to support ample supply, although the risk of boom and bust cycles is ever-present for commodities that feature long lead-times from project planning to production (see Chapter 3).

Prices for minerals tend to be volatile, often more so than for traditional hydrocarbons, due to the mismatch between the pace of changes in demand patterns and that of new project development, and also to the opacity of supply chains. In the late 2010s, prices for minerals with relatively smaller markets – such as lithium and cobalt – recorded a dramatic increase in a short time as the adoption of EVs started to grow in earnest. Although prices have since dropped, as higher prices triggered a swathe of supply expansions (in the form of ASMs for cobalt), this has been a wake-up call about possible strains on supply and market balance. This provides additional reasons for policy makers to be vigilant about this critical aspect of a clean energy future.

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Mineral requirements for clean energy transitions

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Introduction

Minerals and metals[1] have played a critical role in the rise of many of the clean energy technologies that are widely used today – from wind turbines and solar panels to electric vehicles and battery storage. As the deployment of clean energy technology rises, the energy sector is also becoming a vital part of the minerals and metals industry. With clean energy transitions, the linkages between minerals and energy are set to strengthen.

However, this raises the question: will sufficient sustainable and responsibly sourced mineral supplies be available to support the acceleration of energy transitions? The first step to address this is to understand the potential requirements for minerals arising from clean energy transitions.

The type and volume of mineral needs vary widely across the spectrum of clean energy technologies, and even within a certain technology (e.g. wind turbine technologies; EV battery chemistries). In this chapter we assess the aggregate mineral demand from a wide range of clean energy technologies – low-carbon power generation (renewables and nuclear), electricity networks, electric vehicles (EVs), battery storage and hydrogen (electrolysers and fuel cells) – under two main IEA scenarios: the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS).

For each of the clean energy technologies, we estimate overall mineral demand using four main variables: clean energy deployment trends under different scenarios; sub-technology shares within each technology area; mineral intensity of each sub-technology; and mineral intensity improvements.[2] The first two variables were taken from the projections in the *World Energy Outlook 2020*, complemented by the results in the *Energy Technology Perspectives 2020*.

We compiled the mineral intensity assumptions through extensive literature review, and expert and industry consultations, including with IEA Technology Collaboration Programmes. The pace of mineral intensity improvements varies by scenario, with the STEPS generally seeing minimal improvement over time as compared to modest improvement (around 10% in the longer term) assumed in the SDS. In areas that may particularly benefit from economies of scale or technology improvement (e.g. silicon and silver use in solar photovoltaic [PV], platinum loading in fuel cells, rare earth element

[1] This report considers a wide range of minerals and metals used in clean energy technologies, including chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, rare earth elements and others (see Annex for the complete list). Steel and aluminium are not included in the scope for demand assessment, but aluminium use in electricity networks is exceptionally assessed given that the outlook for copper is closely linked with aluminium use in grid lines (see Introduction).

[2] See Annex for methodologies and data sources.

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[REE] use in wind turbines), we applied specific improvement rates based on the review of underlying drivers.

Projected mineral demand is subject to considerable uncertainty. It is highly dependent on the stringency of climate policies (reflected in the difference between the STEPS and SDS), but also on different technology development pathways. As such, in addition to our base assumptions for technology development pathways ("base case") in both the STEPS and SDS, we identified key variables for each technology that could drive mineral demand in different directions. We then built 11 alternative cases under both scenarios to quantify the impacts of varying technology evolution trends.

Alternative technology evolution pathways explored

Technology	Alternative cases
Solar PV	• Comeback of high cadmium telluride • Faster adoption of perovskite solar cells • Wider adoption of gallium arsenide technology
Wind	• Constrained REE supply
Electricity networks	• Increased use of aluminium in underground cables • Wider adoption of direct-current systems
EVs	• Delayed shift to nickel-rich cathodes • More rapid move towards a silicon-rich anode • Faster uptake of lithium metal anode all-solid-state batteries
Battery storage	• Rapid adoption of home energy storage • Early commercialisation of vanadium flow batteries

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While our report focuses on projecting mineral requirements for clean energy technologies, for the five focus minerals – copper, lithium, nickel, cobalt and neodymium (as a representative for REEs) – it also assesses demand from other sectors. This is to understand the contribution of clean energy technologies to overall demand and better assess supply-side challenges. We projected mineral demand for other sectors using historical consumption by end-use applications, relevant activity drivers (e.g. GDP, industry value added, vehicle activities, steel production) and material intensities (see Annex: Scope and methodology).

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Mineral needs vary widely across clean energy technologies

Critical mineral needs for clean energy technologies

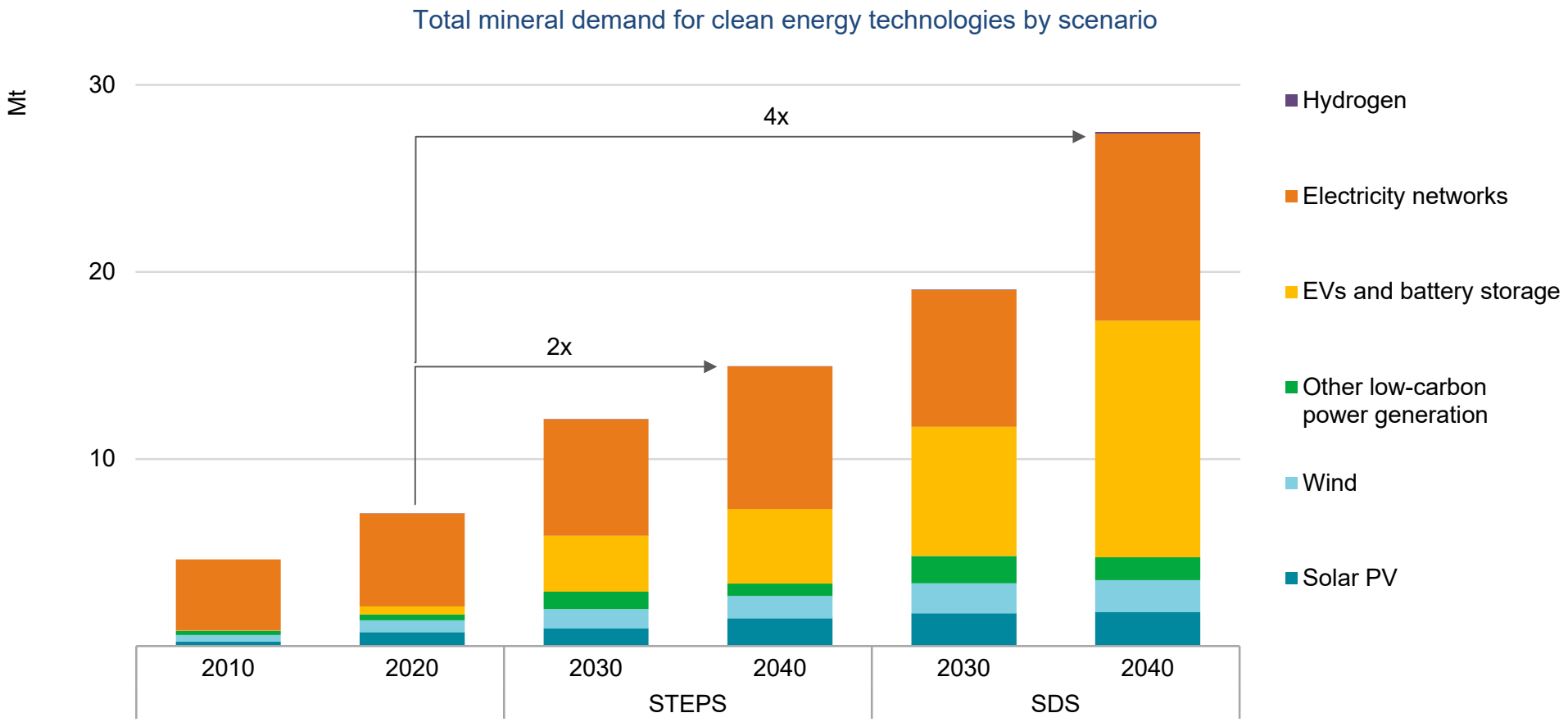
	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	◍	○	●	◍	●	○	◍
Hydro	◍	○	○	○	○	◍	◍	○	◍
CSP	◍	○	◍	○	○	●	◍	○	●
Bioenergy	●	○	○	○	○	○	◍	○	◍
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	◍	○	◍	○	○	◍	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	◍	○	○	●	◍

Notes: Shading indicates the relative importance of minerals for a particular clean energy technology (● = high; ◍ = moderate; ○ = low), which are discussed in their respective sections in this chapter. CSP = concentrating solar power; PGM = platinum group metals.

* In this report, aluminium demand is assessed for electricity networks only and is not included in the aggregate demand projections.

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Total mineral demand from clean energy technologies is set to double in the STEPS and quadruple in the SDS by 2040



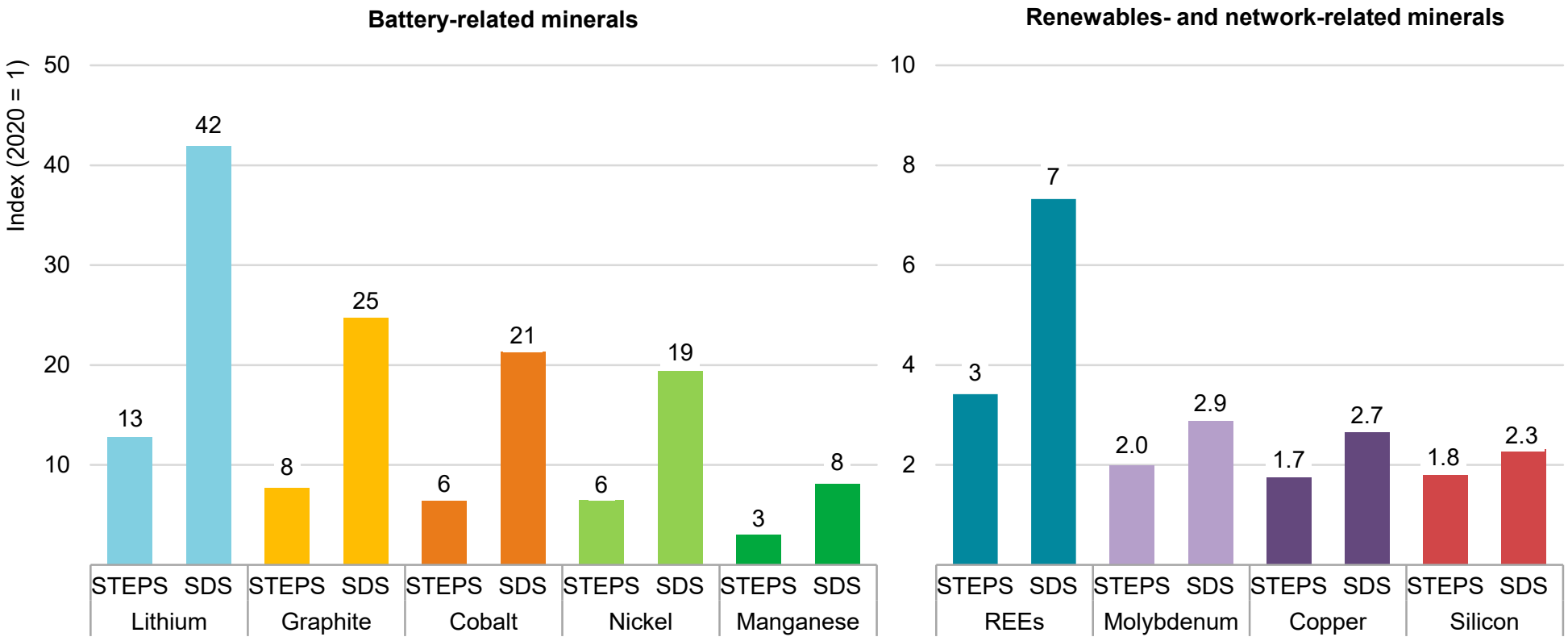
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Notes: Includes all minerals in the scope of this report, including chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, REEs and others, but does not include steel and aluminium (see Annex for a full list of minerals). Mt = million tonnes.

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The relative demand growth is particularly high for battery-related minerals

Growth in demand for selected minerals from clean energy technologies in 2040 relative to 2020 levels

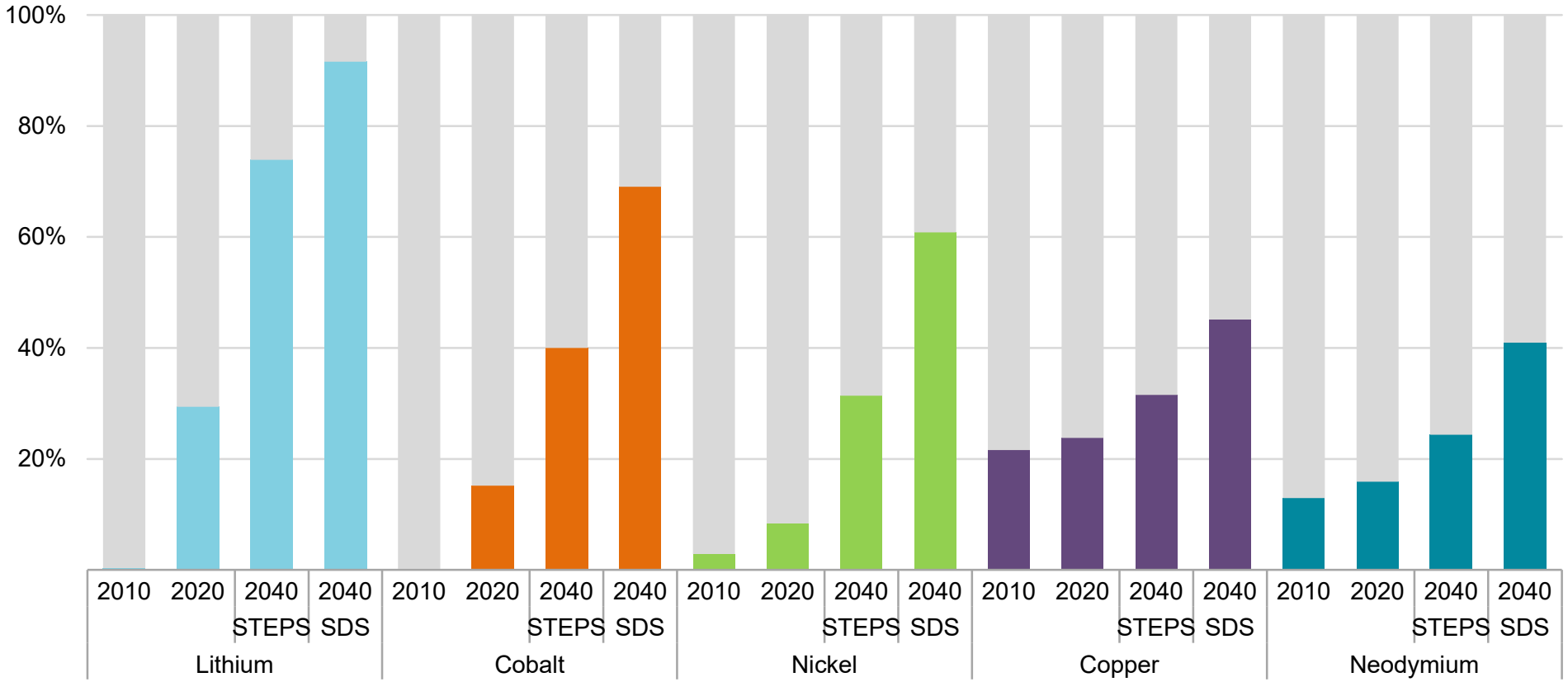


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Clean energy technologies are set to emerge as a major force in driving demand growth for critical minerals

Share of clean energy technologies in total demand for selected minerals



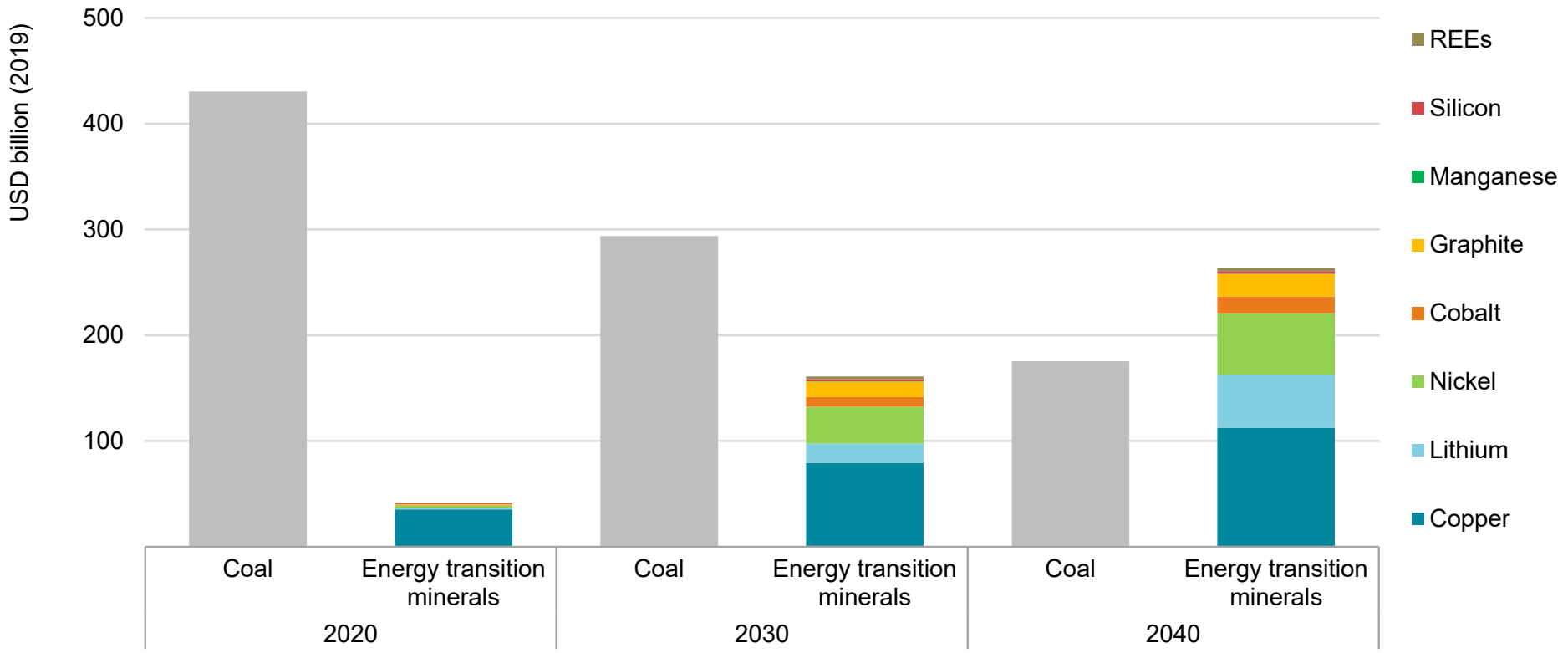
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Note: Demand from other sectors was assessed using historical consumption, relevant activity drivers and the derived material intensity.

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Changing fortunes: Coal vs energy transition minerals

Revenue from production of coal and selected energy transition minerals in the SDS



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Notes: Revenue for energy transition minerals includes only the volume consumed in clean energy technologies, not total demand. Future prices for coal are projected equilibrium prices in *WEO 2020* SDS. Prices for energy transition minerals are based on conservative assumptions about future price trends (moderate growth of around 10-20% from today's levels).

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Rising deployment of clean energy technologies is set to supercharge demand for critical minerals

The global clean energy transitions will have far-reaching consequences for mineral demand over the next 20 years. By 2040 total mineral demand from clean energy technologies double in the STEPS and quadruple in the SDS.

EVs and battery storage account for about half of the mineral demand growth from clean energy technologies over the next two decades, spurred by surging demand for battery materials. Mineral demand for use in EVs and battery storage grows nearly tenfold in the STEPS and around 30 times in the SDS over the period to 2040. By weight, mineral demand in 2040 is dominated by copper, graphite and nickel. Lithium sees the fastest growth rate, with demand growing by over 40 times in the SDS. The shift towards lower cobalt chemistries for batteries helps to limit growth in cobalt, displaced by growth in nickel.

Electricity networks are another major driving force. They account for 70% of today's mineral demand from the energy technologies considered in this study, although their share continues to fall as other technologies – most notably EVs and storage – register rapid growth.

Mineral demand from low-carbon power generation grows rapidly, doubling in the STEPS and nearly tripling in the SDS over the period to 2040. Wind power plays a leading role in driving demand growth due to a combination of large-scale capacity additions and higher mineral intensity (especially with growing contributions from mineral-intensive offshore wind). Solar PV follows closely, with its unmatched scale of capacity additions among the low-carbon power generation technologies. Hydropower, biomass and nuclear make only minor contributions given their comparatively low mineral requirements and modest capacity additions.

The rapid growth of hydrogen use in the SDS underpins major growth in demand for nickel and zirconium for use in electrolysers, and for copper and platinum-group metals for use in fuel cell electric vehicles (FCEVs). Despite the rapid rise in FCEVs and the decline in catalytic converters in gasoline and diesel cars, demand for platinum-group metals in internal combustion engine cars remains higher than in FCEVs in the SDS in 2040.

Demand for REEs – primarily for EV motors and wind turbines – grows threefold in the STEPS and around sevenfold in the SDS by 2040.

For most minerals, the share of clean energy technologies in total demand was minuscule until the mid-2010s, but the picture is rapidly changing. Energy transitions are already the major driving force for total demand growth for some minerals. Since 2015 EVs and battery storage have surpassed consumer electronics to become the largest

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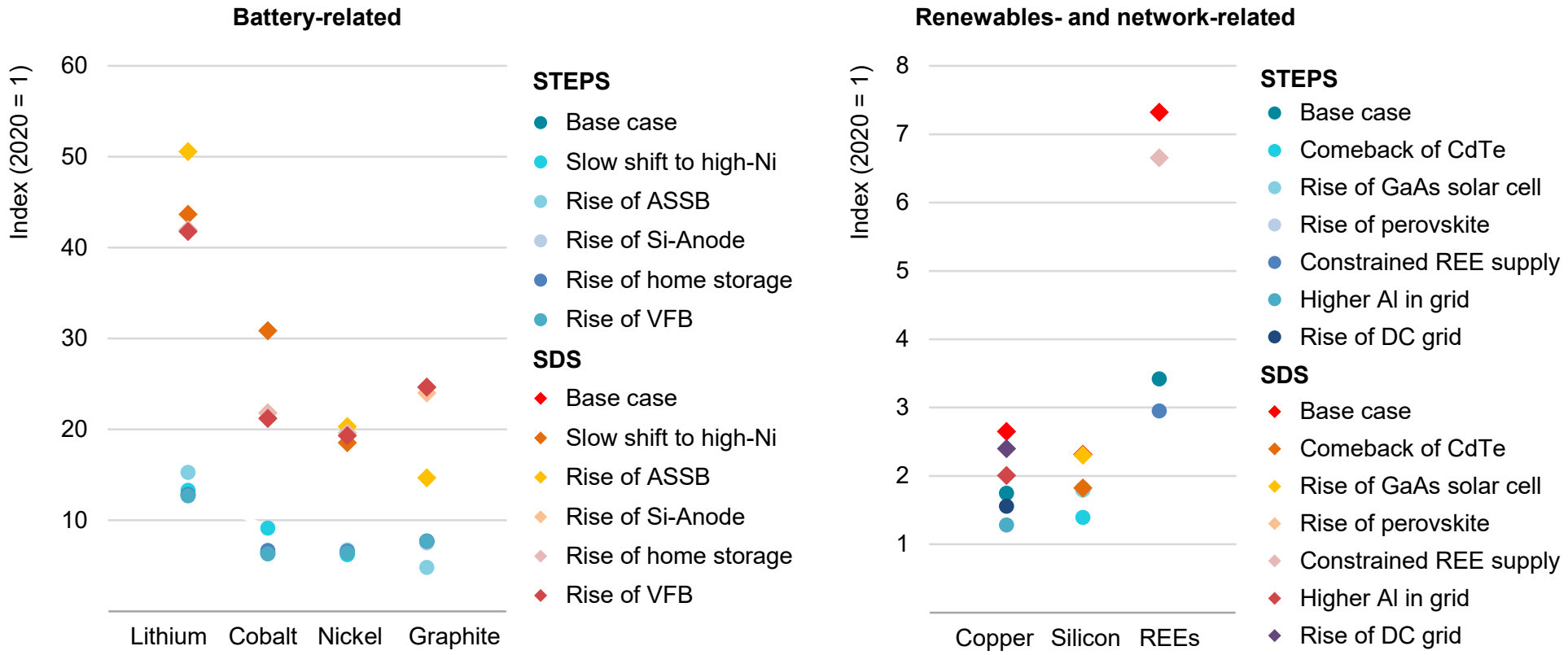
consumers of lithium, together accounting for 30% of total current demand. This trend is set to accelerate as countries step up their climate ambitions. Clean energy technologies become the fastest-growing segment of demand for most minerals, and their share of total demand edges up to over 40% for copper and REEs, 60-70% for nickel and cobalt and almost 90% for lithium by 2040 in the SDS.

Assessments based on total mineral weights often do not adequately account for the significance of certain minerals. It is also useful to consider the revenue generated from producing the minerals, as there is a wide range in monetary value between minerals. Coal is currently the largest source of revenue for mining companies by a wide margin. Revenues from coal production are about ten times larger than those from producing minerals used in clean energy technologies. However, accelerating clean energy transitions are set to change this picture radically. In the SDS, coal's stronghold on the energy system is increasingly challenged by phase-out policies in many countries and also by the rise of renewables. By contrast, many energy transition minerals are likely to face a tailwind from growing demand and upward pressure on prices. This underpins a sharp reversal of fortunes between coal and energy transition minerals. In the SDS, the combined revenue from energy transition minerals (including only the volume used in the clean energy sector) overtakes that of coal by 2040.

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A wide range of futures are possible, mainly related to level of climate ambition and action, as well as technology uncertainties

Mineral demand from clean energy technologies in 2040 relative to 2020 under different scenarios and technology evolution trends



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Notes: Al = aluminium; ASSB = all-solid-state batteries; CdTe = cadmium telluride; DC = direct current; GaAs = gallium arsenide; Ni = nickel; Si = silicon; VFB = vanadium redox flow batteries.

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Strong climate ambitions can reduce uncertainties around demand evolution, thereby stimulating investment and reducing security risks

Demand projections are subject to large variations, which lead to a wide range of possible futures. According to our analysis of the scenarios and alternative cases, lithium demand in 2040 may be 13 times higher (if vanadium redox flow batteries rapidly penetrate the market in the STEPS) or 51 times higher (if all-solid-state batteries commercialise faster than expected in the SDS) than today's levels. Likewise, cobalt and graphite may see 6- to 30-times higher demand than today depending on the scenario that unfolds. Among non-battery materials, demand for REEs grows by seven times in the SDS, but growth may be as low as three times today's levels should wind companies tilt more towards turbines that do not use permanent magnets in the STEPS context.

These large uncertainties around possible futures may act as a factor that hampers companies' investment decisions, which could in turn cause supply-demand imbalances in the years ahead. Despite the promise of massive demand growth, mining and processing companies may be reluctant to commit large-scale investment given the wide range of possible demand trajectories.

However, the biggest source of demand variance does not come from technology. It comes instead from the uncertainty surrounding announced and expected climate ambitions – in other words, whether clean energy deployment and resulting mineral demand follows STEPS or SDS trajectories.

Here, governments have a key role to play in reducing uncertainty by sending strong and consistent signals about their climate ambitions and implementing specific policies to fulfil these long-term goals. The recent pickup in new project investments reflects the way that government climate commitments provide market signals for investments, which could help ensure reliable supply of minerals to support an orderly energy transition. The efforts also need to be accompanied by a range of measures to dampen the rapid growth in primary supply requirements such as promoting technology innovation for material efficiency or substitution, scaling up recycling and extending the lifetime of existing assets through better maintenance (see Chapter 3).

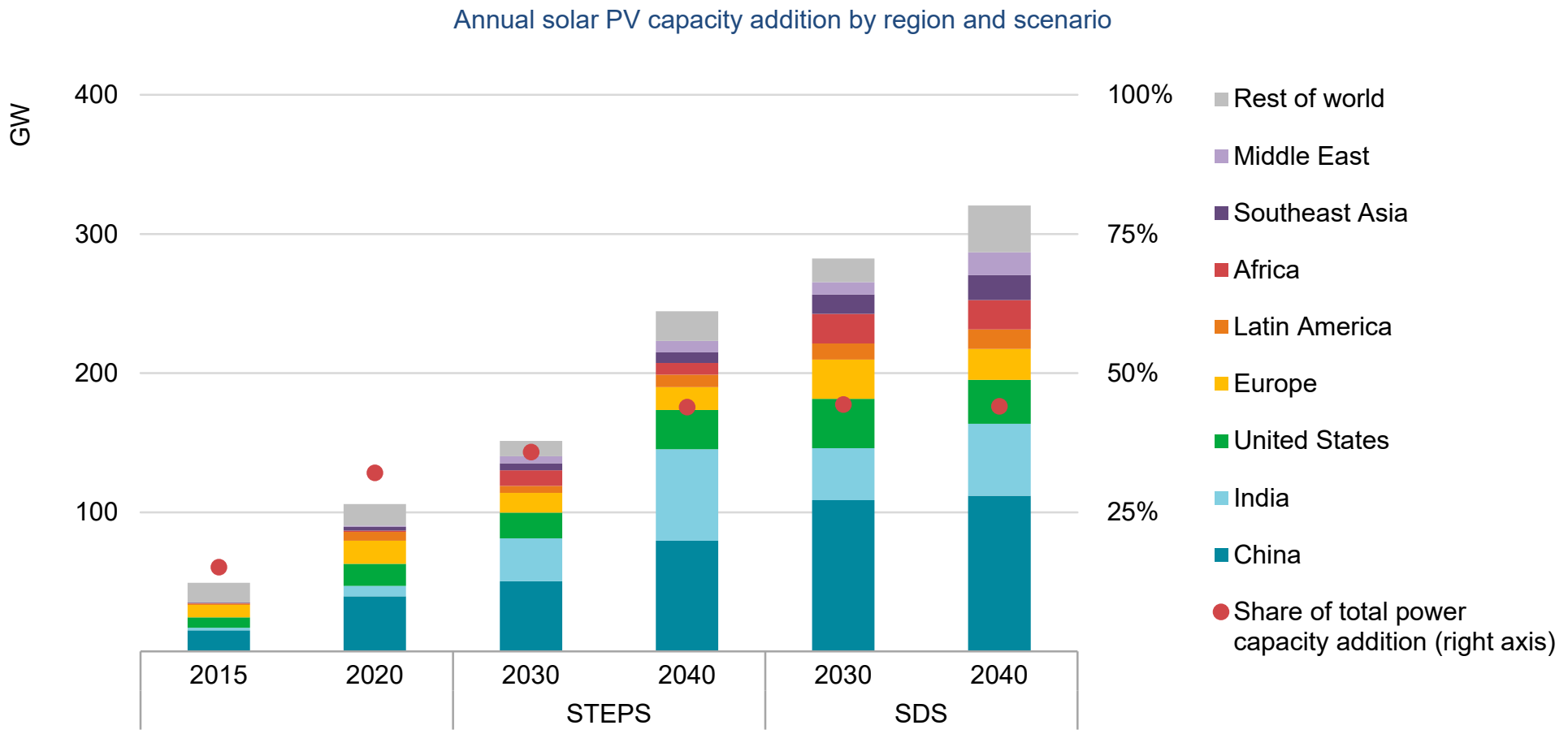
In the following sections we explore the mineral requirements for each clean energy technology under different scenarios and with varying trends in technology evolution.

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Low-carbon power generation

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Solar PV: Annual deployment of solar PV triples in the SDS by 2040, driven by huge growth in emerging economies



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Note: GW = gigawatt. China = People's Republic of China.
Source: IEA (2020c).

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Solar PV: Mineral use in solar PV varies widely by module type, currently dominated by crystalline silicon

Worldwide solar PV capacity has increased by almost 20 times over the past decade, spurred by declining costs and strong policy support in key regions (IEA, 2020c). With sharp cost reductions over the past decade, solar PV now offers some of the lowest levelised electricity costs in most countries, cheaper than new coal- or gas-fired power plants. In both the STEPS and SDS, solar sets new records for deployment each year after 2022, representing 45% of total power capacity additions by 2040. Innovation in solar PV technologies has also enabled remarkable advances in efficiency. For instance, the average module efficiency of commercial wafer-based silicon modules increased from about 12% to 17% in the past decade (Fraunhofer ISE, 2020), while cadmium telluride (CdTe) module efficiency doubled from 9% to 19%.

Solar PV plants are mainly composed of modules, inverters, trackers, mounting structures and general electrical components. For utility-scale solar PV plants, differences in mineral intensities come primarily from differences in module types. Crystalline silicon (c-Si) modules have become the dominant PV technology, followed by the "thin-film" alternatives: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si). By weight, c-Si PV panels typically contain about 5% silicon (solar cells), 1% copper (interconnectors), and less than 0.1% silver and other metals (IRENA, 2016). Thin-film technologies require more glass but less minerals overall than c-Si. CdTe and CIGS panels use no silver or silicon, but instead require cadmium and tellurium (CdTe) or indium, gallium and selenium (CIGS). Distributed solar PV systems tend to have string inverters or microinverters, requiring about 40% more copper than utility-scale projects, which typically use central inverters. Other mineral intensities are similar between utility-scale and distributed applications.

Innovation in the manufacturing and design of c-Si panels over the past decade has contributed to large reductions in materials intensity. Since 2008 silicon intensity has more than halved as wafer thickness diminished substantially (Fraunhofer ISE, 2020), while silver intensity fell by 80% thanks to more efficient and less silver-intensive metallisation pastes (ITRPV, 2020).

Since silicon and silver are among the most expensive elements in solar PV cells, advances in material intensity are expected to continue, with further assumed reductions of around 25% and 30% in 2030 for silicon and silver respectively. The intensities of other minerals are also expected to decrease as overall efficiency improves, including through the use of new technologies such as bifacial, n-type or half-cut cells, multi busbars, dual-glass modules and string inverters.

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Solar PV: Rapid deployment of solar PV in the SDS underpins more than doubling of mineral demand for solar PV by 2040 despite continued intensity reductions

c-Si modules dominate the solar PV market, accounting for 95% of global solar PV capacity additions in 2020. They are expected to continue to dominate over the coming decades, as costs continue to decrease with further automation and larger, more durable cells. In addition, innovation is improving c-Si cell efficiency with the development of passivating contacts, the switch to n-type materials, and multi-junction/tandem solar cells, which helps cement c-Si's leading position. Silicon-based cells can also be combined with perovskite technologies with the aim of addressing their instability/lifetime issue and lowering the barriers to mass production of perovskite solar cells.

In our base case, thin film technologies remain niche over the coming decades, despite seeing further efficiency gains and cost reductions. Their use may be limited to applications where lower weight and/or greater flexibility is required, mostly in distributed and building applications.

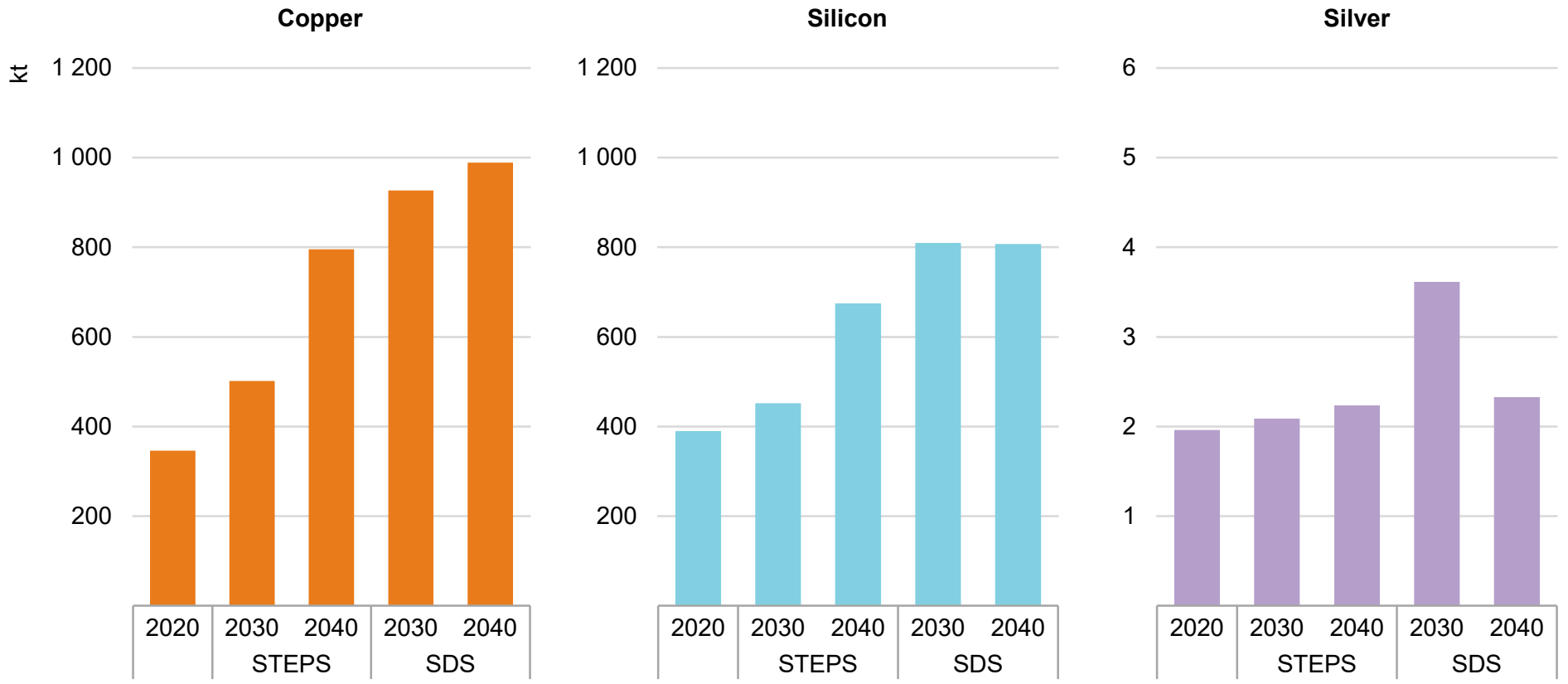
In the SDS, capacity additions in 2040 are triple those of 2020, resulting in a near tripling of copper demand from solar PV. Material intensity reductions help to significantly dampen demand growth for silver and silicon. Despite higher annual capacity additions, demand for silver and silicon is lower in 2040 than in 2030, and only 18% and 45% higher than in 2020.

Capacity additions in 2040 in the STEPS are 25% lower than in the SDS. However, slower assumed improvements in material intensity for silver and silicon offset the lower capacity additions, resulting in similar demand for silver and silicon in the two scenarios.

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Solar PV: Copper demand more than doubles by 2040, but continued innovation to reduce mineral intensity helps to offset demand growth for silicon and silver

Demand for copper, silicon and silver for solar PV by scenario



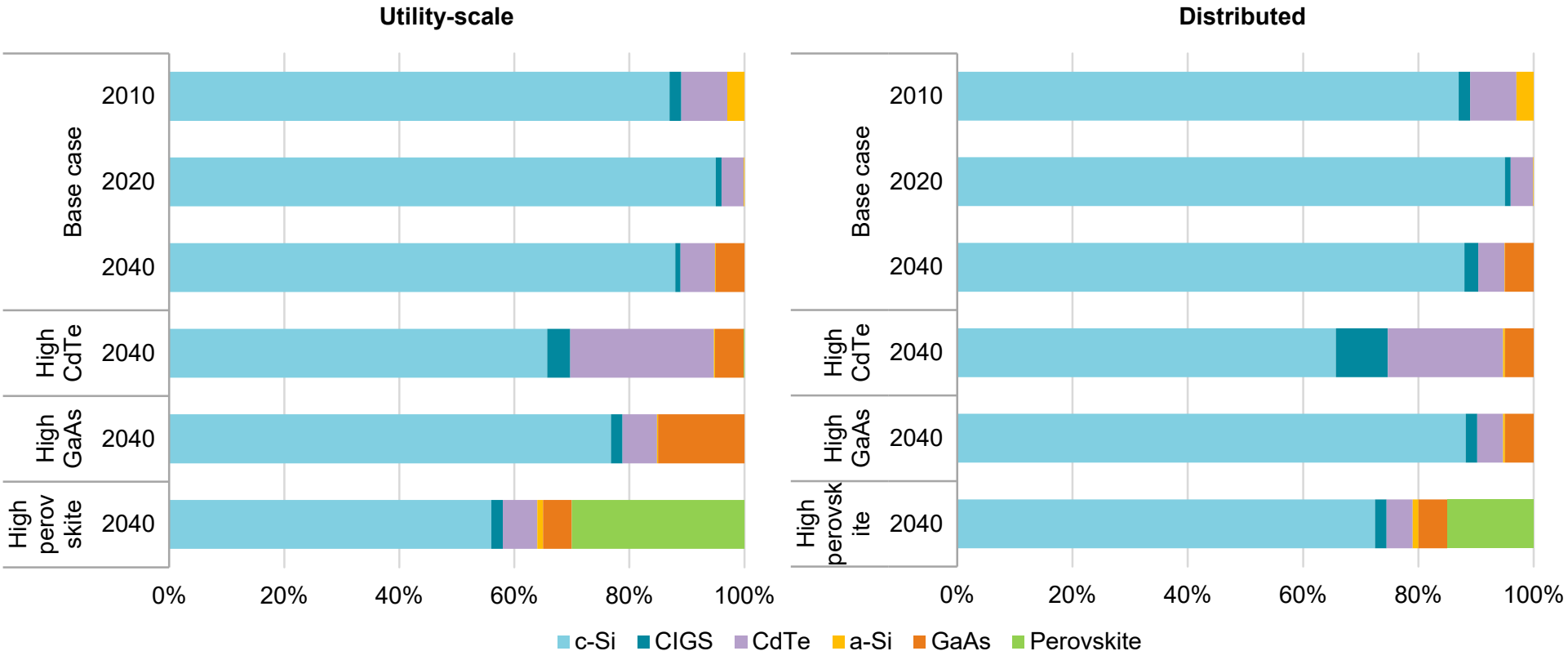
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Note: kt = thousand tonnes.

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Solar PV: Crystalline silicon is expected to remain the dominant PV technology, but further progress on alternative technologies could see them taking significant market share by 2040

Share of annual capacity additions by PV technology under different technology evolution scenarios



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Notes: c-Si = crystalline silicon; CIGS = copper indium gallium diselenide; CdTe = cadmium telluride; a-Si = amorphous silicon; GaAs = gallium arsenide.

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Solar PV: Demand for silicon falls in the alternative cases, but demand for other semiconductor materials rises

While c-Si modules are expected to continue to dominate the solar PV market, further progress on alternative technologies could see these technologies achieving growing market shares by 2040, which we explore in three alternative cases: high CdTe, high perovskite, and high GaAs.

High CdTe case

Further progress in CdTe technologies could lead to higher cell efficiency, longer lifetimes and reduced costs. The High CdTe scenario sees mass production of CdTe cells starting around 2030. The penetration of CdTe would be faster in distributed applications, where their lower weight and higher flexibility are an advantage.

In the High CdTe scenario, demand for cadmium and tellurium grows sevenfold by 2040 in the SDS to 1 300 tonnes and 1 400 tonnes respectively. This rapid growth would put pressure on supply capacities, which are currently around 23 000 tonnes for cadmium and 500 tonnes for tellurium (USGS, 2021).

High perovskite case

Perovskite solar cell technology has received a lot of research attention in the past decade as it holds the promise of much higher efficiency levels, starting at around 9.7% in 2012 (Kim et al., 2012) and exceeding 25% today (NREL, 2019). However, in order to challenge the dominance of silicon in photovoltaics, perovskites will have to overcome significant technological hurdles. Most pure perovskite solar cells that have shown high efficiency are no larger than a fingernail and need to be scaled up enormously to match the output of commercial c-Si solar cells. The second major drawback for these cells is their stability. Perovskites are compounds that are highly soluble in water and even in the moisture in the air. This means that the perovskite layer thickness reduces rapidly within just an hour of exposure to ambient conditions even at a relatively low humidity of 40% (Shirayama et al., 2016). The final concern comes from the chemistry of the most frequently reported perovskite structure for solar cell applications (such as methylammonium lead triiodide or “MAPI”), which uses up to 10% lead by weight in pure perovskite solar cells (Saliba et al., 2018) and could hamper its adoption in certain jurisdictions. Alternative lead-free technologies are being studied, but are still far from reaching the record efficiencies synonymous with the lead-based counterparts (Zhao et al., 2017).

A pure perovskite solar cell does not contain silicon or most of the materials that are used in the fabrication of crystalline silicon solar cells. However, given the limitations of pure perovskite solar cells

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described above, the easiest path to scale up and industrialise perovskite technology and circumvent many of its challenges is to combine it with the crystalline silicon technology (Nature Energy, 2020). This could be the fastest route to market for perovskites primarily because of the large market share held by silicon. Silicon solar cells have almost reached their physical efficiency limit in laboratory devices, but researchers at Oxford PV have demonstrated perovskite/silicon tandem solar cells that reach laboratory efficiencies of up to 28%, outperforming both perovskite and silicon single-junction devices (NREL, 2019).

In light of the constant development and strong research interest, this case assumes that perovskite/silicon tandem solar cell technology will capture 30% of the market for utility-scale PV and 15% for distributed PV by 2040. This would reduce silicon demand in 2040 by over 10%, while raising lead demand by around 45% compared to the base case in the SDS context.

High GaAs case

There are semiconducting materials whose physical and chemical characteristics make them much better candidates for solar cell technology than silicon. The III-V semiconductors such as GaAs, indium arsenide (InAs), gallium nitride (GaN) and indium phosphide, are a family of materials developed as binary compounds between elements from group 13 and group 15 of the periodic table. GaAs has the optimal bandgap energy for solar cell applications. It also has a crystalline structure that makes it much more suitable for fabricating multi-junction solar cells by growing layers of different III-V crystalline materials on top of each other. The advantage of a multi-junction solar cell over a single-junction solar cell is that it allows the absorption of a wider range of the solar spectrum, thereby increasing the power conversion efficiency of the resulting solar cell. The research efficiency of GaAs-based multi-junction solar cells fabricated at the National Renewable Energy Laboratory (NREL) in the United States and Fraunhofer ISE in Germany is rapidly approaching 50%, making them the most efficient solar PV technology known to date (NREL, 2019). GaAs became the most commonly used material for photovoltaic arrays in satellites in the early 1990s and remains the preferred choice for aerospace applications. For terrestrial applications, GaAs-based multi-junction solar cells are most often employed in concentrator solar photovoltaic projects.

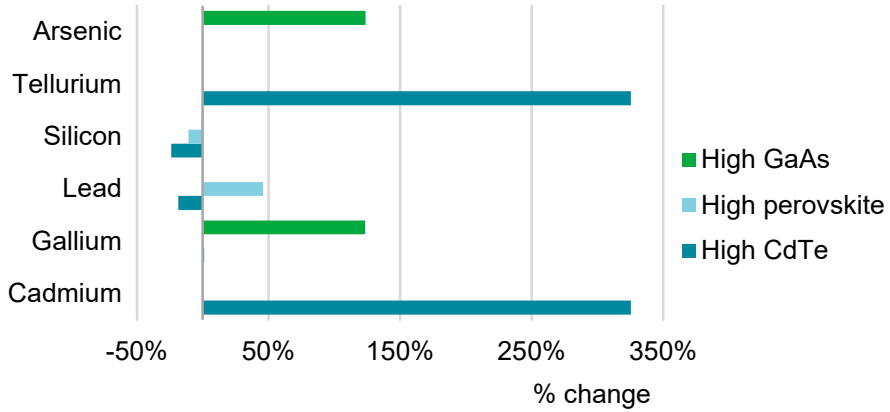
The main challenge to overcome for GaAs-based solar cells is the cost of raw materials and wafer manufacturing. It is reported that a wafer of GaAs is roughly 50 times more expensive than a wafer of c-Si of comparable size (Bleicher, 2010). This significant cost differential is what has prevented GaAs-based solar cells from entering the commercial solar PV market for terrestrial applications. However, latest developments indicate that this situation may not persist for long. In 2020 researchers at NREL reported a breakthrough in III-V cell technology that could significantly bring down costs (Willuhn, 2020). Recent studies (Horowitz et al., 2018)

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suggest ample scope for major cost reductions via scaling up production volumes, reducing the cost of epitaxial crystal growth, lower substrate costs through recycling and lower metallisation costs. This could bring prices closer to c-Si within the next 10 to 15 years. Although direct competition with c-Si may not be possible, such cost reductions combined with advantages in weight, flexibility, energy density, temperature stability, radiation hardness etc. could make them attractive for use in very large terrestrial applications that cannot be served by silicon today.

Although GaAs represents a small share in the base case (5% in 2040), in the High GaAs case we assume a market share of 15% for utility-scale and 5% for distributed applications in 2040. Compared to the base case, this would add 8 kt of arsenic demand (25% of global production today), 3.5 kt of gallium (10 times more than high-purity refined gallium production today), and 0.1 kt of indium demand by 2040 in the SDS. This implies that scaling up the high GaAs technology needs to go hand in hand with efforts to recover more materials from a by-product stream of bauxite, zinc, copper and gold processing or via recycling.

Changes in mineral demand in alternative technology evolution cases in the SDS context



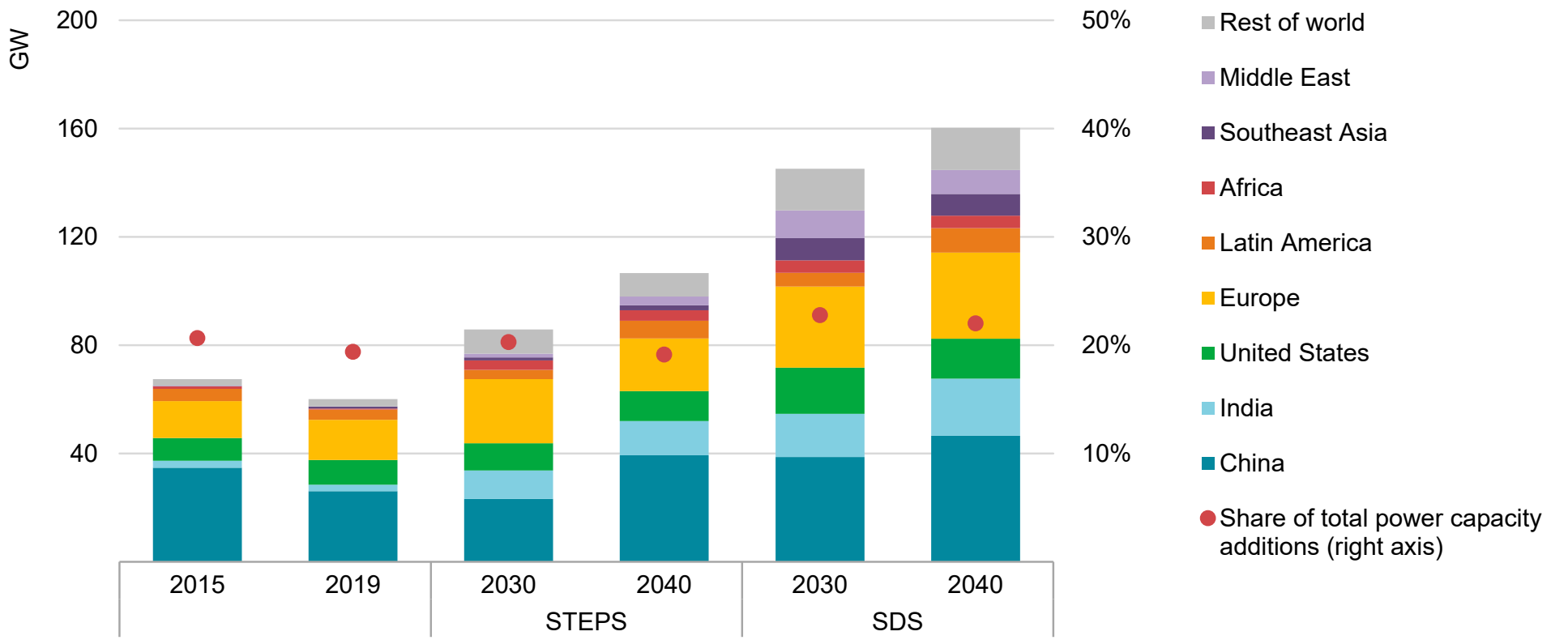
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Note: Relative change compared to the base technology evolution case in the SDS.

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Wind: Wind deployment is expected to accelerate over the coming decades, thanks to falling costs, policy targets and increased investor confidence

Annual wind capacity addition by region and scenario



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Source: IEA (2020c).

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Wind: Larger turbines – particularly offshore – help to accelerate annual capacity additions over the coming decades

Global installed capacity of wind power has nearly quadrupled over the past decade, spurred by falling costs, which have declined by about 40% on average globally, and policy support in more than 130 countries (IEA, 2020c). In both the STEPS and SDS, wind power is set for strong growth, with the offshore wind industry maturing and adding to developments in onshore wind on the back of technology improvements and low-cost financing. Annual capacity installations for wind in the SDS are expected to more than double by 2040 to 160 GW, representing more than a fifth of overall power capacity additions. Installations are currently concentrated in China, Europe and the United States, but the regional picture is set to become diverse with particularly strong growth in Southeast Asia, India, Latin America and the Middle East.

The share of offshore in total wind deployment is poised to grow considerably. Cost reductions and experience gained in Europe's North Sea are opening up huge opportunities in many parts of the world. Offshore wind offers higher capacity factors than onshore wind thanks to larger turbines that benefit from higher and more reliable wind speeds. There are further innovations on the horizon, such as floating turbines that can open up new resources and markets.

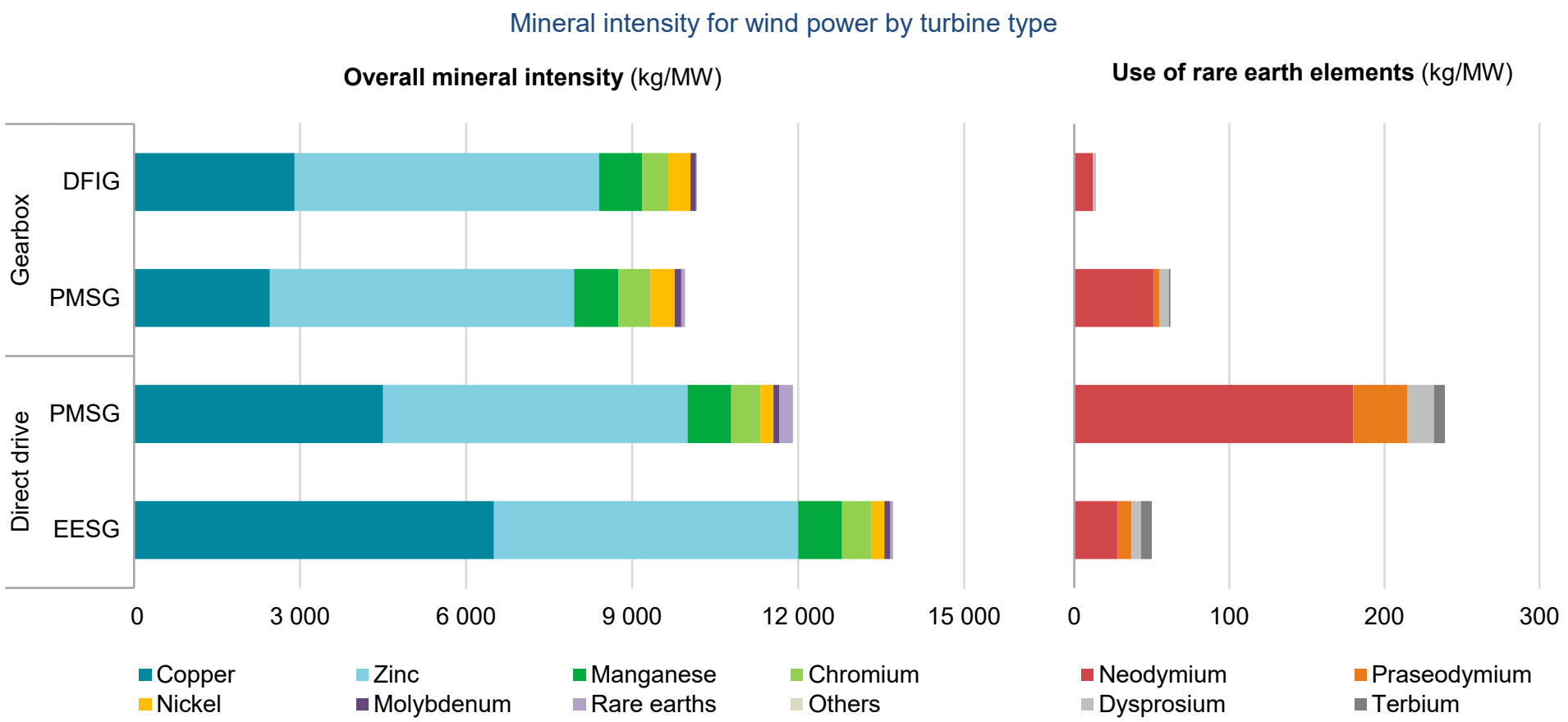
Turbine size has also grown considerably, from a global weighted average of 1.9 megawatts (MW) for onshore turbines installed in 2010 to 2.6 MW in 2018 (IRENA, 2019). Manufacturers are offering 5 MW onshore turbines in 2021. Turbine size has grown even more quickly in offshore wind, with an average rated capacity of 5.5 MW installed in 2018, compared with the newest turbine designs offering capacities of 10-14 MW. Even larger turbines are expected in the coming years, with promises of 20 MW turbines already on the horizon.

The growing size of turbines is an important contributor to the increase in capacity factor and the reduction in material use. Taller towers, larger rotors and lighter drivetrains have enabled higher capacity factors, which have risen from an average of 27% in 2010 for newly commissioned onshore projects to 34% in 2018.

These trends have also helped to reduce the material intensity for some materials in wind power. For example, on a kilogramme (kg) per MW basis, a 3.45 MW turbine contains around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine (Elia et al., 2020).

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Wind: Mineral needs for wind power depend on the turbine type, with particularly high sensitivity for rare earth elements



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Notes: DFIG = double-fed induction generators; PMSG = permanent-magnet synchronous generator; EESG = electrically excited synchronous generator. The intensity numbers are based on the onshore installation environment. More copper is needed in offshore applications due to much longer cabling requirements.

Sources: Carrara et al. (2020); Elia et al. (2020)

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Wind: The growing market for turbines with permanent magnets – particularly for offshore projects – could dramatically increase rare earth demand over the coming decades

Wind turbines – which consist of a tower, a nacelle and rotors erected onto a foundation – require concrete, steel, iron, fibreglass, polymers, aluminium, copper, zinc and REEs.

Mineral intensities not only depend on the turbine size, but also on the turbine type. There are four main types of turbine: gearbox double-fed induction generator (GB-DFIG), gearbox permanent-magnet synchronous generator (GB-PMSG), direct-drive permanent-magnet synchronous generator (DD-PMSG) and direct-drive electrically excited synchronous generator (DD-EESG).

Turbines based on PMSGs require neodymium and dysprosium. DD-PMSGs generally contain larger amounts of REEs compared to GB-PMSGs for smaller overall size and lower weight and higher efficiency. Zinc is evenly used among turbine types as a protective coating against corrosion.

The onshore wind market is currently dominated by GB-DFIGs, accounting for more than 70% of the global market. DD-PMSGs have doubled their market share over the past 10 years from around 10% in 2010 to 20% in 2020. In the offshore sector, DD-PMSG turbines are the main choice, with around 60% of the market worldwide. Requiring taller and larger turbines, offshore wind sites generally opt for DD-PMSG configurations due to their lighter and more efficient attributes as well as lower maintenance costs. In addition to REEs, copper intensity for offshore projects can be more than twice as high as onshore, with substantial copper usage in submarine collector and larger cables.

With increasing power per tower as turbines become taller and larger, lighter and more efficient configurations of PMSG technologies are becoming increasingly preferred. In the base case, PMSG technologies account for around 95% of the offshore market in 2040 and 40% of the onshore market.

In the SDS, demand for REEs in wind – neodymium and praseodymium in particular – is set to more than triple by 2040, driven by the doubling of annual capacity additions and a shift towards turbines with permanent magnets. Copper demand reaches 600 kt per year in 2040, propelled by offshore wind requiring greater cabling. Offshore wind accounts for nearly 40% of copper demand from wind despite accounting for only 20% of total wind capacity additions.

Constrained REE supply case

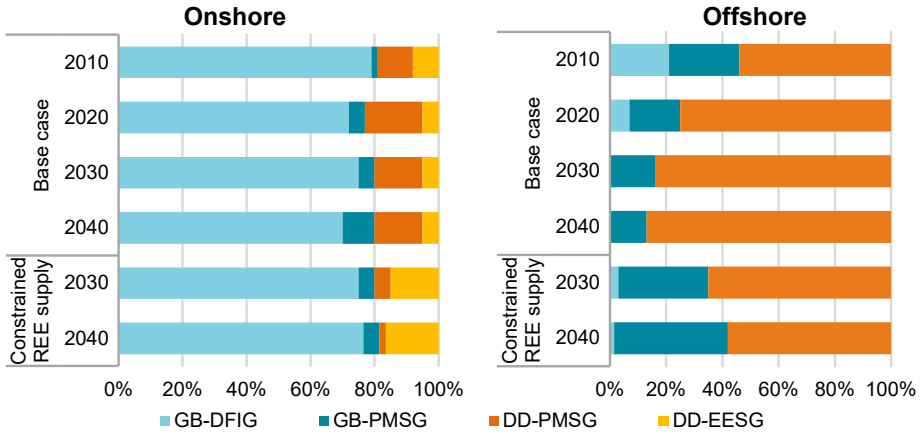
However, mounting demand for REEs from a variety of clean energy technologies such as wind and EVs, coupled with concerns around rising prices and geopolitical events, could lead to different technology choices. This is explored in the Constrained REE supply

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case, which sees manufacturers gradually switching to non-magnet technologies and project developers adopting hybrid configurations with a gearbox and a smaller magnet. Onshore projects move towards DD-EESGs while, in offshore projects, DD-PMSGs cede some market share to technologies with lower REE use such as DD-EESGs. However, there would be no notable switch back to GB turbines given the technical fitness of DD turbines in the offshore environment and industry-wide efforts to reduce REE intensity in DD turbines.

In this case, neodymium demand in the SDS is contained to around 8 000 tonnes in 2030 and 40% lower in 2040 compared to the base case. Demand for praseodymium and dysprosium are 15% and 32% lower, respectively, compared to the base case in 2040.

Turbine shares for wind power capacity additions in the SDS



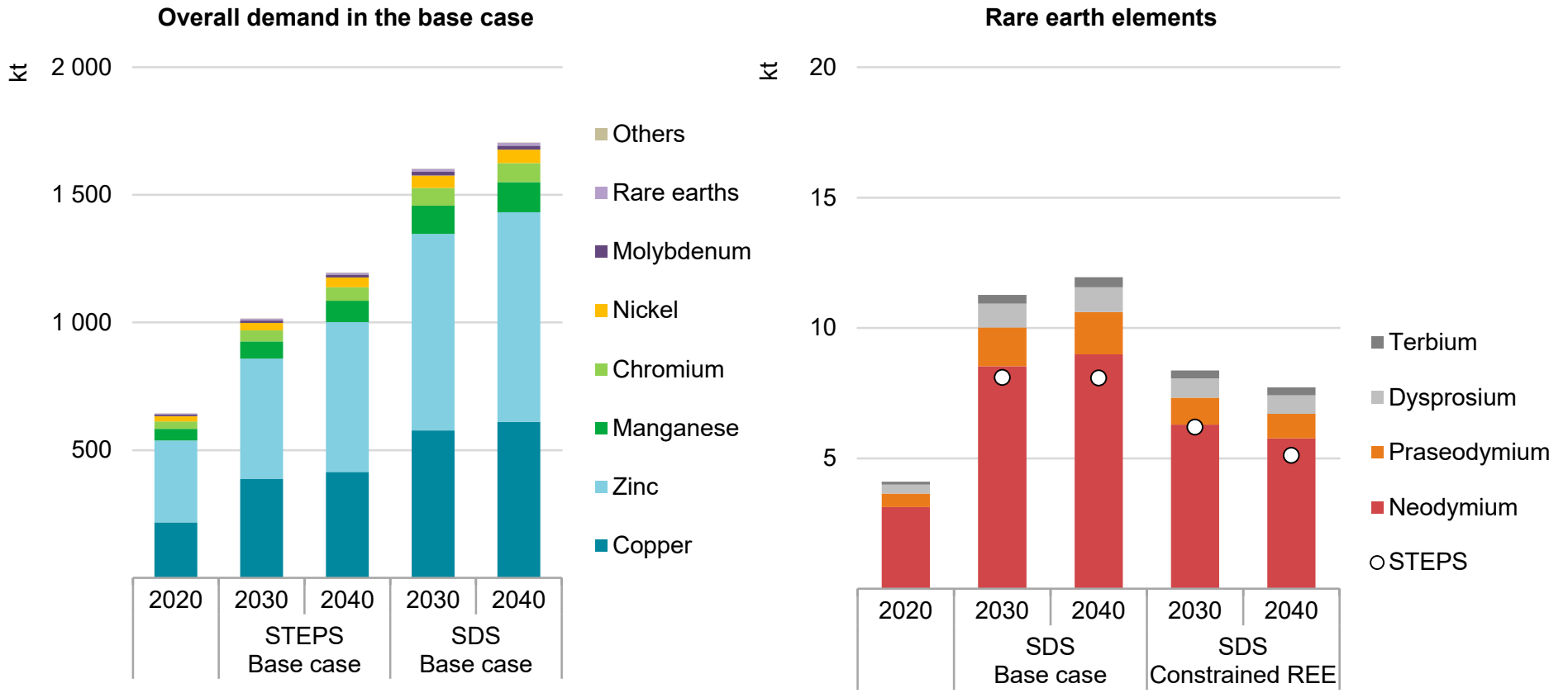
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Another option to reduce REE consumption in permanent magnets is to use a high-temperature superconductor (HTS). This offers potentially substantial reductions in mass and size, as they can achieve enormous current densities, but require extremely low temperatures and expensive cryostats. The technology is still at the R&D stage, with multiple designed prototypes and a sole 3 MW industrial-scale turbine developed so far. Despite promising results, HTS wind farms remain far from being competitive with existing wind technologies and we do not expect them to be a game changer in the next decade.

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Wind: Demand for rare earths quadruples in the SDS by 2040, although the scale of growth may vary depending on the choice of turbine technologies

Mineral demand for wind by scenario

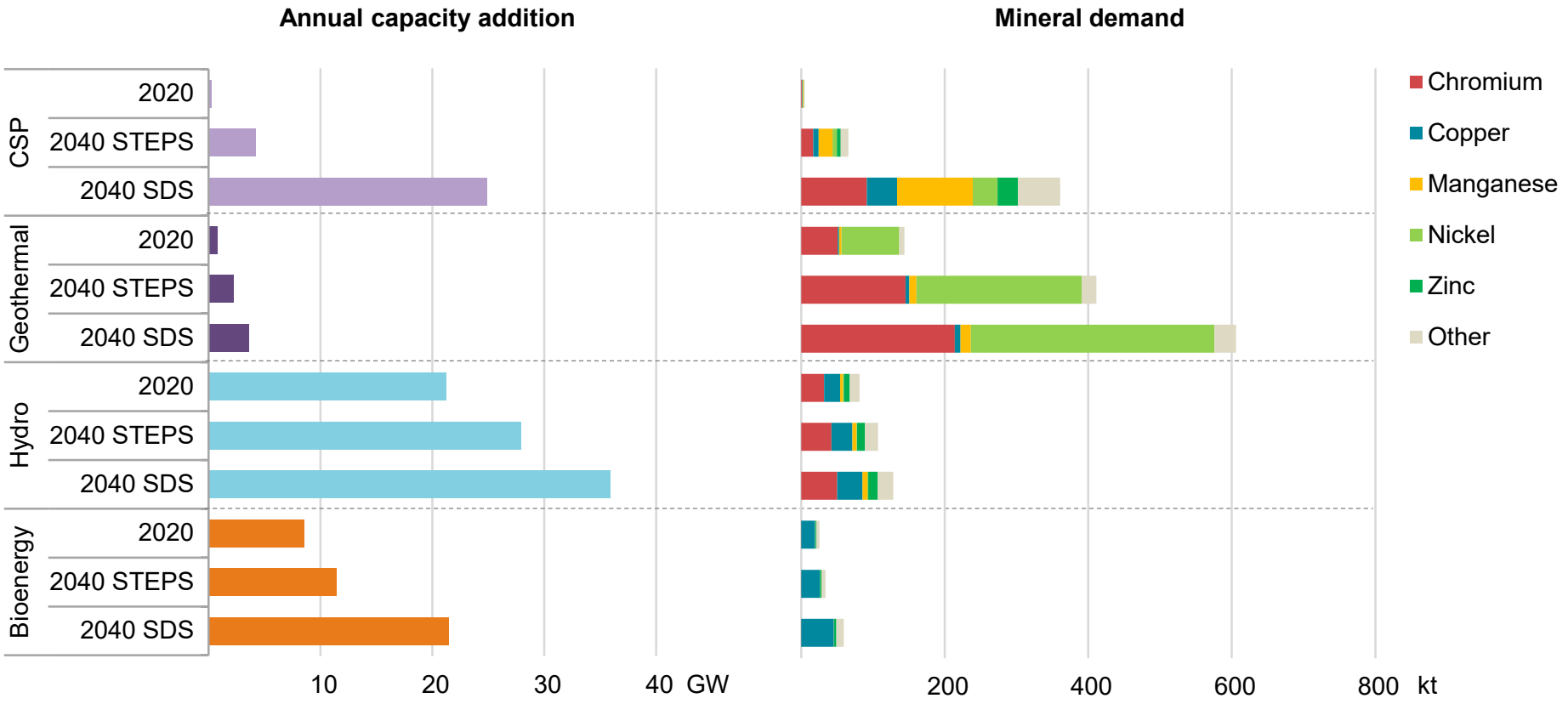


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Other renewables: Mineral demand from other renewables varies significantly depending on their mineral intensities

Annual capacity addition and mineral demand from other renewable technologies by scenario



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Note: CSP = concentrating solar power.

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Concentrating solar power: Rapid growth in capacity additions comes with substantial demand for chromium, copper, manganese and nickel

Since 2010 policy and financing initiatives in Spain and the United States have helped to more than double the global installed capacity of CSP. However, overall installed capacity remains low at around 7 GW in 2020 owing to limited suitable geographies, high project costs and long distances to demand centres. In the SDS, installed capacity grows by nearly 40 times between 2020 and 2040 – albeit from a low base – driven by growth in the Middle East, Africa and Asia Pacific.

CSP systems use mirrors to direct solar radiance to a central receiver where energy is transmitted to a heat-exchange fluid used to generate electricity. Two main types of CSP technology – parabolic troughs and central towers – account for most of the installed, planned and projected additions. Parabolic trough systems direct solar radiance to a tube containing a heat-exchange fluid running along the length of a parabolic mirror. Central tower systems very closely track the movement of the sun reflecting and directing solar radiance to a centralised receiver tower containing a heat-exchange fluid.

Central tower systems generally require more materials than parabolic trough systems, including eight times more manganese, four times more nickel, and twice as much silver. However, parabolic trough systems require more than twice as much copper.

Parabolic troughs accounted for over 80% of CSP capacity additions in 2010, but their share has been steadily declining, ceding market share to central tower systems, which have higher efficiency and greater storage capacity (IEA, 2020c). Central towers accounted for around 60% of CSP capacity additions in 2020, and their share is expected to grow to 75% by 2040 in the SDS.

The expansion of CSP, driven by material-intensive central tower systems, comes with substantial demand growth for chromium, copper, manganese and nickel. Between 2020 and 2040 in the SDS, chromium demand from CSP grows by 75 times (to 91 kt), copper demand grows by 67 times (to 42 kt), manganese demand grows 92-fold (to 105 kt), and nickel demand grows 89-fold (to 35 kt).

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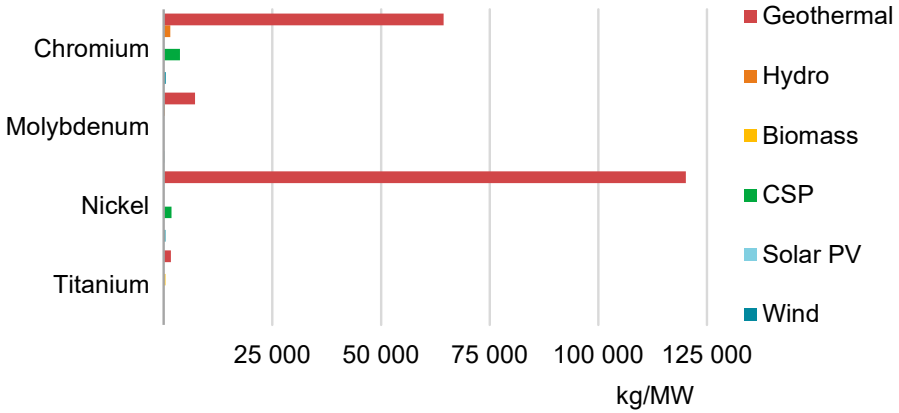
Geothermal: A key driver for growing nickel, chromium, molybdenum and titanium demand from low-carbon power technologies

Around 16 GW of geothermal capacity are currently installed, providing low-carbon baseload power in geo-hotspots such as Kenya, Iceland, Indonesia, the Philippines, Turkey and the United States. In the SDS, installed capacity grows fivefold to 82 GW by 2040.

Geothermal power plants generate electricity by powering turbines using underground hydrothermal resources (steam or hot water) piped to the surface. The very high temperatures and potentially corrosive nature of geothermal reservoirs require the use of specialised steel (high in chromium, molybdenum, nickel and titanium) in order to withstand the harsh operating environment.

In the SDS, mineral demand from geothermal more than quadruples between 2020 and 2040. Despite accounting for less than 1% of all low-carbon power capacity additions in 2040, geothermal power is a major source of demand for nickel, chromium, molybdenum and titanium from the power sector. Of the total mineral demand from all low-carbon power sources in 2040, geothermal accounts for three-quarters of nickel demand, nearly half of the total chromium and molybdenum demand, and 40% of titanium demand.

Mineral intensity of key minerals in geothermal in 2019



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Notes: CSP mineral intensity is for central tower systems; solar PV mineral intensity is for utility-scale cSi; wind mineral intensity is for onshore GB-DFIG.

In addition to power, geothermal resources can provide heating and cooling services. However, ground-source heat pumps require relatively minimal steel and instead rely on plastic piping, with some systems relying high-conduction copper for heat exchange.

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Hydropower and bioenergy: Limited impacts on mineral demand due to low material intensity

Hydropower is the largest renewable source of electricity, accounting for 17% of global electricity generation in 2020. While it plays an important role in providing flexibility to the power system, its share of total power capacity additions continues to decline in the SDS through to 2040, as high capital costs and geographic constraints limit further growth.

In the SDS, hydropower capacity additions in 2040 are only 70% higher than in 2020, representing the lowest relative growth among all renewable sources. Between 2020 and 2040, nearly 60% of cumulative capacity additions occur in Asia Pacific, with China alone accounting for a quarter of the global total.

While hydropower uses substantially more cement and concrete than any other generation technology, it has a relatively low mineral intensity compared to other sources of low-carbon power. Hydropower does not use REEs, and its current use of copper (1 050 kg/MW), manganese (200 kg/MW) and nickel (30 kg/MW) are among the lowest of all low-carbon sources (Ashby, 2013). Hydropower accounts for 2% and 11% of the total demand for copper and chromium respectively from all low-carbon power capacity additions in 2040 in the SDS.

Bioenergy is a major source of renewable power today, generating as much electricity as solar PV in 2019. In the SDS, annual generation triples by 2040 to 2 150 terawatt hours (TWh), with total installed capacity rising to 420 GW. China, the United States, Russia and India account for over half of the cumulative capacity additions to 2040.

Mineral demand from bioenergy comes mostly from copper (2 270 kg/MW in 2019), which is similar to that of most other renewable generation technologies (Ashby, 2013). While the exact design of bioenergy boilers is different, overall mineral requirements are similar to those of coal and gas-fired power generation. However, bioenergy demands significant levels of titanium (400 kg/MW), which is higher than all other generation technologies except geothermal.

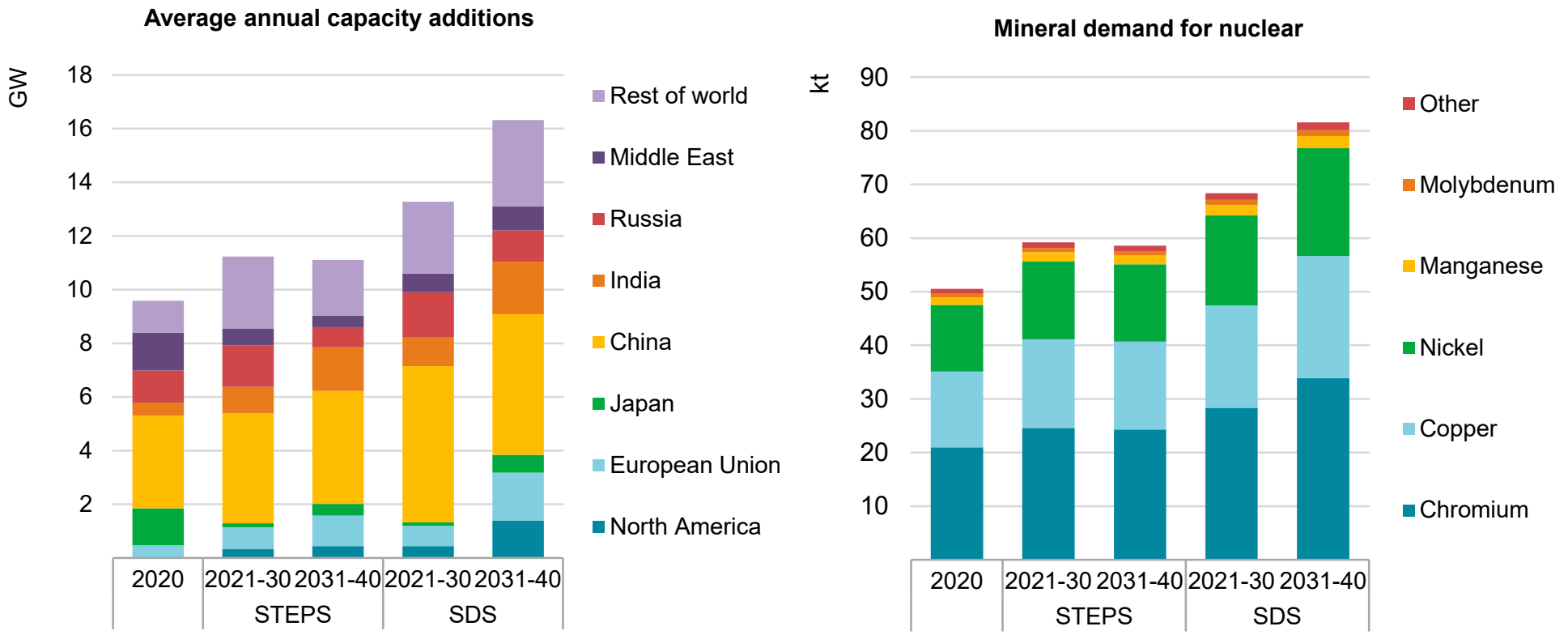
In the SDS, overall mineral demand from bioenergy more than doubles by 2040 compared to 2020, with copper accounting for more than three-quarters of the total. However, copper demand from bioenergy only accounts for 2.5% of the total copper demand from all low-carbon power sources in 2040. Conversely, titanium demand from bioenergy accounts for nearly 60% of all titanium demand from low-carbon power in 2040.

Overall, combined with their modest capacity growth, hydropower and bioenergy are unlikely to face any significant supply constraints for minerals.

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Nuclear: Modest growth in mineral demand from nuclear power

Average annual capacity additions and mineral demand from nuclear power



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Note: Russia = Russian Federation.

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Nuclear: Limited implications for minerals due to low material intensity

Nuclear power is the second-largest source of low-carbon power behind hydropower, accounting for about 10% of global electricity generation in 2020. Global installed capacity of nuclear power grows modestly to 2040 (by 15% in the STEPS and 45% in the SDS compared to 2020), as capacity declines in North America and Europe are offset by growth in emerging economies.

China is on track to become the leader in nuclear power around 2030, overtaking the United States and the European Union, more than doubling its current capacity to around 110 GW in the SDS. Significant programmes underway in India and the Middle East also contribute to the expansion of nuclear power. Capacity additions in 2020 were around 10 GW, and increase to an average of 11 GW in the STEPS and 16 GW in the SDS between 2031 and 2040.

Along with hydropower, nuclear is one of the low-carbon technologies with the lowest mineral intensity. Key mineral needs include chromium (2 190 kg/MW in 2019), copper (1 470 kg/MW), nickel (1 300 kg/MW), hafnium (0.5 kg/MW) and yttrium (0.5 kg/MW) (EC JRC, 2011). Uranium is not within the scope of our analysis, as this report focuses on mineral requirements for production of equipment, and not for operations. Around 16% of the worldwide supply of hafnium is currently used for nuclear reactor applications (EC JRC, 2011). However, the mineral intensity of chromium and nickel are highly sensitive to the use of high-alloy steel in nuclear power plants. Quantities of high-alloyed, low-alloyed and unalloyed steel used in a nuclear power plant are seldom reported.

Considering the maturity of the technology, there are unlikely to be drastic reductions in mineral intensity over the coming decades. As a result, mineral intensity is assumed to be similar in the STEPS, and decline slightly in the SDS.

In the SDS, average annual mineral demand from nuclear power between 2031 and 2040 grows by around 60% compared to 2020 levels, reaching 82 kt. It is dominated by chromium (42%), copper (28%) and nickel (25%). Yttrium demand in 2040 is around 7.7 tonnes, or around 0.0015% of current global reserves.

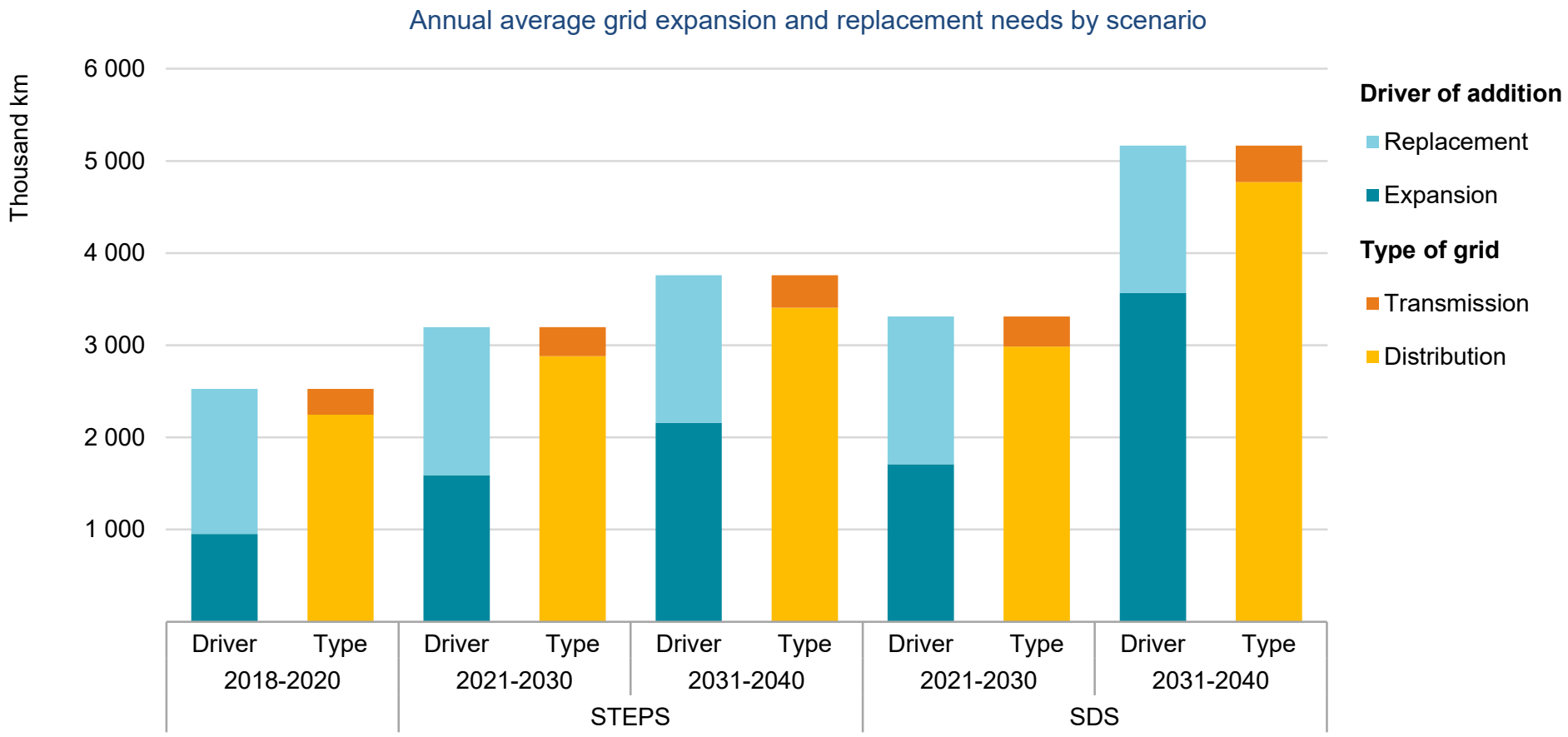
We conducted our assessment based on mineral requirements for light-water reactor technology, which dominates the world's nuclear fleet (accounting for over 80% of all reactors in operation). Both pressurised-water reactors – the dominant choice for future expansion – and boiling-water reactors have similar mineral intensity. However, mineral intensities can be different for small modular reactors or more advanced nuclear technologies, but data for these technologies remains scarce.

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Electricity networks

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Rising electricity demand, alongside much higher shares of wind and solar PV, requires a significant expansion of electricity networks



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Source: IEA (2020c).

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Electricity networks are the backbone of secure and reliable power systems, and have a vital role in integrating clean energy technologies

With over 70 million km of transmission and distribution lines worldwide, electricity networks are the backbone of today's power systems. Distribution systems currently account for over 90% of total line length, and play an increasing role in supporting the integration of residential solar PV and onshore wind capacity, in addition to their traditional role of delivering electricity to regional end users. Likewise, transmission systems, which are instrumental in connecting large hydro, thermal and nuclear power fleets with load centres, have new tasks to fulfil. For example, they now integrate large amounts of solar PV and wind capacity (in particular offshore wind), strengthen interconnection between countries and increase the resiliency of power systems. These new tasks are supported by the rise of high-voltage direct current (HVDC) technologies. HVDC systems have been used since the 1950s, but over two-third of total installed HVDC transmission capacity has been added in the past 10 years. Today, HVDC systems represent around 7% of newly installed transmission systems and their share is expected to rise further given the considerable technological progress made over the past decade.

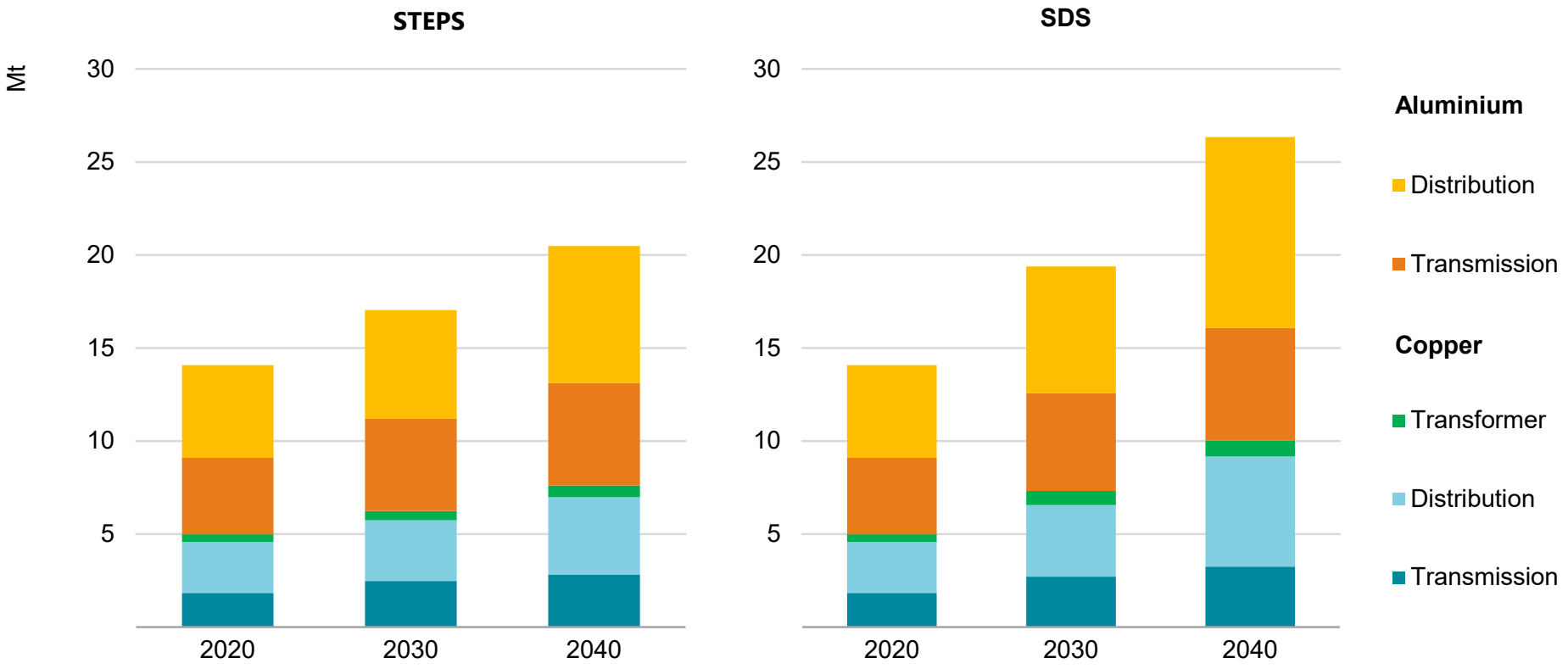
Many of the features that characterise a clean energy system – the growing role of electricity in final consumption, rising contributions from renewables in electricity supply and the greater need for flexibility – all necessitate significant expansion of electricity grids. The projected requirement for new transmission and distribution lines worldwide in the STEPS is 80% greater over the next decade than the expansion seen in the last ten years. The importance of electricity grids is even greater in the case of faster energy transitions. In the SDS, the annual pace of grid expansion needs to more than double in the period to 2040. Around 50% of the increase in transmission lines and 35% of the increase in distribution network lines are attributable to the increase in renewables.

In addition to additional lines, there is scope to refurbish grids to strengthen the resiliency of electricity systems to climate change and extreme weather events. Refurbishment of electricity grids is also strongly linked to digitalisation, given the rising need for smart and flexible grids. Investment in digitalisation and grid flexibility helps increase reliability and can reduce the cost of generating, transmitting and distributing electricity. In the SDS, some 55% of the expansion to 2030 in advanced economies such as the European Union and the United States are attributable to refurbishment and digitalisation.

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Growing need for grid expansion underpins a doubling of annual demand for copper and aluminium by 2040 in the SDS

Demand for copper and aluminium for electricity grids by scenario



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Note: Includes demand for grid expansion and replacement.

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The choice of material in electricity networks is mainly driven by the type of power line, but is also influenced by cost and technical considerations

The huge expansion of electricity grids requires a large amount of minerals and metals. Copper and aluminium are the two main materials in wires and cables, with some also being used in transformers. It is estimated that some 150 Mt of copper and 210 Mt of aluminium are “locked in” the electricity grids operating today.

Copper has long been the preferred choice for electricity grids due to its inherent performance advantages. Its electrical conductivity is the second best among various metals after silver and 60% higher than aluminium. Its thermal conductivity, an often-overlooked attribute when designing and operating a grid, is also some 60% higher than aluminium. However, it also has drawbacks. Copper is over three times heavier by weight than aluminium and is more costly – average prices for copper over the past 10 years were USD 7 100 per tonne (in 2019 dollars) whereas those for aluminium averaged at around USD 2 000 per tonne.

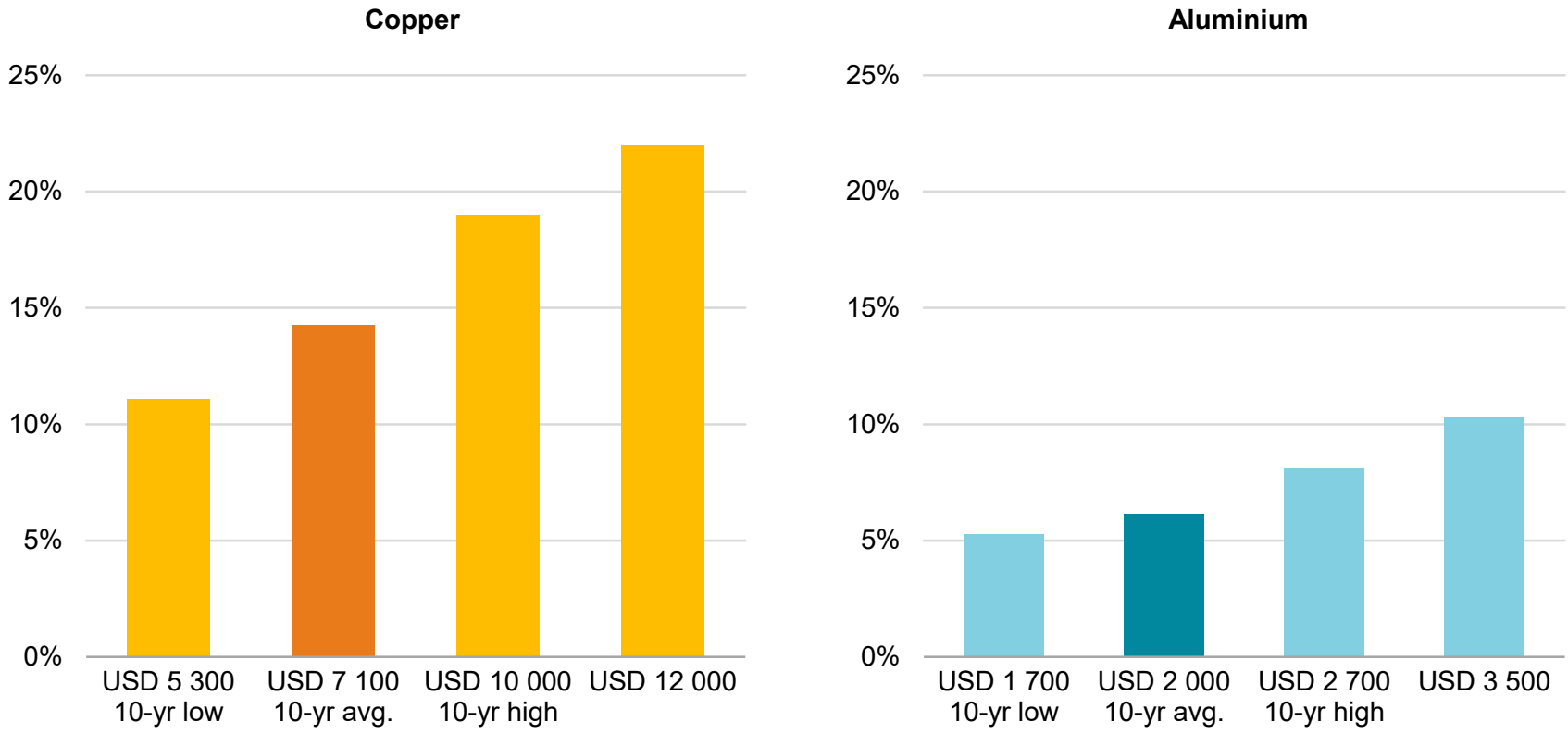
This underpins different material choices according to the type of power line. Copper is widely used for underground and subsea cables where weight is not a major concern and superior technical properties (e.g. corrosion resistance, tensile strength) are required. By contrast, aluminium is commonly used for overhead lines given its weight advantage. In some instances, aluminium is also used for underground and subsea cables.

We estimate that some 5 Mt of copper and 9 Mt of aluminium were used in 2020 to build electricity grids, of which over 55% is attributable to distribution grids. We conducted bottom-up assessments of projected line additions and replacements by type (overhead, underground and subsea), voltage level and respective material choice. These show annual copper demand for electricity grids growing from 5 Mt in 2020 to 7.5 Mt by 2040 in the STEPS, and more than double that to almost 10 Mt in the SDS. Aluminium demand increases at a similar annual pace, from 9 Mt in 2020 to 13 Mt in the STEPS and 16 Mt in the SDS by 2040. Overhead lines account for a larger share of future expansion by line length, but underground and subsea cables require higher mineral content per unit length. The scope for significant demand growth, coupled with a higher share of raw materials in total cost, raises questions over how companies can reduce material intensity in their grids in order to lower material cost.

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Costs for copper and aluminium currently represent around 20% of total grid investment; higher prices could have a major impact on the adequacy of grid investment

Share of copper and aluminium costs in new grid investment under different price assumptions



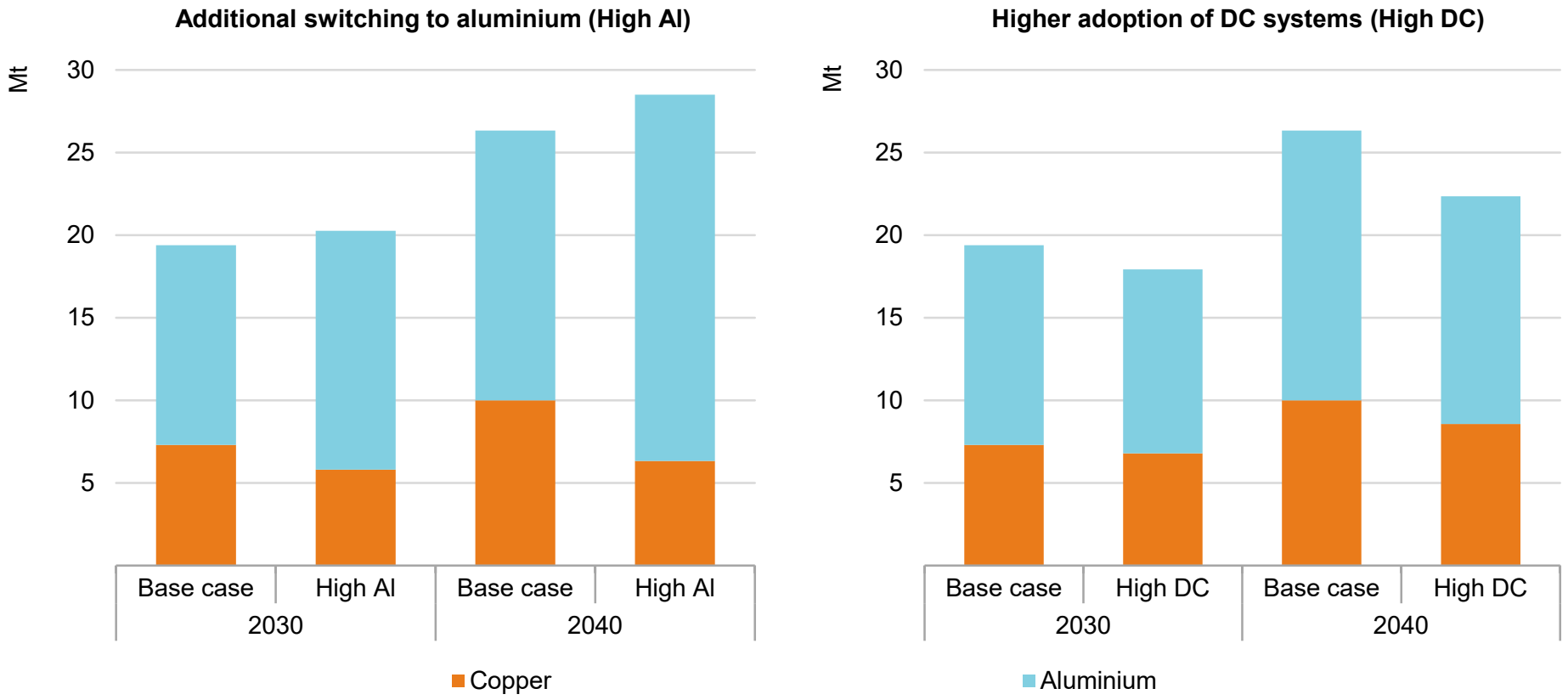
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Notes: The shares have been calculated according to total electricity grid investment in 2019, with raw material prices adjusted. Darker bars indicate average costs between 2010 and 2019; costs are in USD per tonne.

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Additional switching to aluminium for underground cables and the wider uptake of DC systems can alter the material requirements considerably

Copper and aluminium demand for electricity networks in the SDS under alternative cases



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Increased use of aluminium could reduce copper demand by one-third, while wider adoption of DC systems could reduce aluminium and copper demand by 15%

As grids are modernised, expanded and digitalised, projected investment in electricity grids reaches USD 460 billion in 2030 in the STEPS and USD 620 billion in the SDS. However, shortfalls in grid revenues can put the adequacy of grid investment at risk.

Prices for minerals may add to this pressure given their considerable share in total investment costs. Using average prices over the past 10 years, copper and aluminium costs are estimated to represent around 14% and 6% of total grid investment respectively. At the highest prices observed over the past decade, these increase to almost 20% and 8% respectively, highlighting the major impacts that mineral prices can have on the ability of grid operators to undertake investment.

Increased use of aluminium in underground cables

Grid operators have long been working to reduce raw material costs. One option is to switch from copper to more affordable aluminium. When comparing the costs of the two materials, this seems to be an obvious option to improve the economics of grid investment. This is possible in cases where technical or regulatory boundaries allow, and has happened in recent years. Some drawbacks such as the lower electrical conductivity of aluminium can be compensated by the use of larger conductors, although technical or environmental requirements often do not allow such shifts.

If aluminium takes a higher share in underground and subsea cables than our base case assumptions – accounting for 50% for distribution lines and 30% for transmission lines by 2040 – this reduces copper demand in 2040 by 3.7 Mt (down by a third) while raising aluminium demand by 5.8 Mt (up by over a third).

Wider adoption of DC systems

Another option is to adopt HVDC systems more widely. At present electricity networks are largely operated via alternating current (AC) systems, which require a minimum of three wires to transmit electricity. However, HVDC systems use only two wires, which implies a direct saving on metal consumption of one-third compared to AC systems. HVDC systems are also capable of transporting more electricity (theoretically up to 3.5 times more) compared to AC systems, which could reduce copper and aluminium demand and also the need for grid expansion (which results in further savings).

In the case of a wider uptake of HVDC systems – accounting for 50% of new transmission lines and 30% of distribution lines by 2040 – would reduce combined demand for copper and aluminium in 2040 by 4 Mt (or 15%) in the SDS.

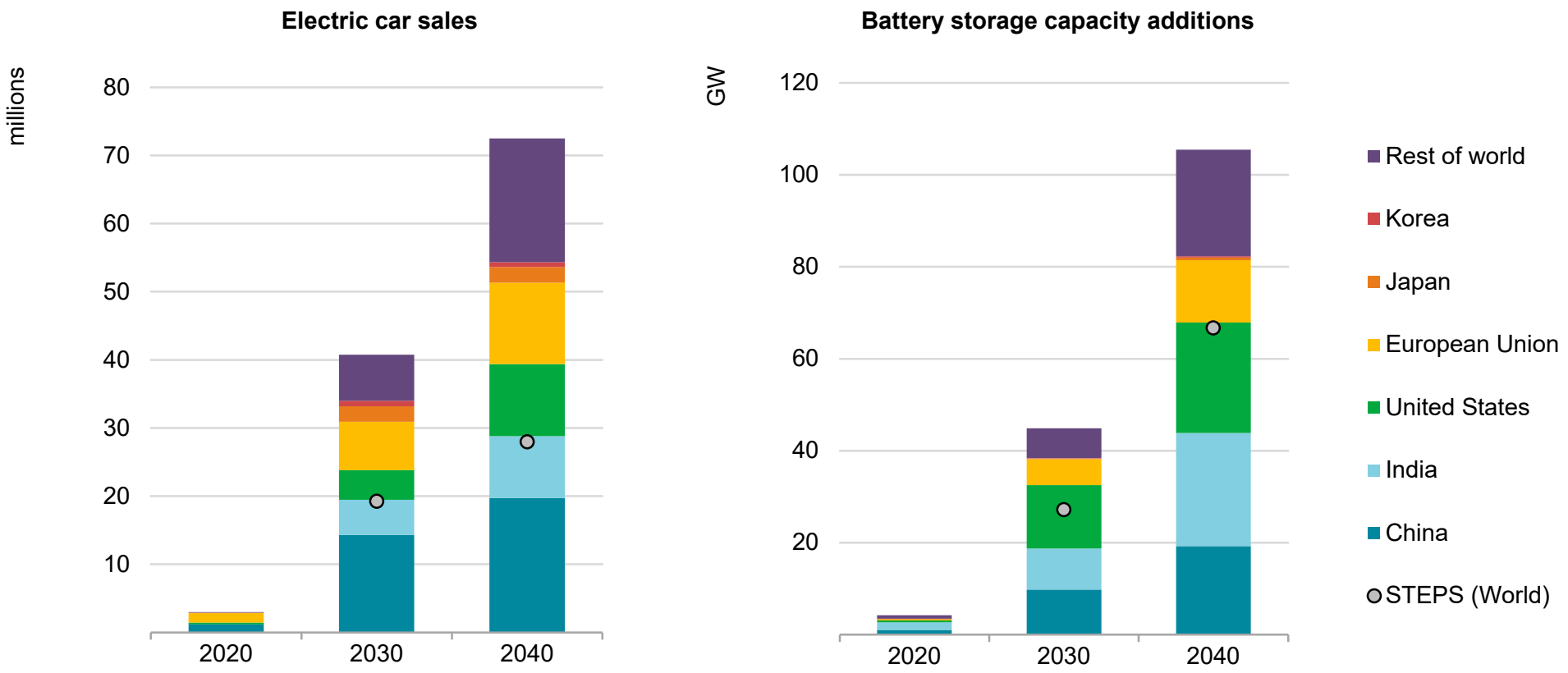
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Electric vehicles and battery storage

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The adoption of EVs and battery storage is set to accelerate rapidly over the coming decades

Annual electric car sales and battery storage capacity additions in the SDS



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Notes: Electric cars include battery electric and plug-in hybrid electric passenger light-duty vehicles, but exclude 2/3-wheelers.
Source: IEA (2020c).

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Policy support will continue to play a key role in accelerating the growth in EVs and battery storage, alongside a wider range of model offerings from automakers

EVs

Electric car sales worldwide climbed 40% in 2020 to around 3 million, reaching a market share of over 4% (IEA, 2021). As a result, more than 10 million electric cars are now on the road globally. However, to achieve global climate goals, their share of sales needs to climb rapidly to around 40% by 2030, alongside the rapid electrification of light commercial vehicles, buses and freight trucks.

Policy support has been a major driver of initial EV deployment, and will continue to play a critical role in accelerating the growth of the EV fleet over the coming decades. As of April 2021, over 20 countries and 70 subnational and city governments have announced 100% zero-emission vehicle targets or the phase-out of internal combustion engine (ICE) vehicles before 2050 (Cui et al., 2020; Hall et al., 2020; IEA, 2021; Wappelhorst & Cui, 2020).

Most major car markets currently offer some form of subsidy or tax reduction for the purchase of electric cars as well as support schemes for deploying charging infrastructure (IEA, 2020b, 2021). Provisions in building codes to encourage charging facilities and the "EV-readiness" of buildings are becoming increasingly common. So too are mandates to build fast charging infrastructure along highways.

Policy developments over the past year have been positive for EVs, and are discussed in further detail in *Global EV Outlook 2021* (IEA, 2021). In the European Union, increased stringency of the CO_2 emissions regulation for cars and vans in 2021 and beyond should contribute to maintaining the momentum for EV deployment. The European Commission is also in the process of revising the 2025-2030 targets for CO_2 emissions regulation for cars and vans, the Alternative Fuels Infrastructure Directive, the Batteries Directive and the EURO pollutant emissions standard.

Sales are likely to grow in Japan and Korea over the near term, with these governments significantly increasing EV subsidies. China has set a target of 20% of vehicle sales to be ZEVs by 2025, and announced plans to phase out conventional gasoline-powered vehicles by 2035 (General Office of the State Council of the People's Republic of China, 2020; Nishiyama, 2020). In India, national, state and city governments have announced efforts to accelerate the adoption of EVs. For example, New Delhi recently announced major EV subsidies and awareness programmes to achieve its target for battery EVs to account for 25% of all new vehicles sales by 2024 (Times of India, 2021).

In the United States stimulus measures and longer-term goals adopted by the new administration will be critical to further

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accelerating EV deployment. In particular, the new administration appears likely to prioritise fuel economy standards, promote charging station deployment, provide tax credits and help factories making internal combustion engine cars retool to make EVs.

Several major automakers have announced plans to invest aggressively in EVs and to rapidly scale up model availability. There were around 370 EV models available in 2020, a 40% increase from 2019 (IEA, 2021). Automakers have announced plans to have an additional 450 models available by 2022 (McKinsey, 2020). General Motors recently announced plans to phase out conventional gasoline and diesel vehicles by 2035, while Volvo's CEO indicated that the company would only sell EVs by 2030 (Campbell, 2021).

Emerging technologies and business models such as shared and/or autonomous vehicles – expected to have much more intensive use patterns than privately owned vehicles – could alter demand projections for new vehicles and minerals over the longer term. However, given the uncertainty of their uptake, we do not consider these trends within the scope and timeline of this analysis.

Battery storage

As of the end of 2020, around 15.5 GW of battery storage capacity were connected to electricity networks. After annual installations of battery storage technologies fell for the first time in nearly a decade in 2019, they rebounded by over 60% in 2020 (BloombergNEF, 2021; IEA, 2020a).

Prospects for battery storage systems look set to improve as advances in technological innovation and new business models emerge. Battery storage systems are well suited to short-duration storage that involves charging and discharging over a span of hours or days. This makes them a good partner for short-run fluctuations in the output from variable renewables, and there is a growing trend for battery storage paired with solar PV and wind.

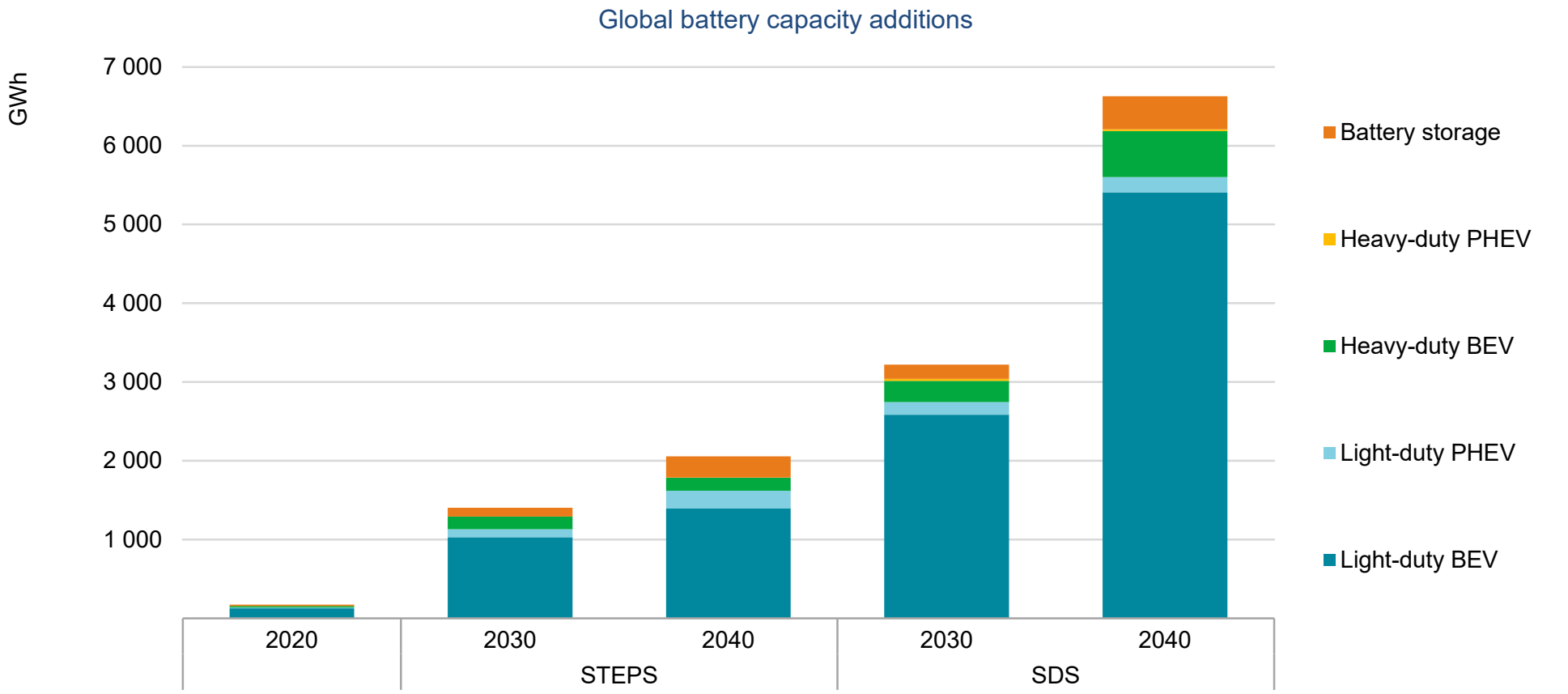
In the SDS, global installation of utility-scale battery storage is set for a 25-fold increase between 2020 and 2040, with annual deployment reaching 105 GW by 2040 (IEA, 2020c). The largest markets for battery deployment in 2040 are India, the United States and China.

The growth of battery storage remains strongly dependent on effective regulation that reflects the value of the flexibility services it provides and enables fair access to markets. The need to properly value the high performance of battery storage systems, including their accurate and fast frequency response, is one aspect of a broader need for wholesale electricity market reform in the face of rapidly evolving power systems.

A number of regulatory barriers specific to batteries are starting to be addressed, including the rates applied to behind-the-meter batteries and the issue of double-charging, where energy storage systems are charged twice for using the grid – once when charging and again when discharging.

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EV and battery storage deployment grows rapidly over the next two decades, with light-duty EVs accounting for around 80% of the total



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Notes: Light-duty includes passenger light-duty vehicles, light commercial vehicles, and two- and three-wheelers. Heavy-duty vehicles include medium-sized freight trucks, heavy freight trucks and buses. BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; GWh = gigawatt hour.

Source: IEA (2020c).

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A range of minerals are needed in EV motors and batteries

Most of the critical minerals in EVs are in two components: electric motors and batteries.

EV motors

The two most common electric motor technologies for plug-in EVs are permanent-magnet synchronous motors and asynchronous induction motors (Ballinger et al., 2019).

Permanent-magnet motors have the highest efficiency and power density, but their use of REEs make them expensive compared to other technologies. In addition to neodymium (0.25–0.50 kg/vehicle) and other REEs (0.06–0.35 kg/vehicle), permanent-magnet motors also require copper (3–6 kg/vehicle), iron (0.9–2 kg/vehicle) and boron (0.01–0.03 kg/vehicle) (Ballinger et al., 2019; Fishman et al., 2018; Nordelöf et al., 2019; Sprecher et al., 2014).

Induction motors have the advantage of lower costs, but only have moderate efficiencies due to electrical losses in copper windings. While induction motors do not require REEs, they require a substantial amount of copper (11–24 kg/vehicle) for the rotor cage and copper stator (Ballinger et al., 2019).

We assume that permanent-magnet motors remain the dominant EV motor. We discuss alternative motors and the implications of high REE prices at the end of the EV section.

Batteries

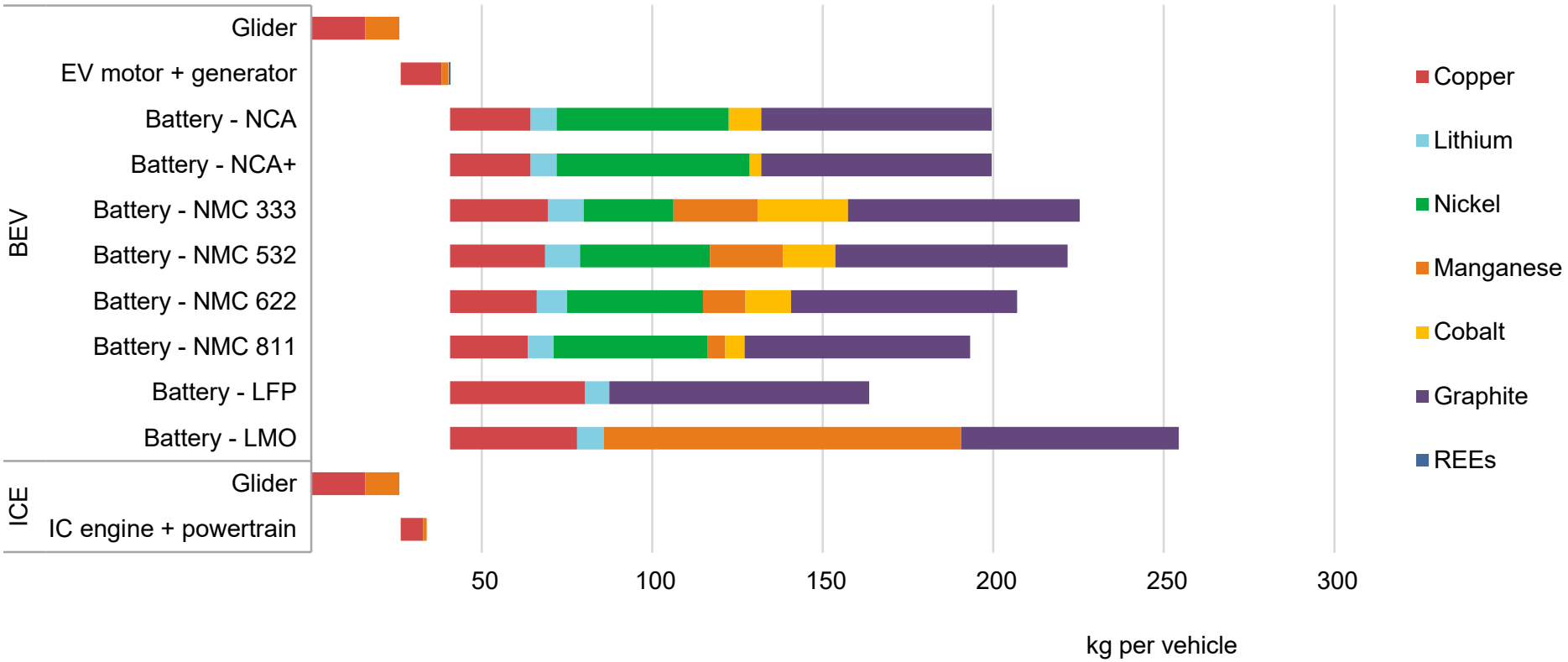
Lithium-ion batteries used in EVs and energy storage are composed of battery cells contained in battery modules within a battery pack. Cells typically account for 70% to 85% of the total battery weight, and contain a number of minerals in the active cathode material (e.g. lithium, nickel, cobalt and manganese), anode (e.g. graphite), and current collector (e.g. copper) (Argonne National Laboratory, 2020a). The remaining modules and pack components consist mostly of aluminium, steel, coolants and electronic parts.

The need for each mineral varies considerably depending on the cathode and anode chemistries. For example, nickel manganese cobalt oxide (NMC) 111 batteries typically require almost eight times more cobalt than nickel cobalt aluminium oxide (NCA+) batteries, but half as much nickel. Lithium iron phosphate (LFP) batteries do not require nickel, cobalt or manganese, but need about 50% more copper than NMC batteries.

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EVs use around six times more minerals than conventional vehicles

Typical use of minerals in an internal combustion engine vehicle and a battery electric vehicle



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Notes: For this figure, the EV motor is a permanent-magnet synchronous motor (neodymium iron boron [NdFeB]); the battery is 75 kilowatt hours (kWh) with graphite anodes.

Sources: Argonne National Laboratory (2020b, 2020a); Ballinger et al. (2019); Fishman et al. (2018b); Nordelöf et al. (2019); Watari et al. (2019).

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The evolution of cathode and anode chemistries could drive mineral use for batteries in varying directions

From the perspective of global energy transitions, the last ten years have proved to be the decade of the lithium-ion battery. The 2019 Nobel Prize-winning innovation not only transformed the world of electronics and realised the dream of electric mobility more rapidly than any of its predecessors, but it is also widely considered to be a vital missing piece of the puzzle integrating greater shares of variable renewables into our conventional electricity networks.

The fundamental advantage of lithium-ion batteries over alternatives like lead acid or nickel cadmium batteries is their much higher energy density. While lead acid batteries have specific energies in the range of 35 to 40 watt-hours per kilogramme (Wh/kg), lithium-ion batteries have a range of around 90–260 Wh/kg. This allows them to be stacked into far lighter and more compact battery packs than those made of other materials. The four main components of a lithium-ion cell are the cathode, anode, liquid electrolyte and separator. The lithium-ion donor from the cathode that travels through the liquid electrolyte is the primary determinant of cell properties and gives the technology its name.

Cathode chemistries

Lithium-ion batteries are often categorised by the chemistry of their cathodes. The most commonly used varieties are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). The different combination of minerals gives rise to significantly different battery characteristics.

Among the variants, LCO has the greatest energy density. Its high specific energy (150–190 Wh/kg) and technological maturity makes it a popular choice for portable electronics. The main drawback of the LCO battery is its thermal instability and its relatively short cycle life (500–1 000 full cycles). Coupled with safety concerns, LCO batteries are not favoured for application in EVs.

The LMO battery has a high specific power, a longer cycle life (1 000–1 500 cycles) and much better thermal stability than LCO. Being cobalt-free is often considered as a key advantage of this chemistry. However, it has a notably lower energy density, in the range of 100–140 Wh/kg. Presently, it finds use in the production of electric bikes and some commercial vehicles.

The LFP battery offers thermal stability even at high temperatures, low cost and high durability (up to 2 000 full cycles while maintaining its performance). However, its relatively low specific energy (90–140 Wh/kg) is a limitation for use in long-range EVs compared with other chemistries. Nevertheless, LFP batteries could be particularly

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favoured in stationary energy storage applications and heavy-duty vehicles like trucks where the size and weight of a battery are secondary considerations. Automakers in China are showing renewed interest in using LFP technology for manufacturing electric cars as they are cheaper, safer, simpler to package and do not require the use of cobalt or nickel. Volkswagen recently announced plans to use LFP batteries in its entry-level models (S&P Global Platts, 2021).

The NCA battery has the highest specific energy range (200–250 Wh/kg) in the current class of technologies as well as high specific power, combined with a lifetime of 1 000 to 1 500 full cycles. NCA is the technology preferred by manufacturers like Tesla, and has immense potential for use in power systems in backup and load shifting applications. However, they are more expensive than other chemistries.

NMC batteries have longer cycle life (1 000–2 000 cycles) compared to NCA, but a lower energy density (140–200 Wh/kg). It has dominated the BEV and PHEV markets since its commercialisation in the early 2000s. While NCA batteries have higher specific energy to their name, NMC batteries possess longer lifetimes, which makes them the favoured choice for PHEVs. Manufacturers producing both BEVs and PHEVs, such as General Motors, are known to use NMC variants of lithium-ion batteries.

Tug of war between nickel and cobalt

Advancement in lithium-ion battery technology involves more than just the challenge of improving energy density, durability, safety and cost. It also includes the effort to do so while minimising the environmental, social and political costs of acquiring their constituent materials.

Owing to price spikes and concerns over ethical mining practices in the 2010s, EV producers have been working to reduce the amount of cobalt in batteries over the past several years — this implies, in many cases, an increase in the quantity of nickel. NCA batteries transitioned to NCA+, a nickel-rich variant of NCA, and NMC 111 batteries have moved increasingly towards NMC 532, NMC 622 and NMC 811, and could move to even more nickel-rich chemistries (e.g. NMC 9.5.5). This trend of moving away from cobalt could therefore have major implications for the requirement for nickel.

Recent efforts to reduce the use of nickel capitalise on the potential of manganese, which is in relatively ample supply. SVOLT Energy Technology introduced battery cells that have a lower share of nickel and no cobalt by raising the use of manganese (Kane, 2021). A manganese-rich cathode is less expensive and safer than nickel-rich chemistries, but decreases the cathode's stability, which can have impacts on performance over the longer term (Nunez, 2020).

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Anodes must complement the cathode chemistries

Anode materials are selected for their charge collection capability. Graphite is currently the dominant choice for the anode in most lithium-ion batteries, although certain manufacturers also use lithium titanate instead of graphite. Efforts to replace some or most atoms of carbon in the graphite anode with silicon atoms are underway (e.g. Tesla, Porsche) and are expected to drastically improve the energy density of the cells. However, silicon anodes swell during charging, causing its surface to crack and performance to drop.

Another alternative to the graphite anode is pure lithium metal, which also has far greater charge collection capability than graphite. But this anode cannot be used with liquid electrolyte batteries due to undesirable chemical interactions between the electrolyte and the metal anode, which drastically reduces the lifetime of the cell. The use of a lithium metal anode may increase significantly with the advent of all-solid state batteries (ASSBs). Lithium-metal anodes do not have the expansion problem of silicon anodes, but they are expensive and present other technical problems.

Further technology innovation is needed to continue cost reductions

The average cost of lithium-ion batteries has declined by almost 90% over the past decade, falling to USD 137/kWh in 2020 (BNEF, 2020). These rapid cost reductions were made possible thanks to the remarkable growth in EV sales over the past decade and the continued penetration of high-energy density cathodes.

New pack designs and falling manufacturing costs can lead to further cost reductions in the near term. Costs are expected to fall below USD 100/kWh by the mid-2020s, a milestone often considered as one that will bring price parity between EVs and internal combustion engine vehicles (BNEF, 2020).

The path to lower battery costs could follow many routes, depending on a few major factors. First, as demand growth accelerates, maintaining a steady supply to meet that demand and preserve the drop in costs is likely to be increasingly challenging. Next, as we analyse in the next chapter, the sources and supply chains of the various critical minerals that are needed to bring these energy density improvements are often geographically concentrated in certain regions, and an uninterrupted supply cannot be taken for granted. Finally, as we reach the physical limits of improvement with current technology and materials, notable cost reductions can only be achieved by the disruption of the current technology – for example in the form of ASSB with lithium anodes or increased used of silicon in graphite anodes for existing chemistries. Therefore, the continued cost decline at a pace observed during the past decade cannot be taken for granted without a further acceleration in technology innovation.

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Innovation on the horizon: The advent of all-solid state batteries

As current technology and materials bring us ever closer to the theoretical limits of improving energy density, and battery prices start to plateau by the middle of this decade, the world needs to look beyond the liquid electrolyte-based lithium-ion batteries. A significant improvement in the energy density of EV batteries and a steep decline in battery prices would require the disruption of the present technology. Such a breakthrough is expected from the advent of lithium metal anode all solid-state batteries (ASSBs).

Most state-of-the-art commercial batteries with NCA, NMC or LFP cathodes require a liquid electrolyte for ion transfer and a graphite-based anode. These two components fundamentally limit the functionality and energy density of lithium-ion batteries today. The flammability of the solvent in the electrolyte raises many safety concerns (Hess et al., 2015), and undesirable reactions between the solvent and the conductive lithium salt lead to capacity fading and ageing (Hendricks et al., 2015). Moreover, the electrolyte filling process makes the production line more cumbersome and expensive (Wood et al., 2015). A compact solid electrolyte not only circumvents these issues but also enables[3] the use of lithium metal as the anode (Varzi et al., 2016).

ASSBs equipped with lithium metal anodes could achieve a volumetric energy density up to 70% greater than today's lithium-ion batteries that have conventional graphite anodes (Janek & Zeier, 2016), making them the ideal batteries for EVs of the future. As an added advantage, ASSB do not require expensive cooling systems due to the absence of a flammable electrolyte. They have in fact displayed better functionality at higher temperatures due to increased conductivity.

While experts predict that current lithium-ion batteries could reach a maximum energy density of 300 Wh/kg after 2025, lithium metal solid-state batteries with densities of 320 Wh/kg have already been fabricated (Placke et al., 2017) and their maximum potential could be as high as 480 Wh/kg. This improvement in energy density would mean that batteries of the same size could contain much more energy in the future, thereby resulting in an effective reduction in the weight and cost of the new battery packs. The greatest challenge facing this new technology is scaling up the production to make it commercially viable, since a direct transfer of laboratory preparation methods to industrial-scale fabrication is not always successful.

[3] Solid electrolytes act as a physical barrier to the formation of lithium dendrites that could form from the lithium anode and short-circuit the cell by connecting the anode and the cathode.

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Solid-state lithium metal anode batteries are reported to mostly be designed with NMC cathodes; however, they could also be combined with new cathode chemistries. The use of sulphur in lithium-based cathodes (Li-S) is being viewed as a promising technological avenue because of its very high theoretical energy density. Current prototypes developed by start-ups (Oxis-energy) already reach cell-level energy densities of over 500 Wh/kg; however, they are limited to aerospace applications due to their low cycle life. Another study published by Samsung reported an anode made of carbon black, and silver nanoparticles (Ag-C) coated on stainless steel as the anode (Lee et al., 2020). This allows even better energy density than a lithium metal anode. Nevertheless, for this analysis the ASSB scope is limited to lithium-metal anodes combined with traditional NMC cathodes, due to greater availability of data and information on the prototypes of this technology.

After a robust and cost-effective scale-up process is found, the design of electric cars equipped with ASSB would take between three to five years; this explains why several manufacturers have already begun investing in R&D for this new battery technology. For example, Colorado-based start-up Solid Power already has partnerships with Ford Motor Company and BMW Group, and they believe the roadmap for commercial use of their ASSB in the automotive industry is well-defined. The company estimates a 10–15% reduction in the total cost of a battery pack compared to their liquid electrolyte counterparts, with most of the savings coming from enhanced packing density. If researchers and manufacturers find the solution to mass producing these new batteries within the next five years, ASSB would be competing with the incumbent lithium-ion batteries for space on the roads by the early 2030s and, thus, launch the next phase of electric mobility.

Synergies between EVs and battery storage

Historically, trends from the automotive industry have often transferred to the power sector. Progress on improvement in EV batteries could benefit stationary storage system technologies, while the converse may not necessarily be true. Batteries for EVs must be energy dense, small, safe and light, and have high cycle life. Energy storage systems, by contrast, do not have such strict requirements for size and weight, but instead prioritise cost, durability and safety.

Although NCA and NMC batteries might be considered too expensive for most large-scale energy storage systems, they are ideal for wall-mounted residential batteries used in combination with solar panels, and their price could also be justified in certain large-scale storage applications in cities with high population densities, where space is limited and energy density becomes crucial. A fair compromise between the two applications is the LFP battery, with lower energy density than NMC and NCA, but still small enough for buses and trucks, inherently safer chemical composition, non-reliance on cobalt and nickel, and lower prices more suitable for stationary applications.

Besides lithium-ion batteries, flow batteries could emerge as a breakthrough technology for stationary storage as they do not show

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performance degradation for 25–30 years and are capable of being sized according to energy storage needs with limited investment. One of the most modern commercial Vanadium redox flow batteries, with a lifetime of 12 000 cycles at full power, went online in eastern Spain to operate with the Vega wind farms in December 2019 (Bellini, 2020). However, flow batteries employ a completely different technology, wherein their specific energy depends on the volume of the electrolyte and specific power depends on the surface area of the electrodes, and they are therefore much too large for EV applications.

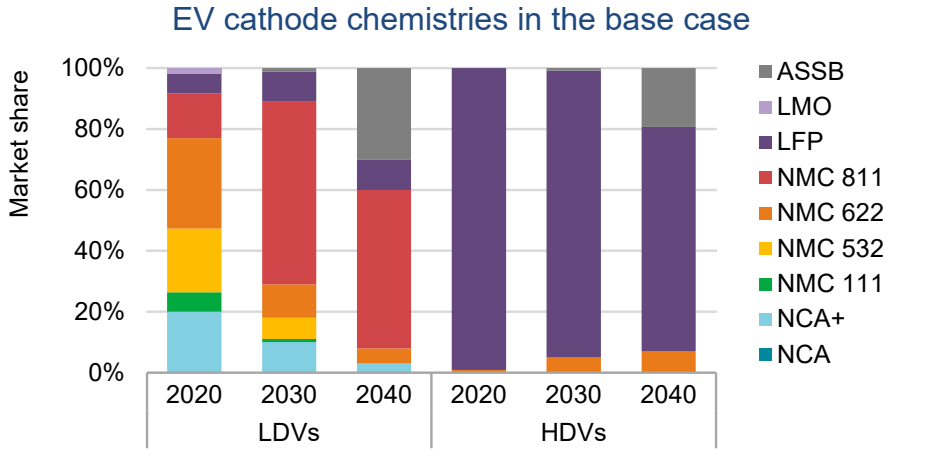
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Passenger EVs shift from cobalt towards nickel-rich cathodes, with a slow uptake of solid state batteries

As it has become evident that reducing cobalt content in the cathode and striving for higher energy density are key concerns for most manufacturers and countries, the base case scenario sees a shift away from cobalt-rich chemistries. This is achieved in both NCA batteries and NMC variants, where the ratio of nickel and manganese are increased in the transition from NMC 111 to NMC 532, NMC 622 and ultimately NMC 811.

While most heavy trucks are reliant on LFP batteries in the medium term, our base case also sees modest growth in the market share of LFP for cars due to its increasing use in China and entry-level models from VW.

The base case sees ASSB becoming commercially available by around 2030 and requiring another 5 years for manufacturing capacity to build up. Even in 2040, ASSB remain more expensive than lithium-ion batteries and are therefore limited to premium vehicles and developed countries. In the longer term, heavy trucks operating long haul are likely to use ASSB as soon as they become available because of the great benefits of energy density improvement in these applications. They would enable increased payload, greater operating range and shorter charging times.



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Notes: LDVs = light-duty vehicles (passenger cars and vans, light commercial vehicles, and 2- and 3-wheelers); HDVs = heavy-duty vehicles (trucks and buses).

Sources: IEA analysis complemented by Adamas Intelligence (2021a) and EV-Volumes (2021).

For the anode, natural graphite is expected to continue to account for the majority of market share. Even as artificial graphite starts to replace natural graphite for reasons of improved purity and hence energy density, a small number of manufacturers choose lithium titanate (LTO) instead of graphite for heavier vehicles due to its fast-charging advantages. The dominance of graphite declines very slightly over the years to make way for nanocomposite graphite

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doped with silicon and for lithium metal that emerges with the advent of ASSBs.

Results

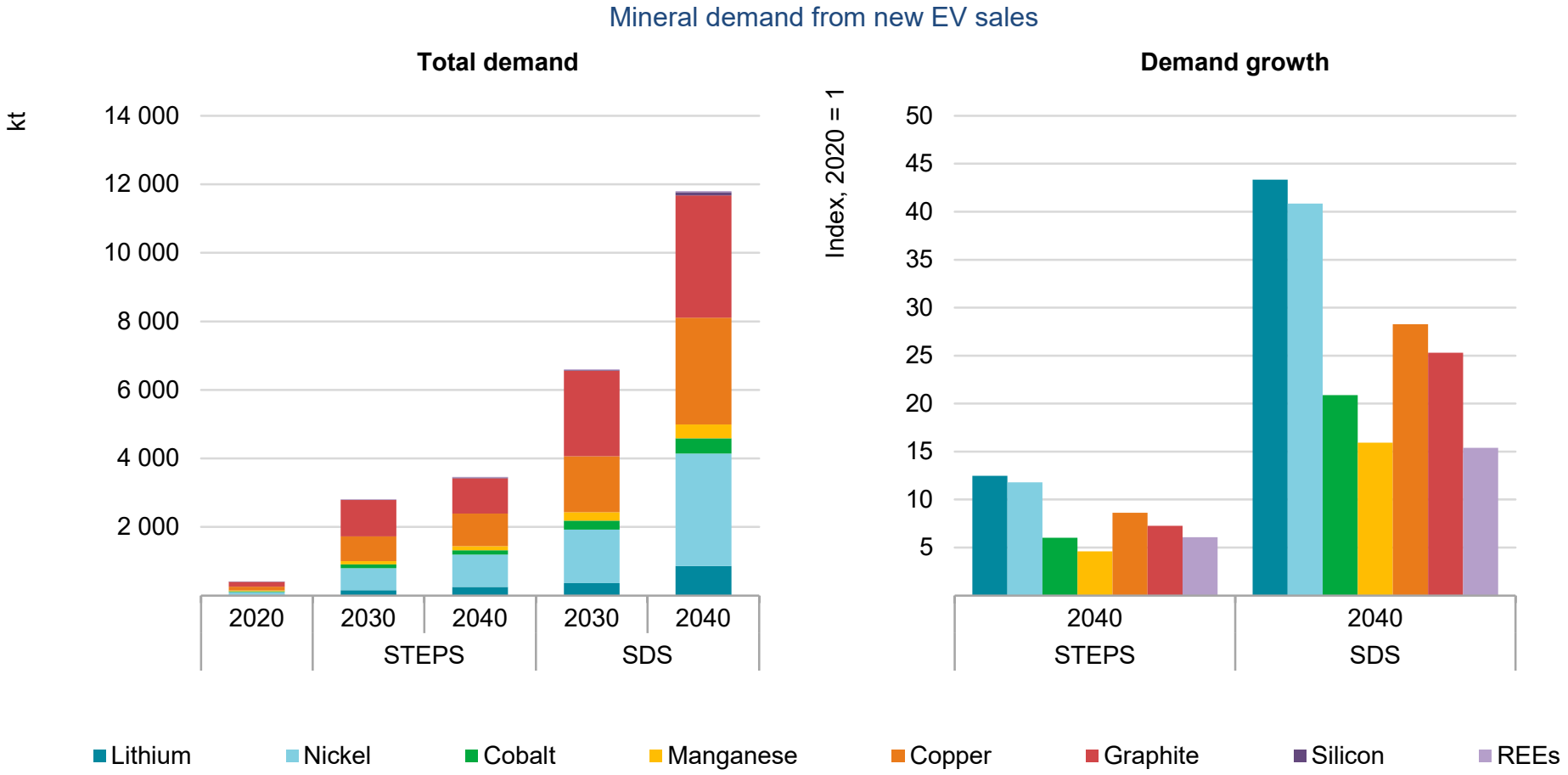
In the SDS, battery demand from EVs grows by nearly 40 times between 2020 (160 GWh) and 2040 (6 200 GWh). Overall demand for minerals under the base case assumptions grows by 30 times between 2020 and 2040, from 400 kt to 11 800 kt. In the STEPS, battery demand from EVs grows just 11 times to nearly 1 800 GWh in 2040, with demand for minerals growing ninefold to around 3 500 kt in 2040.

In the SDS, nickel demand grows by 41 times to 3 300 kt, while cobalt increases by only 21 times, as cathode chemistries shift away from NMC 111 towards lower-cobalt chemistries (NMC 622 and NMC 811). Lithium demand grows by 43 times, while copper grows 28 times.

Graphite demand grows 25 times from 140 kt in 2020 to over 3 500 kt in 2040. Silicon registers the largest relative growth, up over 460 times, as graphite anodes doped with silicon grow from a 1% share in 2020 to 15% in 2040. Demand for REEs grows 15 times to 35 kt in 2040.

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Mineral demand for EVs in the SDS grows by nearly 30 times between 2020 and 2040, with demand for lithium and nickel growing by around 40 times



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Note: Silicon is excluded from the demand growth graph due to its very high growth (over 500-fold increase), starting from a low base.

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Alternative cases for EVs

The base case projections are founded on a set of assumptions, which, when altered due to reasons of technology advancements, could result in scenarios that produce very different results. We therefore built three alternative scenarios and assessed how the demand outlook for various minerals could change under varying technology evolution trends.

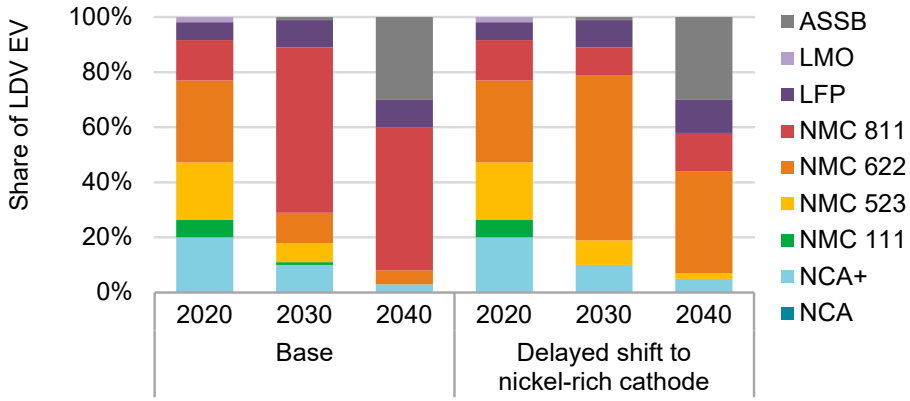
Delayed shift to nickel-rich cathode

On the cathode side, price spikes and social concerns surrounding cobalt mining a few years ago triggered efforts to reduce cobalt content in lithium-ion batteries. But cobalt currently appears to be well supplied, at least in the short term. Instead, a rapid move towards nickel-rich chemistries may be causing signs of tightness in the nickel supply chain. The near-term supply prospects for Class I nickel depend on whether planned projects in Indonesia can be carried out smoothly (see Chapter 3).

The first alternative case therefore explores the outcome of the growing concerns about nickel supply and potential price increases in the medium term. Should there be delays and cost overruns at planned projects, it is not inconceivable for battery-grade nickel prices to rise, in conjunction with relatively stable cobalt prices, to slow shift towards the nickel-rich chemistries.

In this case, we study the impact of a delayed shift to nickel-rich chemistries for NCA and NMC batteries due to supply uncertainties for nickel, while LFP, the emergence of ASSB and anode materials remain as they are in the base case.

Cathode chemistries for light-duty EVs in the delayed shift to nickel-rich cathode case



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A delayed shift to nickel-rich chemistries (and away from cobalt-rich chemistries) results in nearly 50% higher demand for cobalt and manganese in 2040 compared to the base case. Nickel demand is 5% lower in 2040 compared to the base case.

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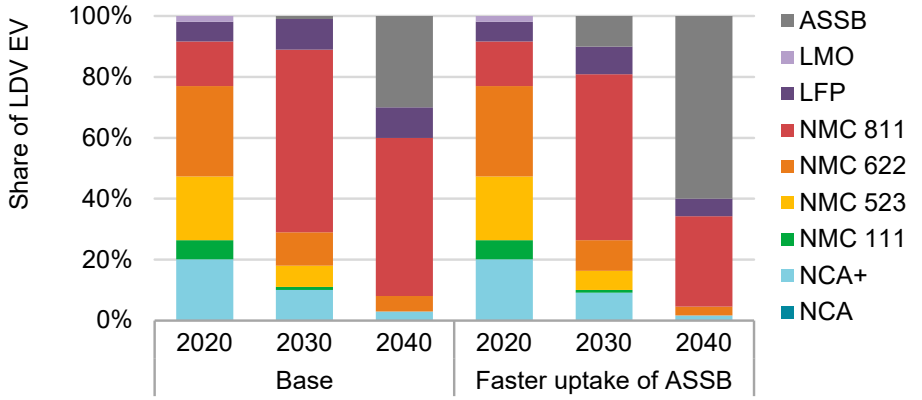
Faster uptake of lithium metal anode all-solid state batteries

While we assumed ASSB to take off meaningfully in the 2030s given the challenges around scale-up, much earlier commercialisation and faster penetration of ASSB in the EV market could alter the outlook for minerals considerably. This would reflect major breakthroughs in ASSB that have been made in recent years. ASSBs are safer as they do not contain a flammable liquid electrolyte and could be cheaper as their cell structure is simpler and does not need cooling mechanisms for safety. They represent disruption of current technology, rather than incremental improvements in existing lithium-ion technologies.

We explore a much faster uptake of ASSB in the EV market, starting with a small market share as early as the late 2020s. Its presence in the market then grows significantly in the 2030s, even taking up more than half the market by 2040 and ultimately capturing around three-quarters of the electric car market by 2050. This case would imply higher consumption of lithium, as ASSBs considered in this report use pure lithium metal anodes instead of graphite. (Lithium metal can only be used as the anode in ASSBs; undesirable interactions with the liquid electrolyte in lithium-ion batteries rapidly reduces the lifetime of the battery.)

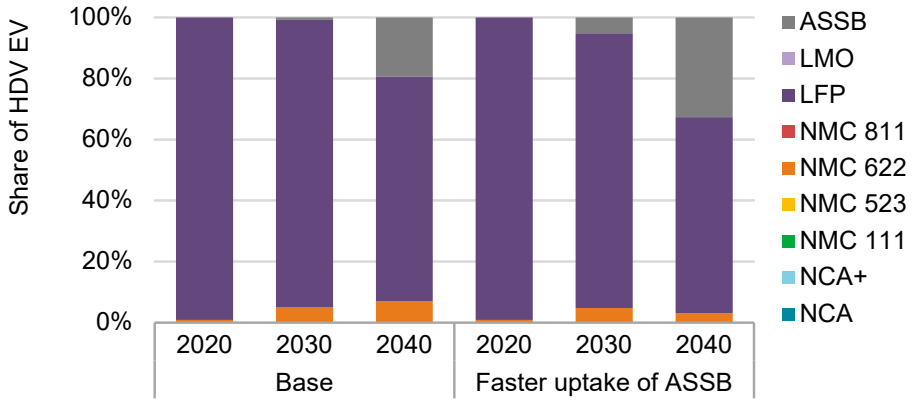
The faster uptake of lithium metal anodes and ASSB results in 22% higher lithium demand in 2040 compared to the base case, but also much lower demand for graphite (down 44%) and silicon (down 33%).

Cathode chemistries for light-duty EVs in the faster uptake of ASSB case



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Cathode chemistries for heavy-duty EVs in the faster uptake of ASSB case



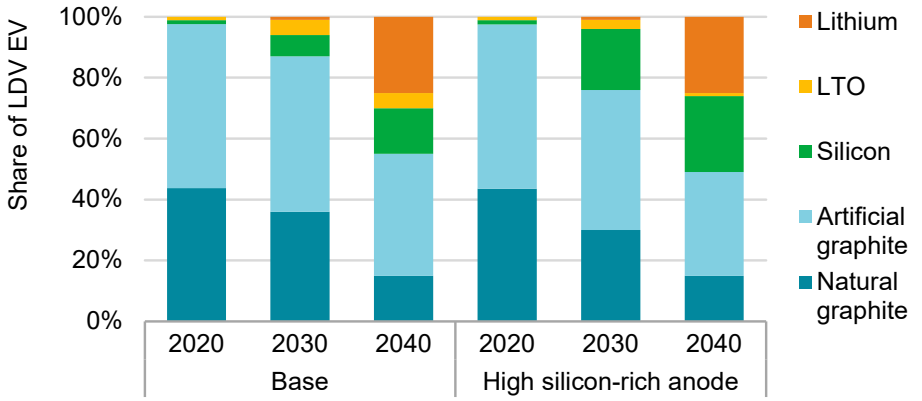
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Moving more rapidly towards a silicon-rich anode

For the anode, silicon (and lithium) have roughly 10 times as much capacity to hold electrons as graphite and, thus, can improve the energy density of a battery by 20–50%. Many major manufacturers of lithium-ion batteries are increasingly venturing into higher silicon quantities in the anode in order to improve energy density. In this alternative case, we consider the result of achieving higher-level (around 20%) silicon doping for graphite anodes compared to the base case by 2030, and further improvement in the technology leading to even higher doping levels by 2050.

Anode shares for light-duty EVs in the high silicon-rich anode case



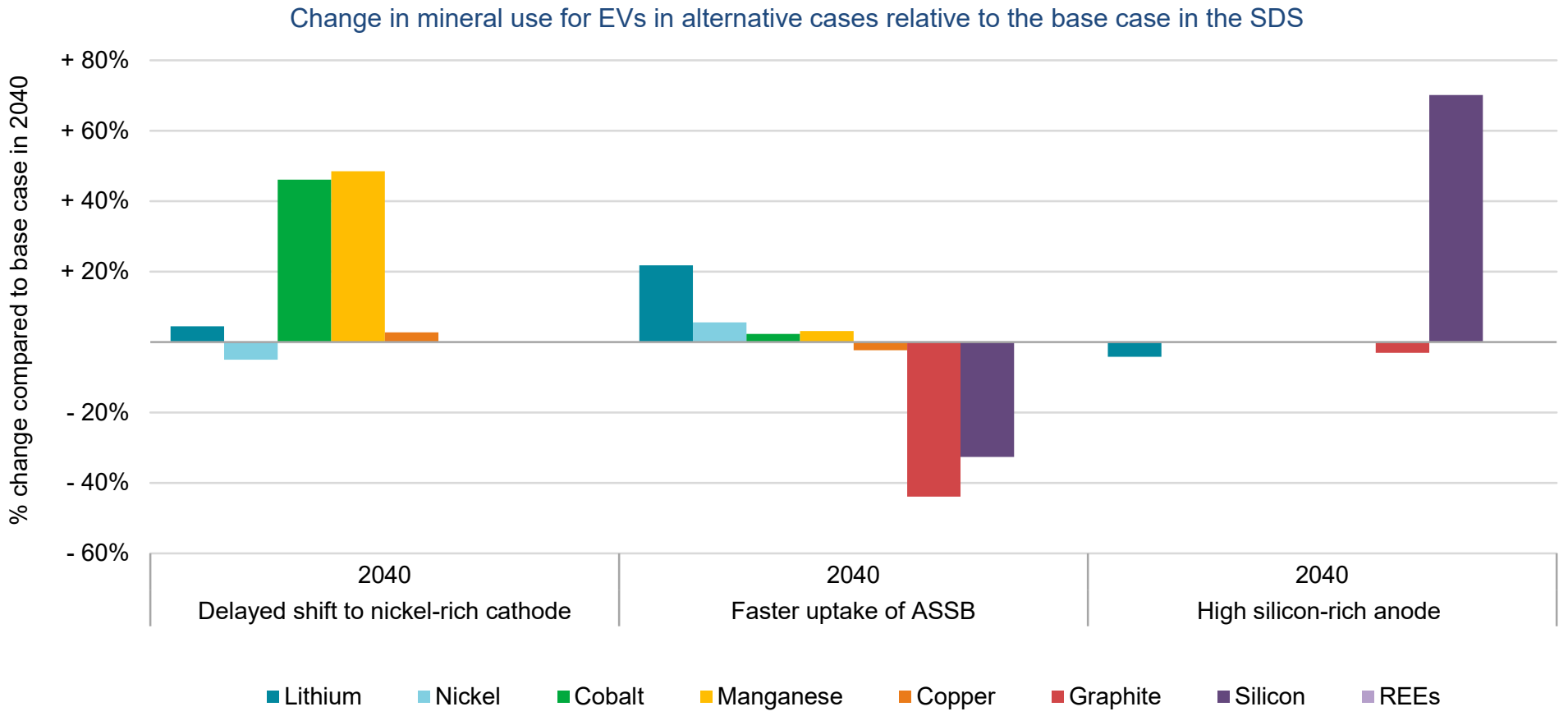
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Note: LTO = lithium titanate oxide.

Moving rapidly towards a silicon-rich anode results in nearly three times as much silicon demand in 2030 compared to the base case, and a slight decrease in graphite demand (down 6%). By 2040 silicon demand is only 70% higher, owing to a higher adoption of silicon-rich anodes even in the base case.

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The alternative cases demonstrate the considerable sensitivity and uncertainty of mineral demand to the future mix of EV battery chemistries



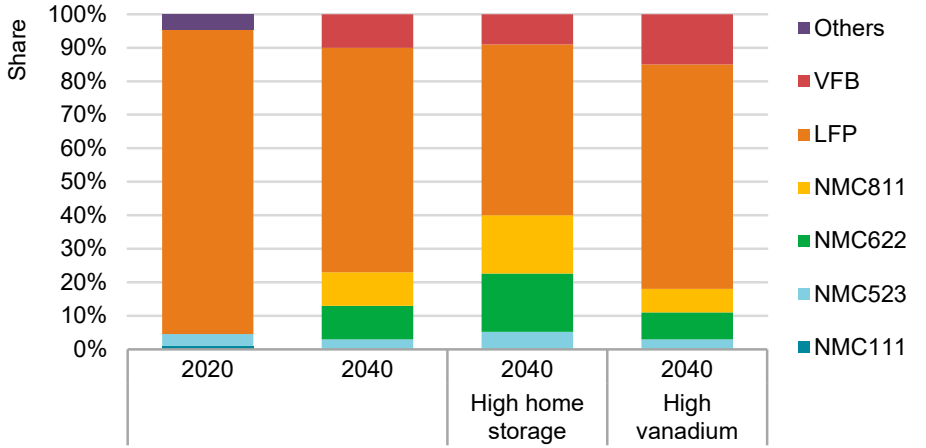
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Utility-scale storage is expected to dominate the battery storage market

Safe and cheap LFP batteries for utility-scale storage are expected to dominate the overall battery storage market. The remaining demand is covered by the more expensive, but energy-dense, NMC 111 and NMC 532 used predominantly for home energy storage. The NMC variants transition towards NMC 622 and NMC 811 in a similar way to the market for EV batteries, albeit with a delay owing to the time needed for transfer of technology and sufficient reduction in prices. Vanadium flow batteries (VFBs) first become commercially suitable in 2030 with a small share, growing modestly to capture a wider market for storage applications in large renewables projects.

Cathode chemistries for storage



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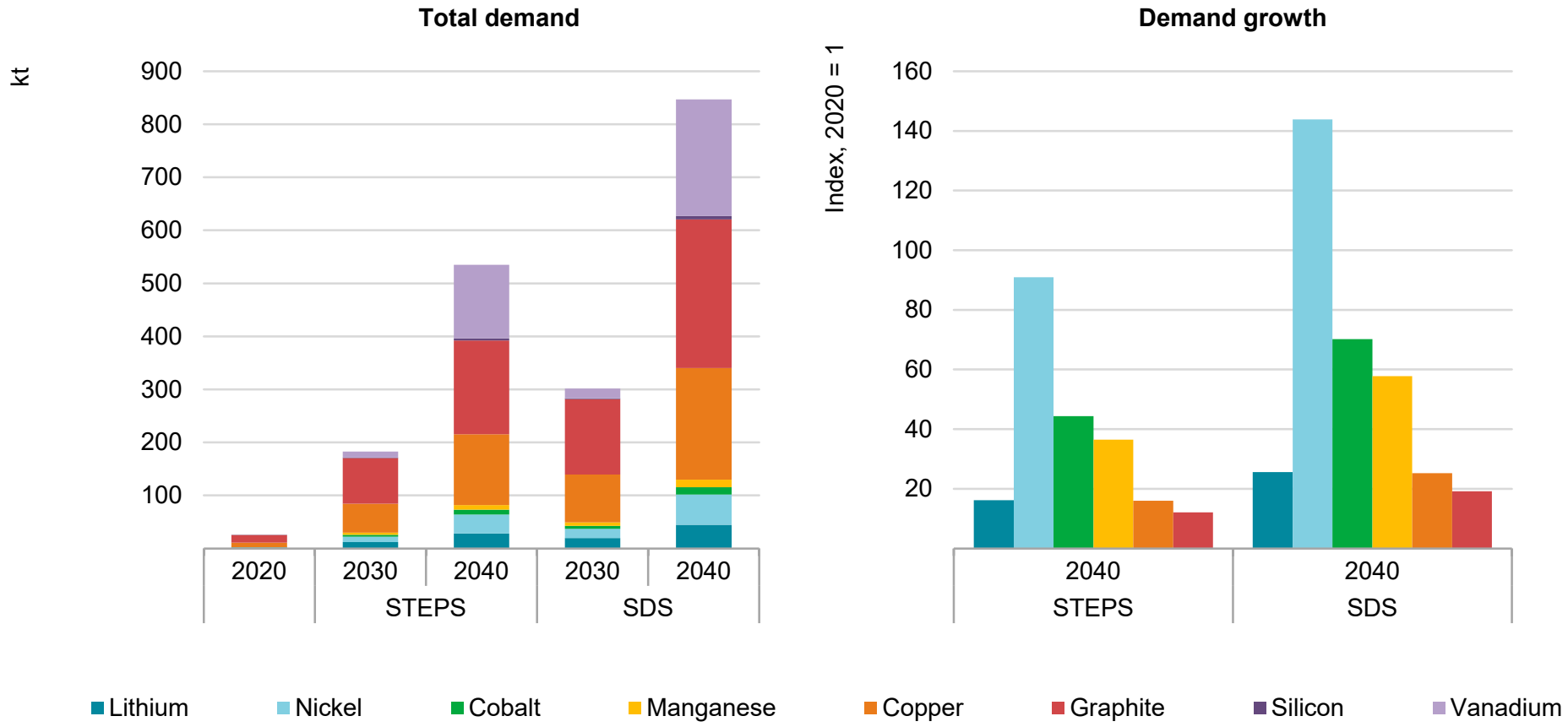
In the SDS, battery storage grows by 11 times between 2020 (37 GWh) and 2040 (420 GWh). Overall demand for minerals in the base case grows by 33 times between 2020 and 2040, from 26 kt to nearly 850 kt. Overall mineral demand outpaces battery demand growth, as the market share for LFP batteries is displaced by more mineral-intensive NMC chemistries.

The largest relative growth is seen in nickel, which grows more than 140 times from 0.4 kt in 2020 to 57 kt in 2040. Cobalt demand increases by 70 times while manganese demand increases by 58 times.

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Mineral demand for storage in the SDS grows by over 30 times between 2020 and 2040, with demand for nickel and cobalt growing by 140 times and 70 times respectively

Mineral demand from battery storage additions in the SDS



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Note: Silicon and vanadium are excluded from the demand growth graph.

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Alternative cases for energy storage

The base case for energy storage systems is built on the assumption that utility-scale storage forms a major proportion of the demand, wherein cost (and not space) is the primary concern for the technology selection. However, several alternative scenarios could alter the base case projections. For instance, more rapid adoption of wall-mounted home energy storage would make size and thus energy density a prime concern, thereby pushing up the market share of NMC batteries such as those already used by the Tesla Powerwall. Conversely, if the technology for flow batteries, which have the advantage of virtually unlimited energy capacity and very long lifetimes, reaches a stage of widespread commercialisation earlier than expected, then utility-scale storage technology could shift away from LFP batteries towards VFBs.

Rapid adoption of home energy storage

In this alternative case, we investigate the outcome of a scenario where demand for storage beyond utilities grows rapidly. Here, the NMC battery share grows faster, achieving around a quarter of the market share by 2030 and almost half by 2050. They are used in applications such as home energy storage (e.g. storing solar electricity for self-consumption, time-of-use load shifting, backup power and increased off-grid applications). In many of these applications, space is one of the most important concerns, making the more energy-dense NMC more favourable than their LFP counterparts. The split between NMC 532, NMC 622 and NMC 811 evolves more or less as for the EV batteries base case. The trajectory for VFBs remains as for the base case.

The rapid adoption of home energy storage with NMC chemistries results in 75% higher demand for nickel, manganese and cobalt in 2040 compared to the base case. A faster uptake of silicon-rich anodes also results in 20% greater demand for silicon compared to the base case in 2040.

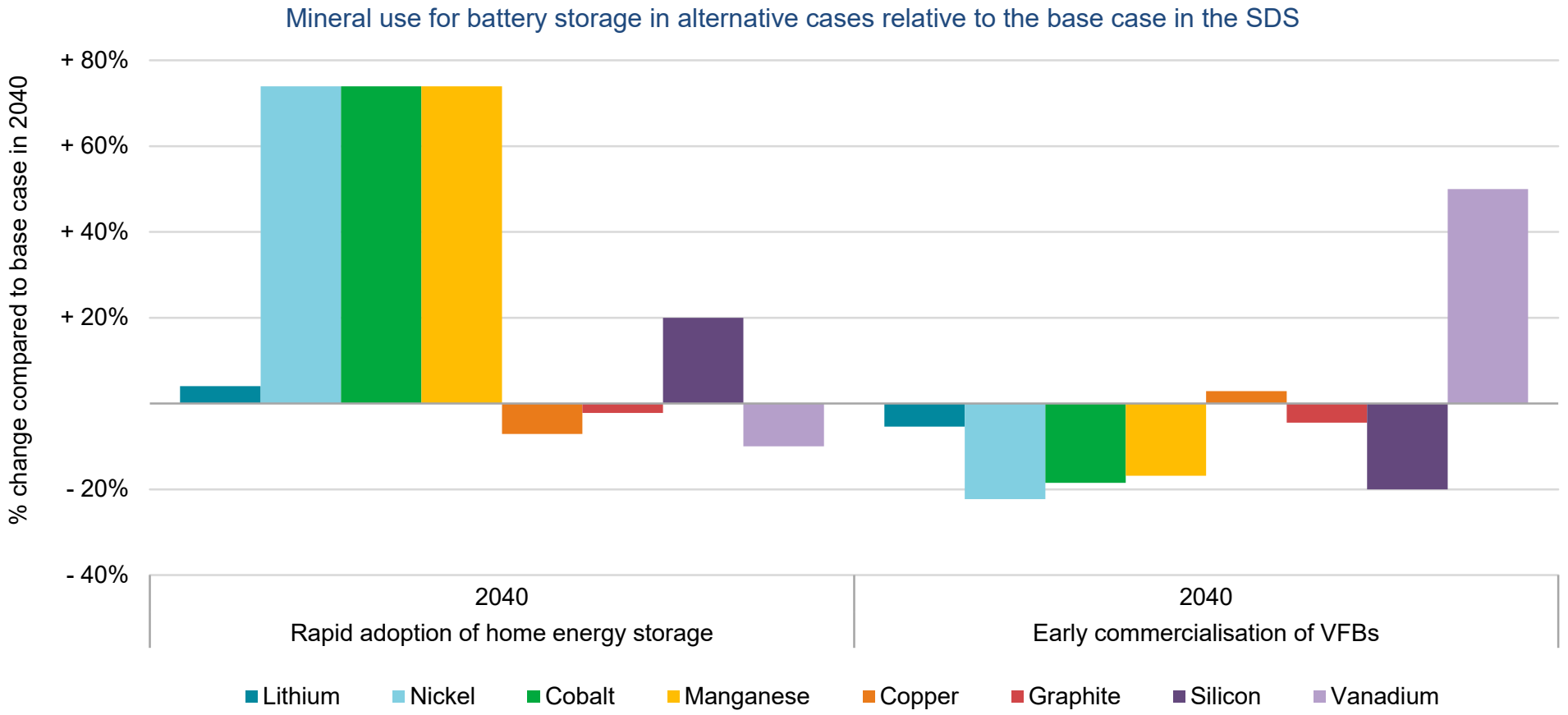
Early commercialisation of Vanadium flow-batteries

In this case, the technology for VFBs reaches the level of maturity required to be deployed in large-scale projects earlier than in the base case. They increase their market share from 2030 onwards and capture almost a third of the energy storage market by 2050, with maximum applications in large wind and solar farms.

The early commercialisation of VFBs results in 2.5 times more demand for vanadium compared to the base case in 2030 and 50% more demand in 2040. As a result of lower market shares for NMC chemistries, demand for nickel, cobalt and manganese are about 20% lower in 2040 compared to the base case.

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More rapid adoption of home energy storage could increase demand for nickel, cobalt and manganese – but these increases are dwarfed by demand from EVs



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Could mineral prices be an obstacle for further battery cost declines?

The average cost of lithium-ion batteries has fallen dramatically over the past decade, reaching USD 137/kWh in 2020 (BloombergNEF, 2020). Further cost reductions are necessary for EVs to achieve the adoption rates observed in the SDS. In the near term, the US Department of Energy has set a target of reaching USD 125/kWh by 2022 for BEVs to attain cost parity with internal combustion engine vehicles. Tesla expects to slash costs by half between 2020 and 2023 to achieve pack costs of around USD 60/kWh (Irvine & Rinaldo, 2020). The SDS requires battery prices to reach USD 100/kWh by 2030.

Several automakers are scaling up battery production to drive further cost reductions. For example, Tesla's first Gigafactory in Nevada began mass production of cells in January 2017, helping to reduce battery production cost by 30%. In addition to scaling up production volume, further cost reductions can be achieved by optimising cell fabrication to increase energy density, reducing manufacturing costs and enhancing pack assembly efficiency (Ding et al., 2019).

However, with major technological improvements achieved over the past decade, raw materials now account for the majority of total battery costs (50–70%), up from around 40-50% only five years ago (Argonne National Laboratory, 2020a; Pillot, 2017, 2019). Cathode (25–30%) and anode materials (8–12%) account for the largest shares. Labour costs account for around 2–4%.

Models used to project future battery costs typically rely on production volume assumptions and technology learning rates. However, the growing share of raw materials in total battery costs implies that this approach based on economies of scale and efficiency improvement might not provide a good guide to future cost developments, as raw material costs may well develop in a different direction from other cost components.

Given the importance of material costs in total battery costs, higher mineral prices could have a significant effect on achieving industry cost targets. For example, a doubling of lithium or nickel prices would induce a 6% increase in battery costs. If these events happen at the same time, the cost increase would eat up the anticipated learning effects associated with a doubling of capacity.

It is therefore of paramount importance for governments and industry to work to ensure adequate supply of battery metals to mitigate any price increases, and the resulting challenges for clean electrification.

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High prices for rare earth elements could see a shift away from permanent-magnet motors towards induction motors, increasing demand for copper or aluminium

Over 90% of the EVs marketed today use permanent-magnet synchronous motors due to their high efficiency, compact size and high power density (Adamas Intelligence, 2021b; Pavel et al., 2017). However, their use of REEs such as neodymium, praseodymium, dysprosium and terbium – upwards of 1 kg per motor – raises concerns given the geographical concentration of raw material and processing in China, the lack of recycling pathways and high price fluctuations. For example, the price of neodymium has surged over the past six months from around USD 60/kg in June 2020 to over USD 120/kg in February 2021.

There are several pathways to reducing REE use in EV motors: (i) improving material efficiency in magnet production to obtain NdFeB magnets with less REE content but with similar performance; (ii) reducing the amount of NdFeB magnets in permanent-magnet synchronous motors; (iii) substituting permanent-magnet motors with REE-free motors.

Improved material efficiency in magnet production can reduce REE content in permanent magnets but with similar performance characteristics. For example, material efficiency for neodymium and praseodymium may improve by up to 30% between 2015 to 2030 in a permanent magnet of equal magnetic strength and cost (Pavel et al., 2017).

The use of permanent-magnet motors with less (or no) rare-earth magnets could also reduce REE use. For example, the BMW i3 uses a “hybrid” motor that uses around half the REE. Induction motors use no REEs, but require a substantial amount of copper (11–24 kg/motor) and are less efficient than those with permanent magnets. They are already used in several BEV models, including the Tesla Model S. There are options to also reduce copper use in induction motors: for example, the Audi e-tron uses an aluminium-rotor induction motor. Switched reluctance motors are also REE-free, but are still in the early stages of development.

Summary of motor types

	Mineral use	Current status and examples
Permanent-magnet synchronous	Neodymium, dysprosium, dysprosium, terbium	Used in all HEV and most PHEV and BEV
Induction	No rare earths; but significant copper or aluminium use	Some BEVs (e.g. Tesla S, Mercedes B)
Permanent-magnet without REE	No rare earths; potentially some nickel and cobalt use	Prototypes using ferrite or AlNiCo magnets
Switched reluctance	No rare earths or copper	First prototypes

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Note: HEV = hybrid electric vehicle.

Sources: Agamloh et al. (2020); Pavel et al. (2017); Widmer et al. (2015).

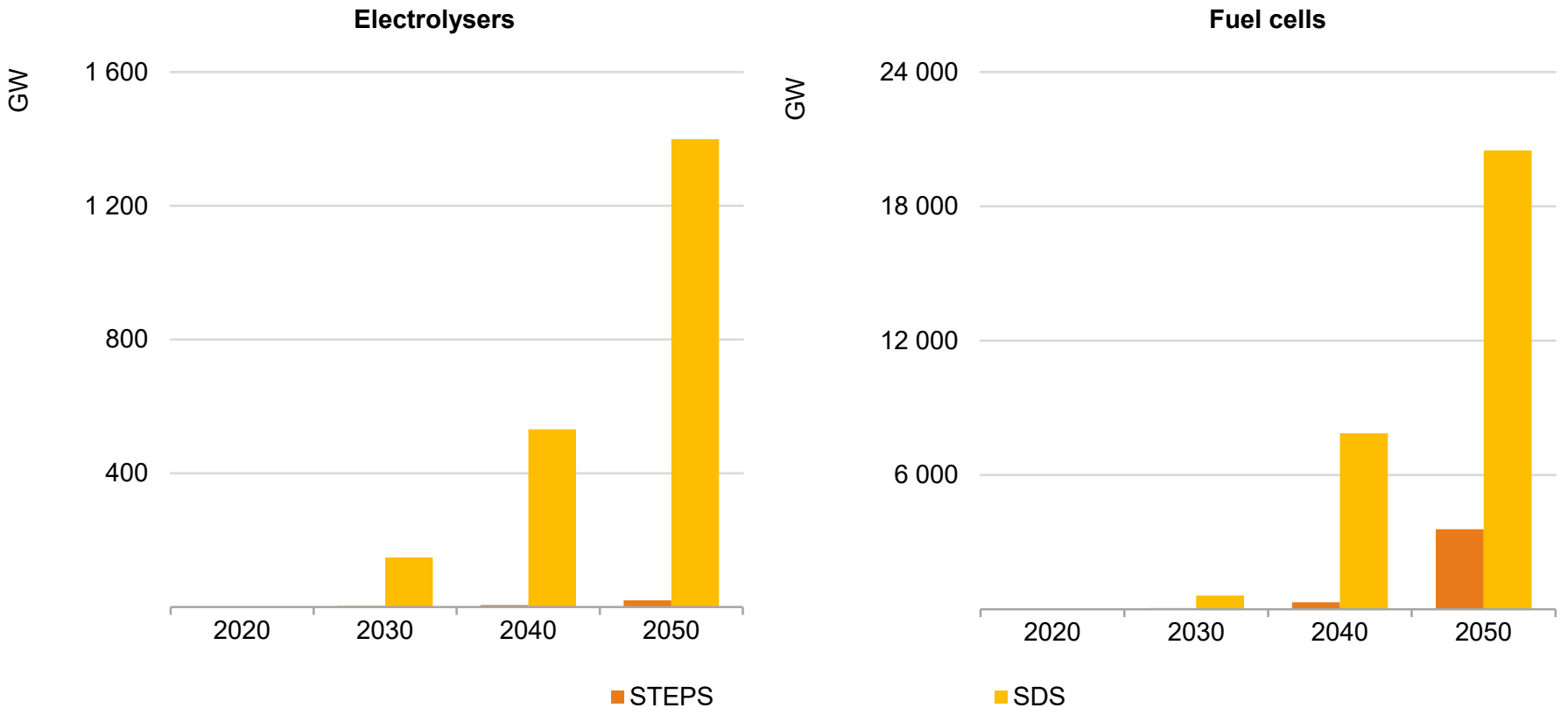
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Hydrogen

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Electrolysers that supply hydrogen and fuel cells that use it in vehicles are both major growth areas in the SDS, and present different mineral requirements

Global installed capacity of electrolysers and fuel cells in the SDS

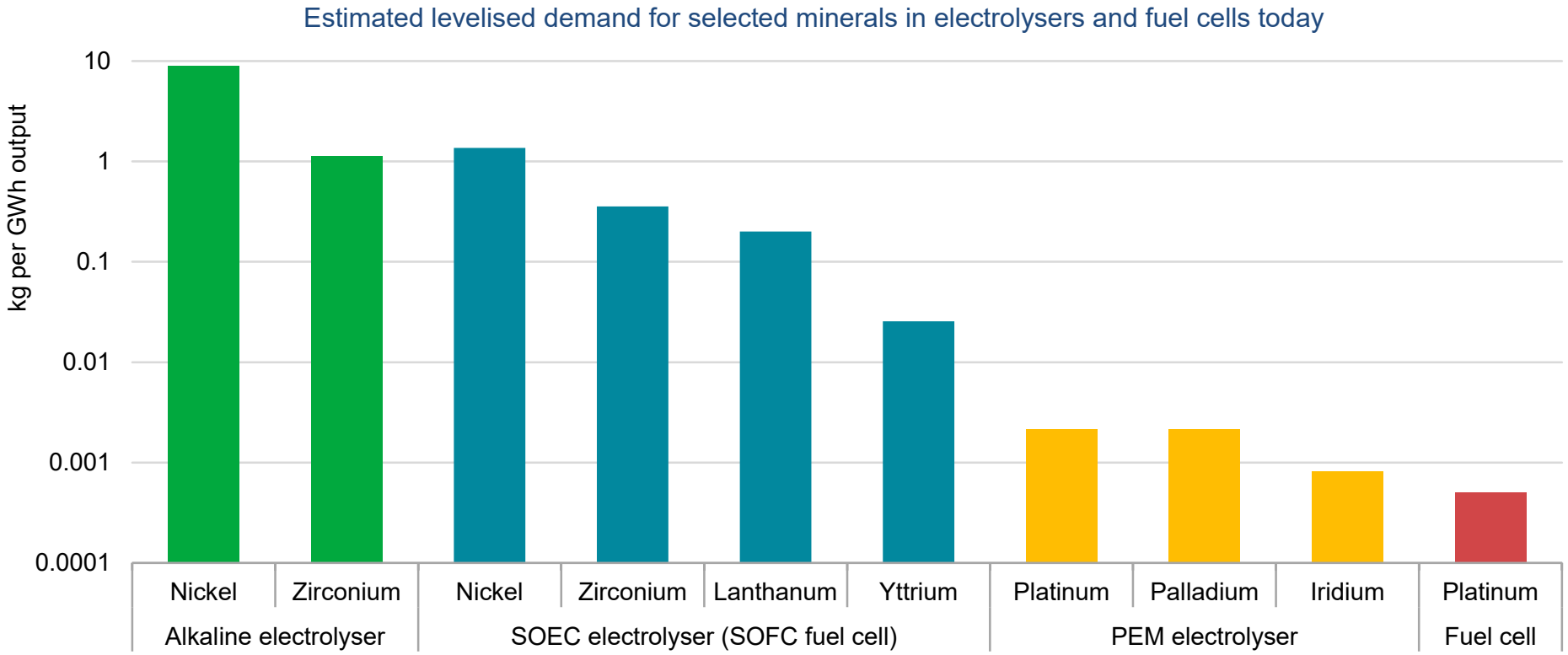


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Source: IEA (2020c).

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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



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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).

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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

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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.

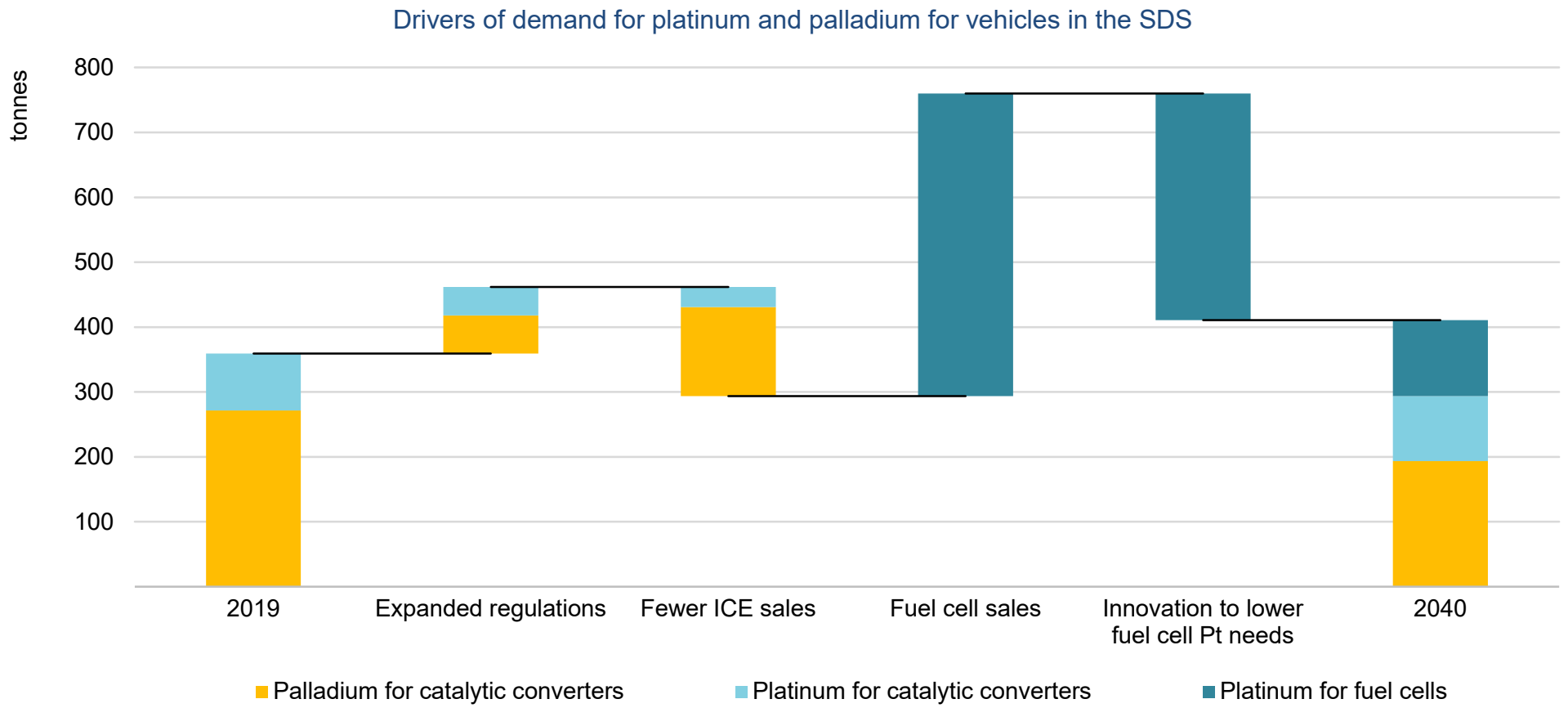
If PEM were to dominate the hydrogen market, it would increase energy-sector demand for platinum and iridium. PEM catalysts currently use around 0.3 kg of platinum and 0.7 kg of iridium per MW. Experts believe reductions to one-tenth of these amounts are possible in the next decade in order to minimise 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.

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



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Note: Pt = platinum.

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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.

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Reliable supply of minerals

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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.

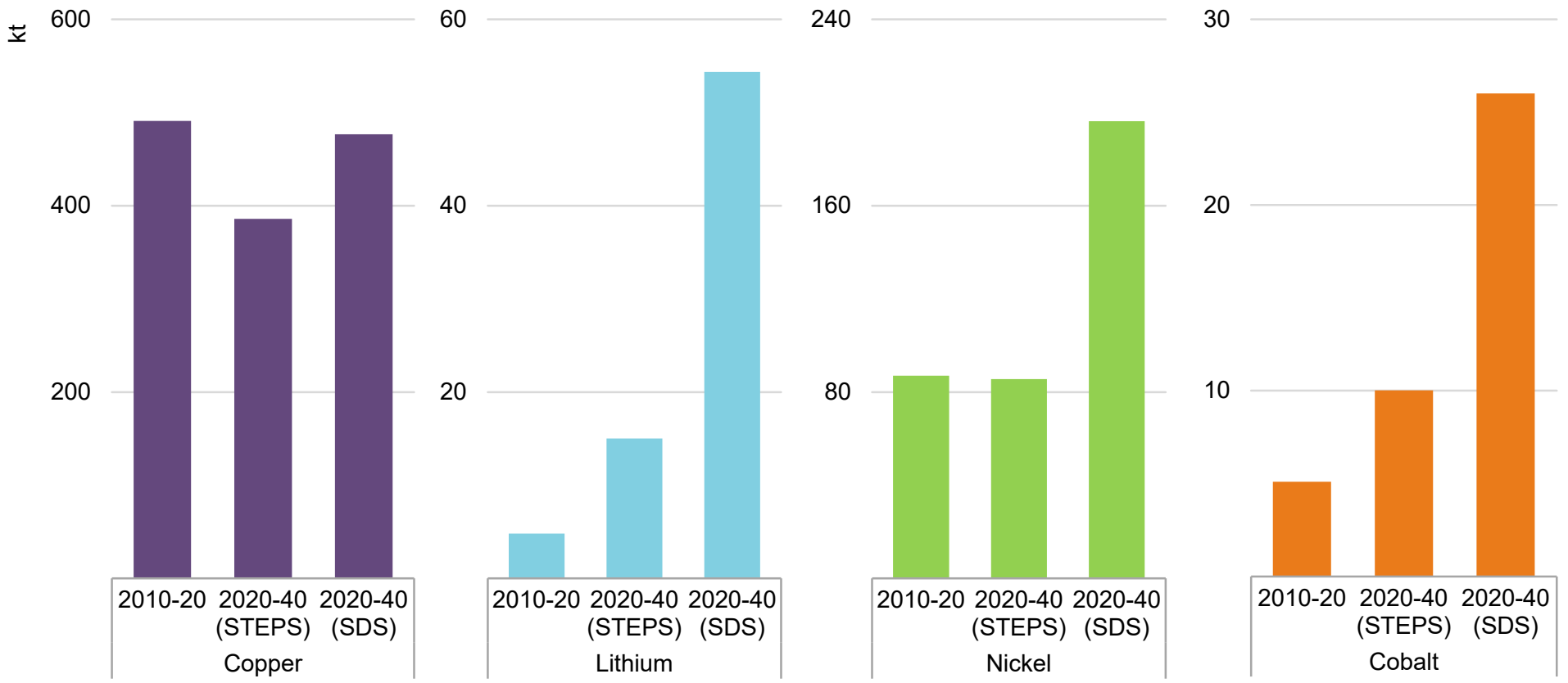
In this chapter we examine some of the major vulnerabilities that may hinder adequate supply and lead to greater price volatility, focusing on the five focus minerals (copper, lithium, nickel, cobalt and rare earth elements [REEs]) that play a particularly important role in many clean energy technologies. 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.

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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



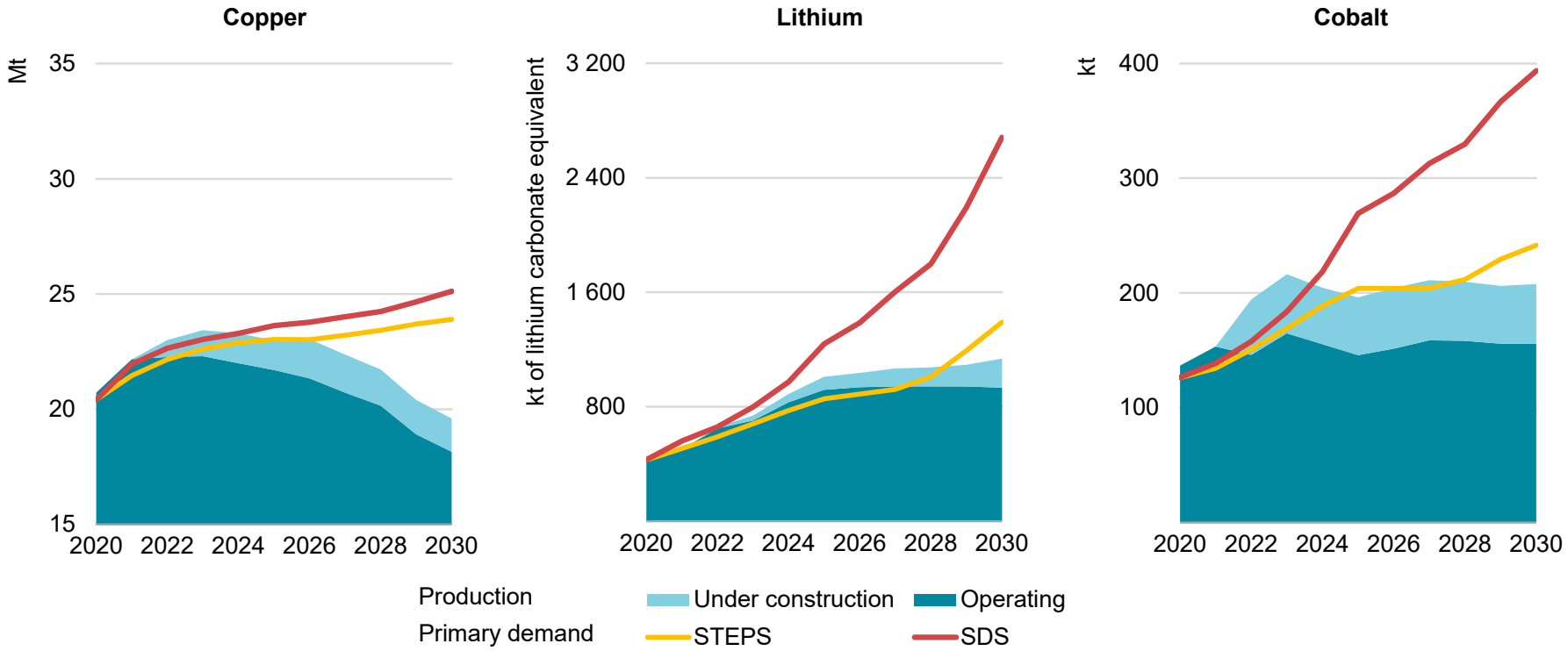
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Notes: Total demand includes both demand from clean energy technologies and other consuming sectors. kt = thousand tonnes; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

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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



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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).

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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.

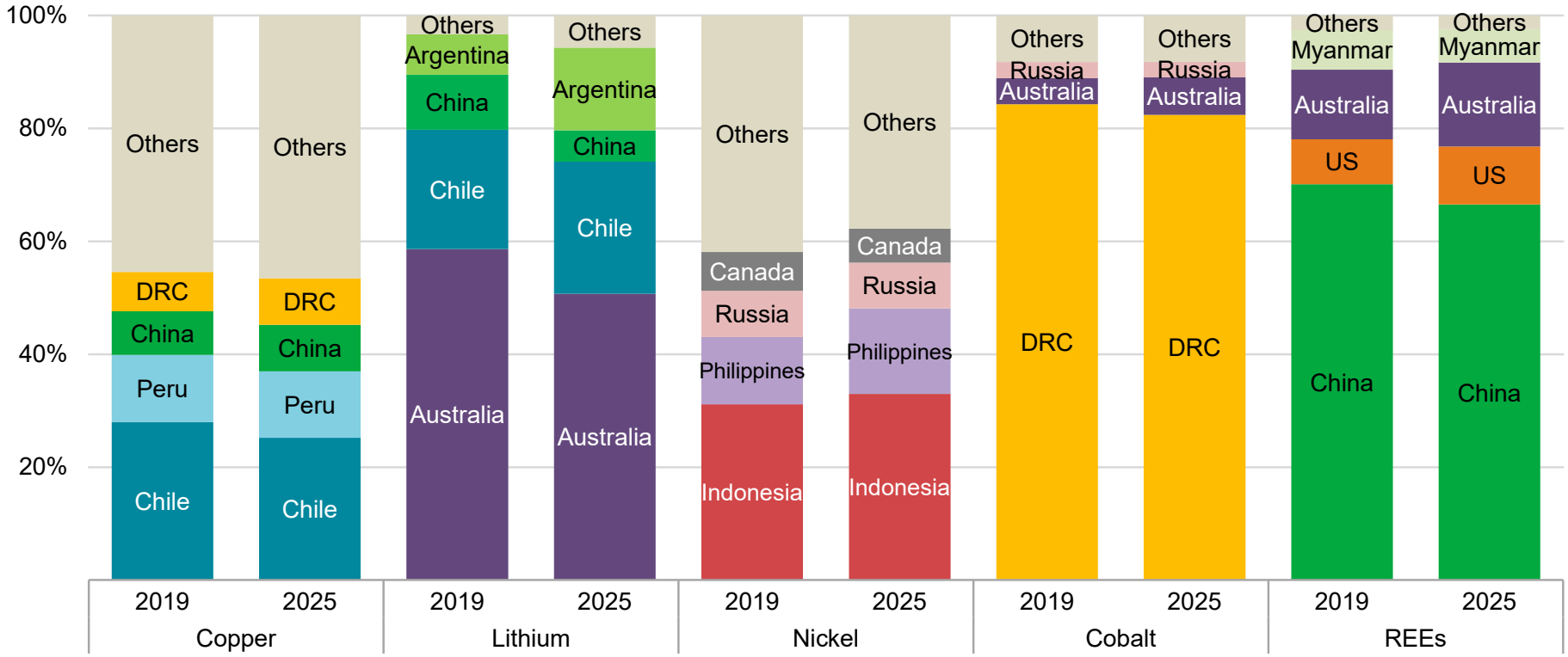
The picture for near-term supply is mixed. Some minerals such as lithium raw material, copper and cobalt are expected to be in surplus in the near term, while lithium hydroxide, battery-grade nickel and certain REEs (e.g. neodymium and dysprosium) might face tight supply in the years ahead as demand 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).

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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



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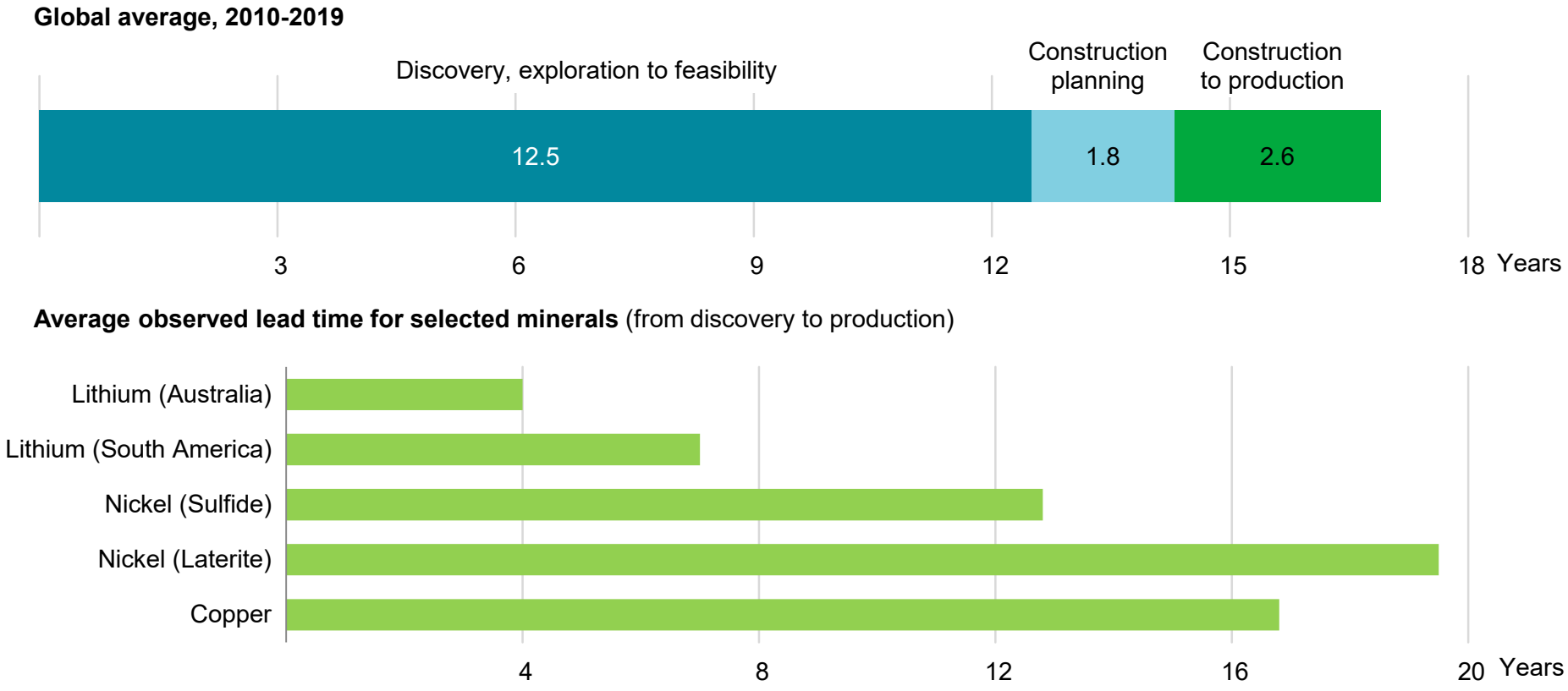
Note: Due to the availability of data on projections for future production, REEs here comprise neodymium, praseodymium, terbium and dysprosium only. DRC = Democratic Republic of the Congo; US = United States; Russia = Russian Federation.

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).

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

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



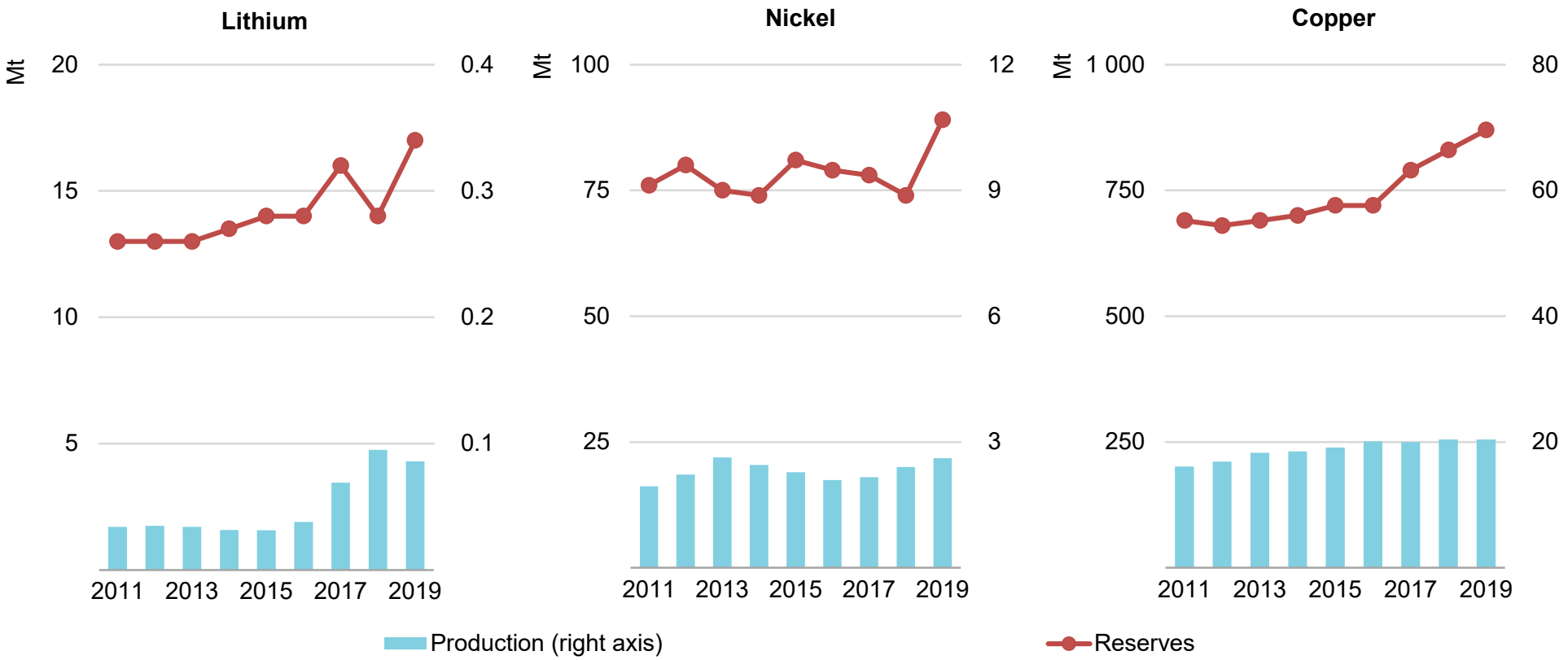
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Note: Global average values are based on the top 35 mining projects that came online between 2010 and 2019.
Source: IEA analysis based on S&P Global (2020), S&P Global (2019a) and Schodde (2017).

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

Reserves and production for selected mineral resources



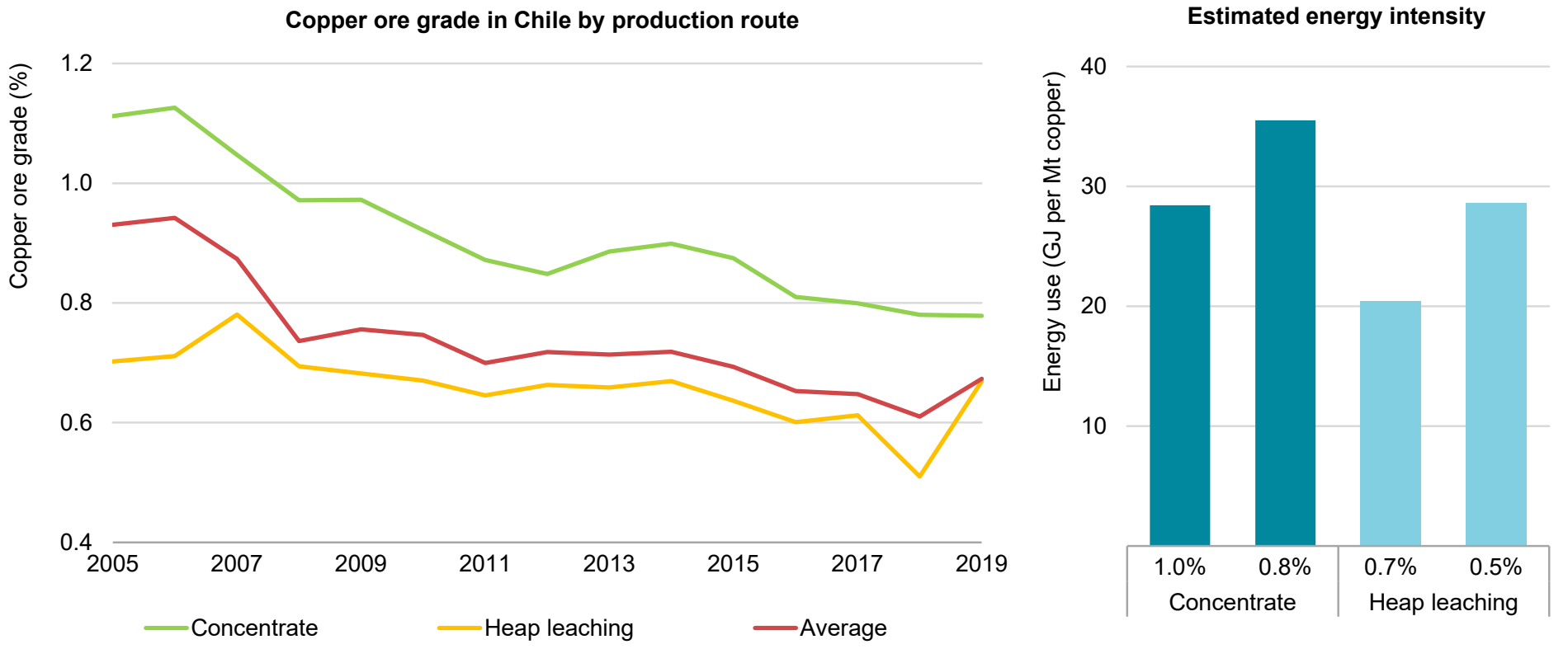
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Sources: USGS (2021); USGS (2020).

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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



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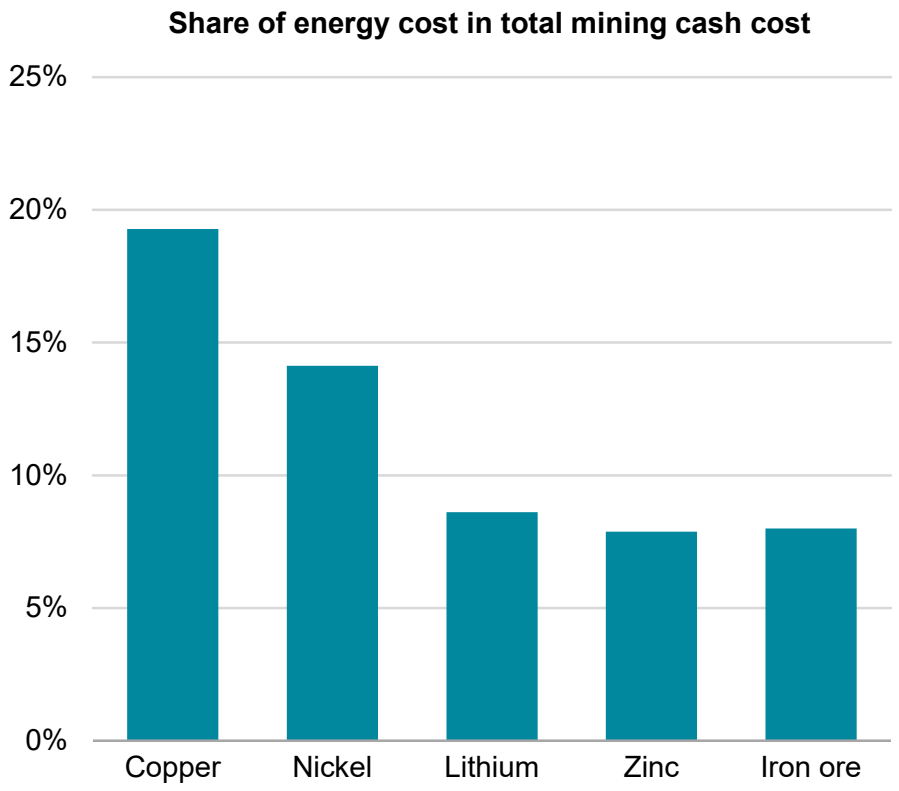
Notes: Energy use for concentrate covers mine, concentrating plant, smelter, refinery and services. For heap leaching, energy use covers mine, leaching, solvent extraction, electro-winning processes and services. GJ = gigajoule.

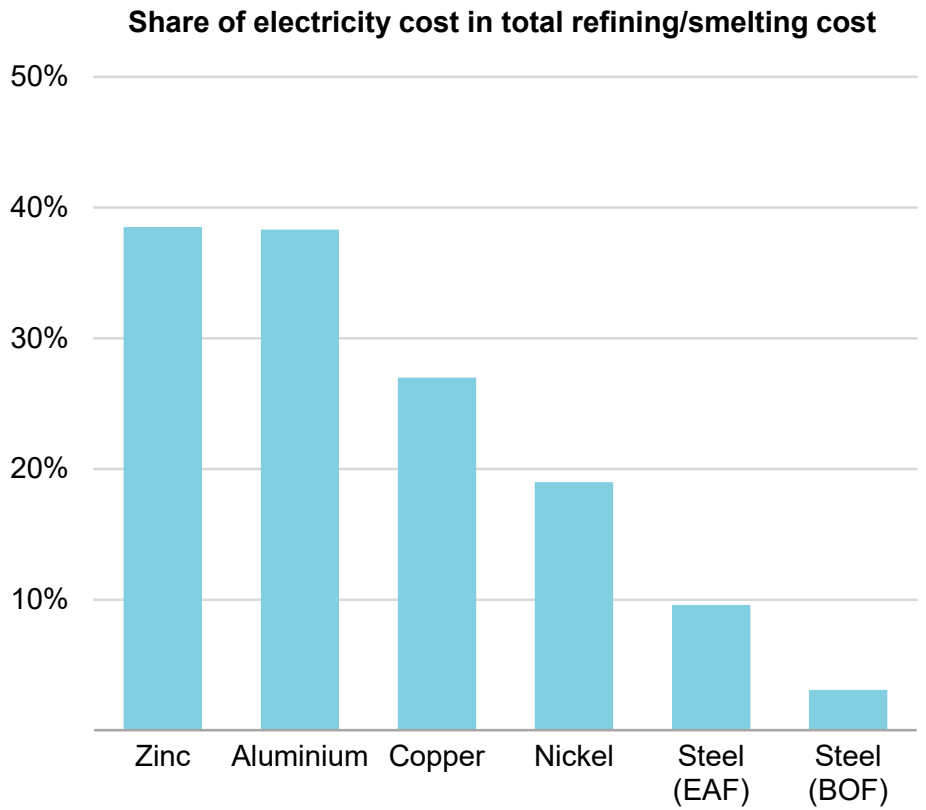
Source: IEA analysis based on COCHILCO (2019) and Rötzer and Schmidt (2020).

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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





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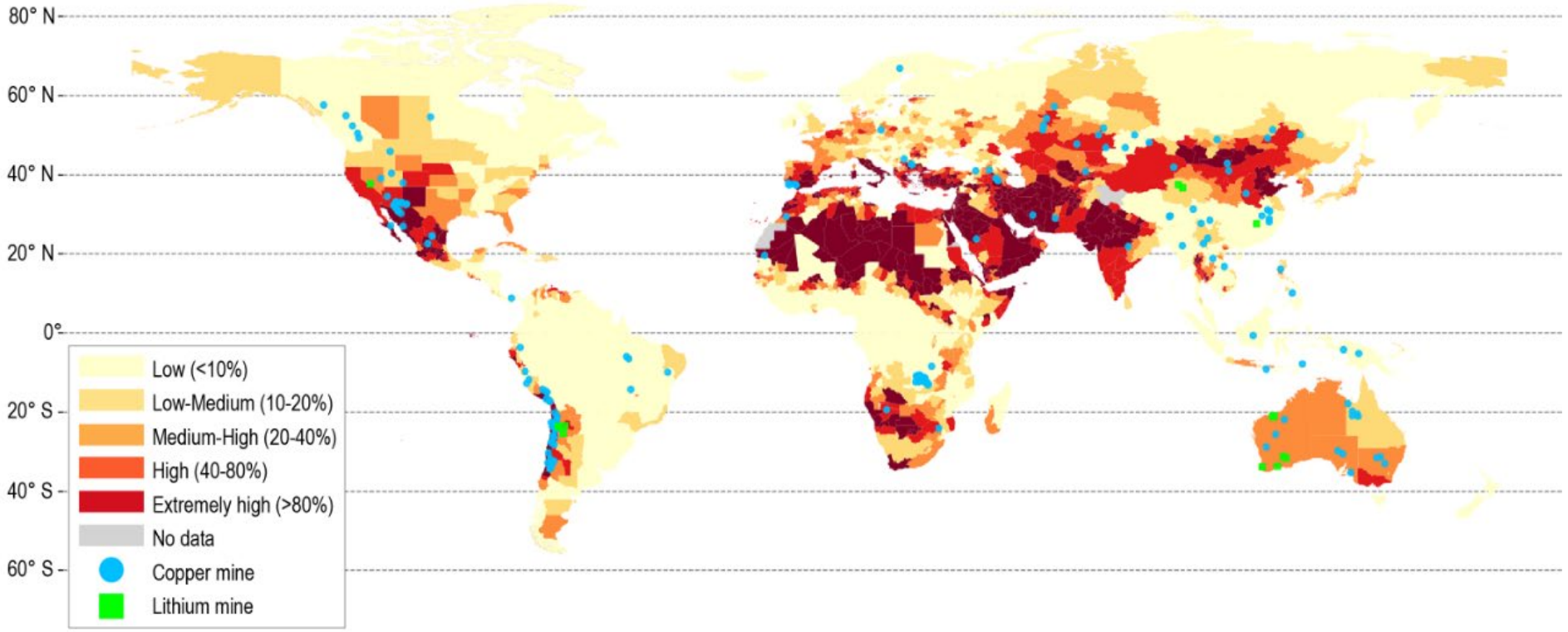
Notes: ESG = environmental, social and governance; EAF = electric arc furnace; BOF = basic oxygen furnace. Energy and electricity costs show global average values, and can vary by region and operational practice.

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

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

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



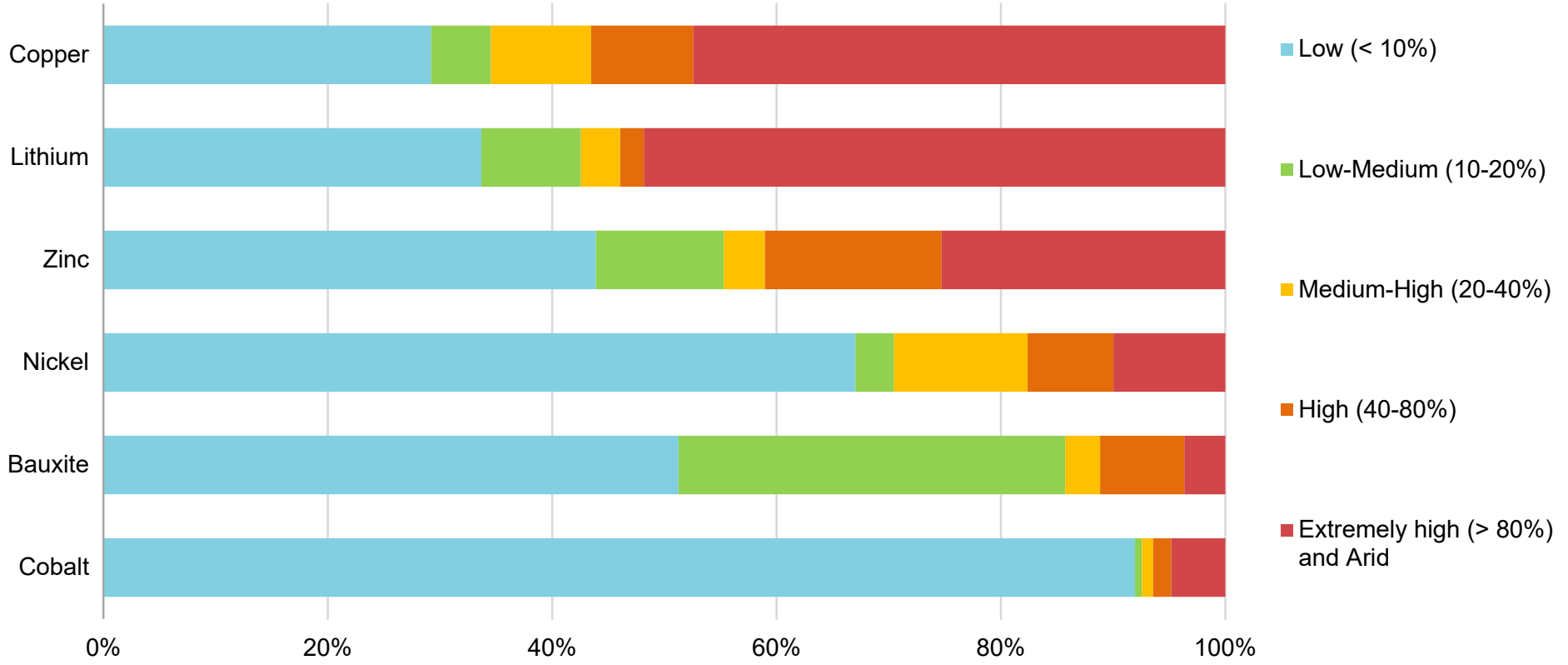
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Note: The exact water stress levels vary by location. While we assessed the share of mines located in water stress areas according to granular regional representations (shown on the following page), we aggregated them at the sub-national level on the 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.

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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



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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.

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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

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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

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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.

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.

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Supply prospects for the focus minerals

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

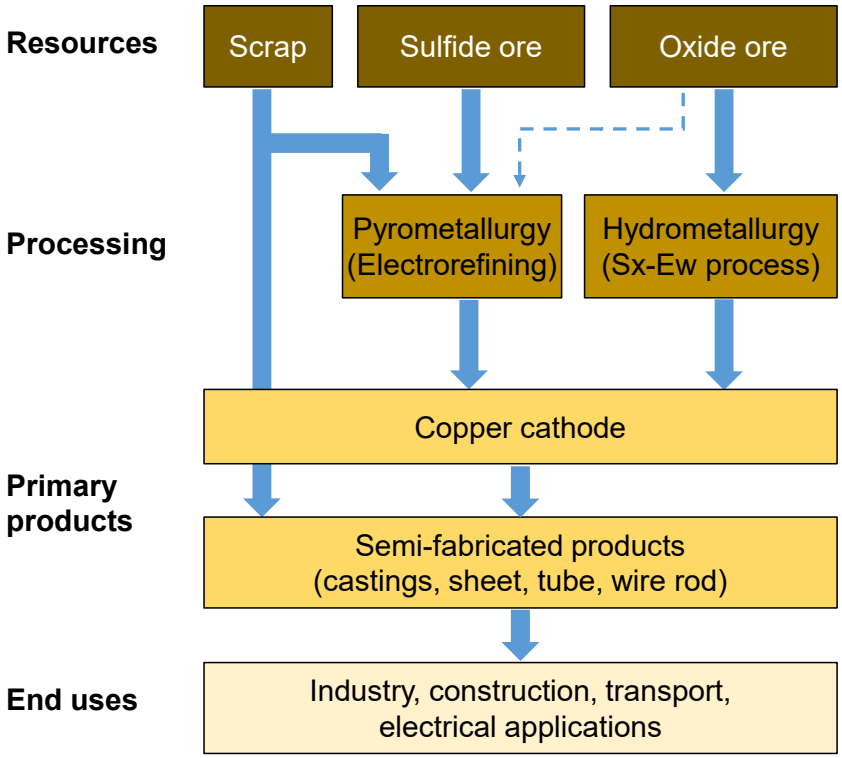
Mineral	Key challenges
Copper	• Challenging to substitute due to its superior performance in electrical applications • Mines currently in operation are nearing their peak due to declining ore quality and reserves exhaustion • Declining ore quality exerts upward pressure on production costs, emissions 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.

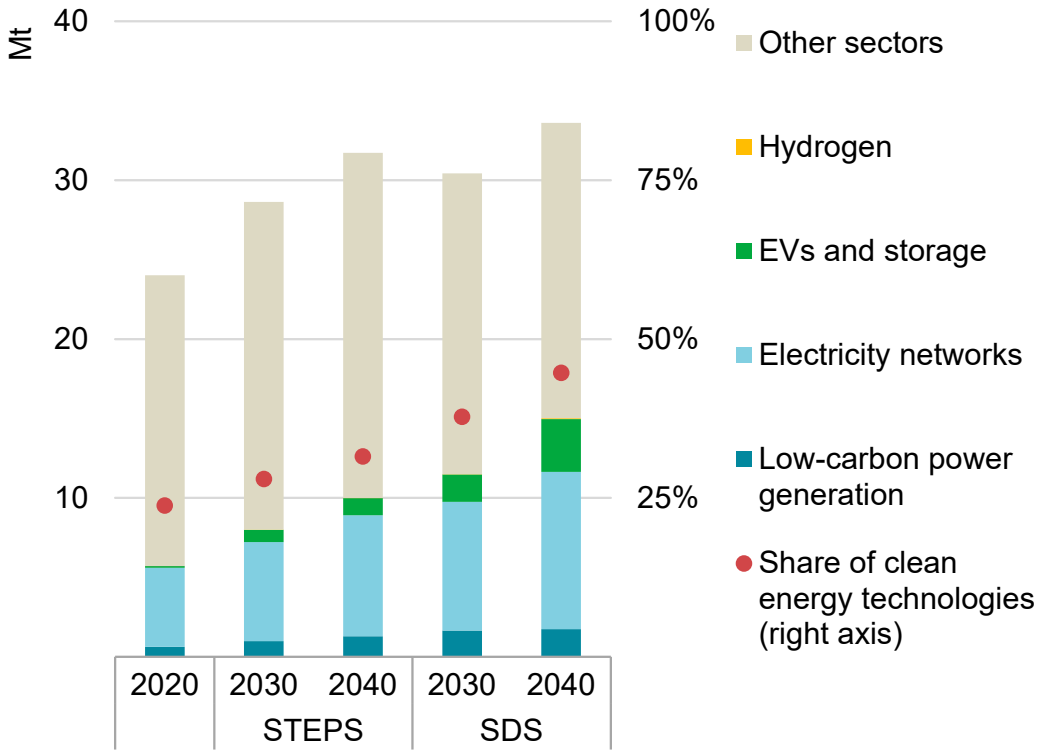
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Copper: From resource to consumer

Copper supply chain



Total copper demand by sector and scenario



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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.

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

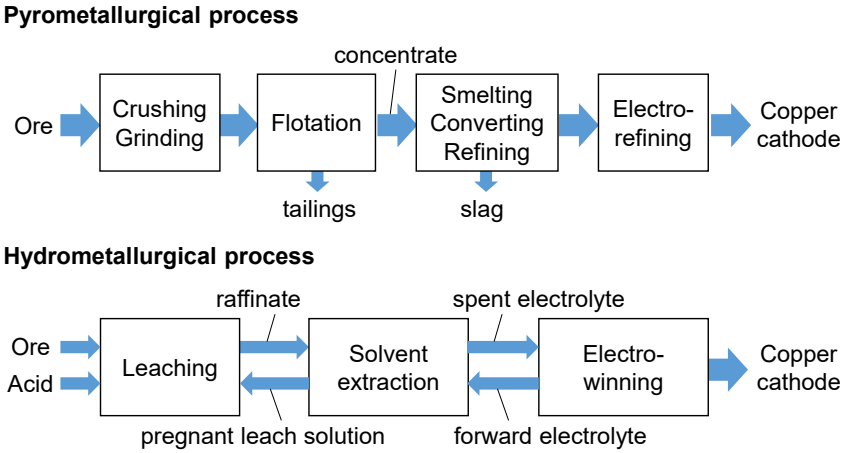
Thanks to its unmatched thermal and electrical conductivity, copper is widely used in a broad range of electronic and industrial applications. Its attributes make it challenging to substitute.

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



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

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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.

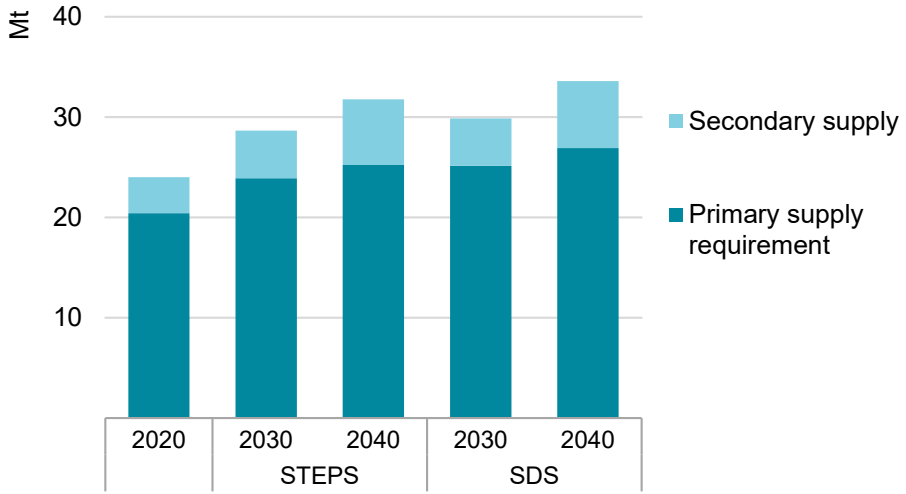
However, past trends may not be a good guide to what could happen in the coming decades. Production at today's major copper mines has already peaked or is expected to peak in the early 2020s due to declining ore quality and reserve exhaustion. For example, the world's largest copper mine, Escondida in 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



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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.

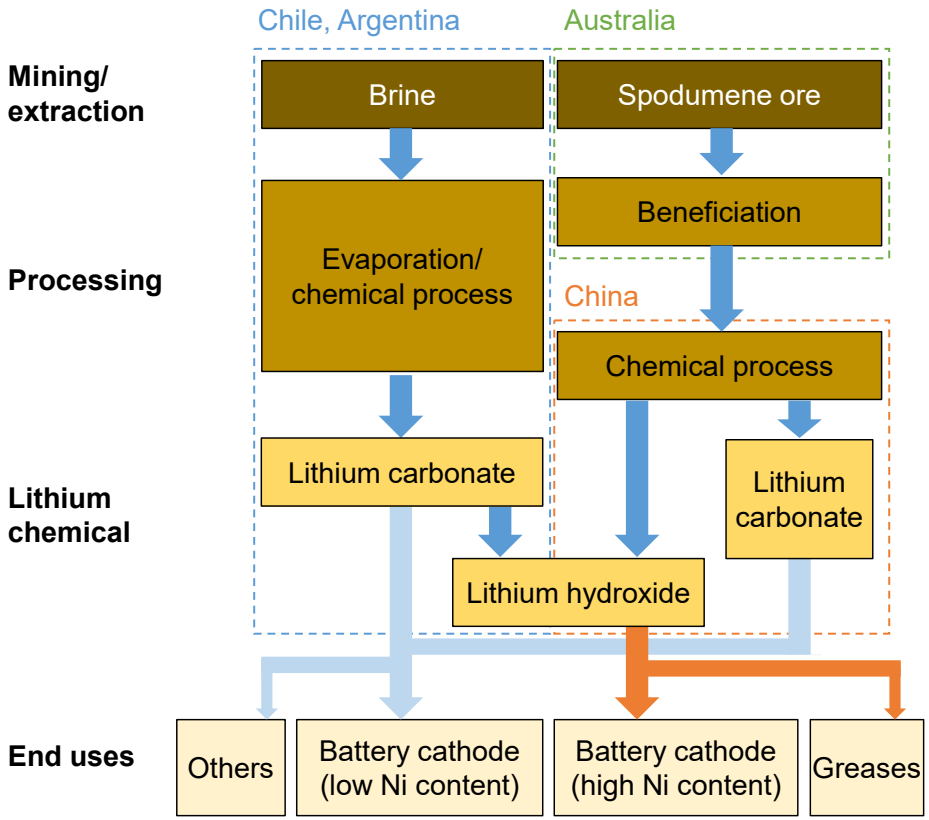
While cost escalations are a major challenge for the copper industry, the impacts of resource depletion can be offset by technology innovation. Until the late 19th century, average ore grades were 10-20%; then they decreased to 2-3% in the early part of 20th century (Henckens and Worrell, 2020). More 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.

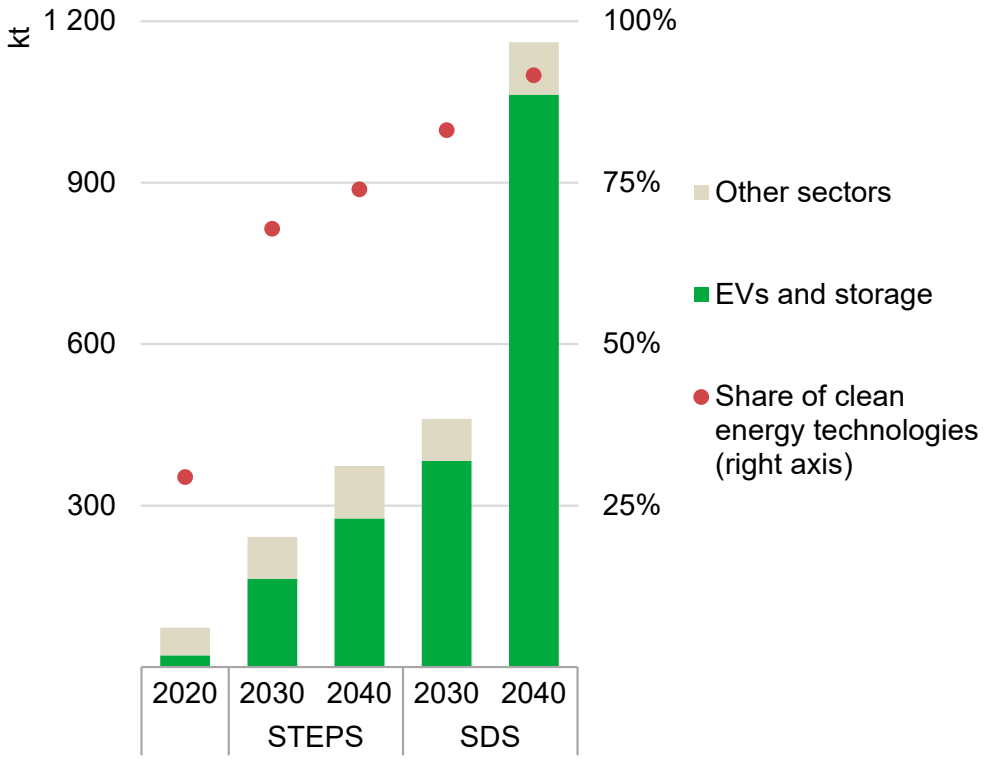
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Lithium: From resource to consumer

Lithium supply chain



Total lithium demand by sector and scenario



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

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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.

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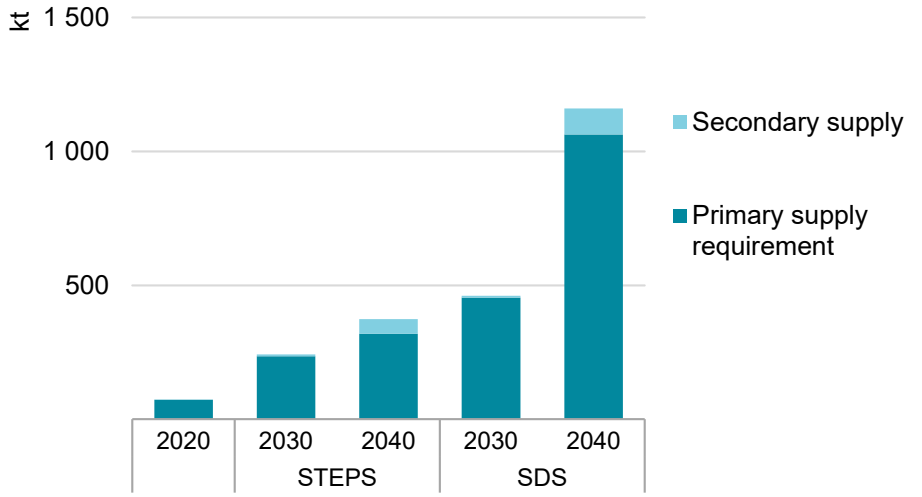
Lithium: The adequacy of lithium raw material supply depends critically on the demand trajectories. New extraction technologies could help broaden the supply pool

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

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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).

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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).

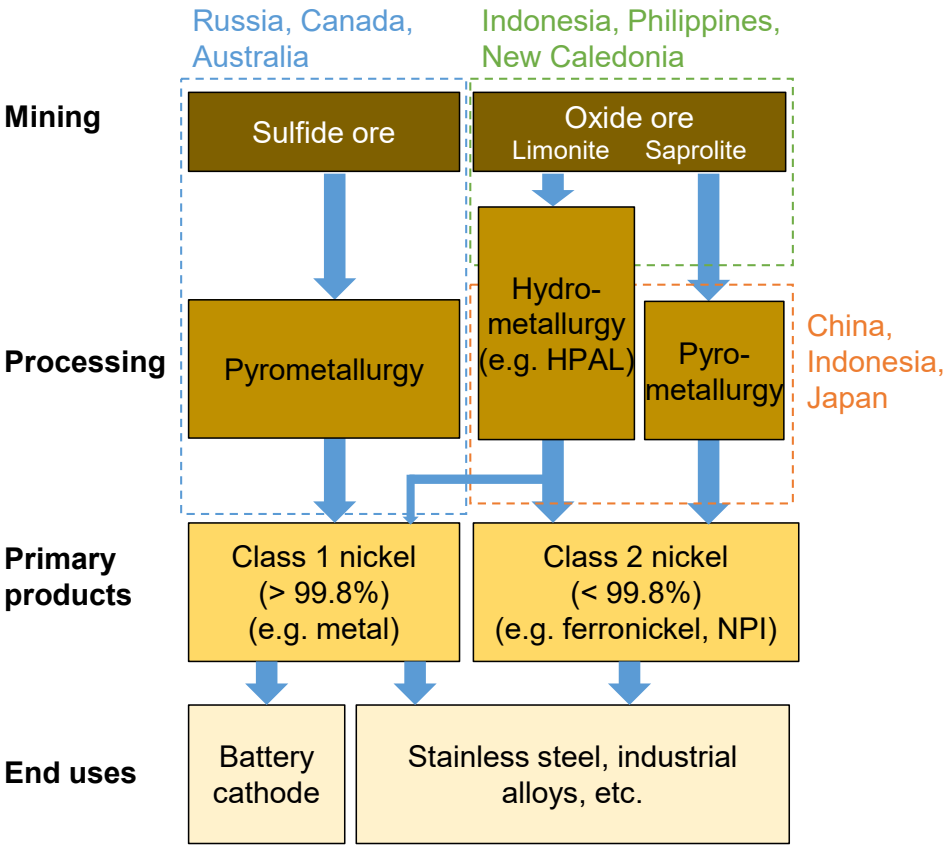
A higher level of concentration is another challenge. Close to 60% of global lithium chemicals are produced in China. Chinese companies have also invested in companies in South America. For example, Tianqi Lithium, a large lithium chemical producer in China, acquired a minority stake (23.8%) in Chilean 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.

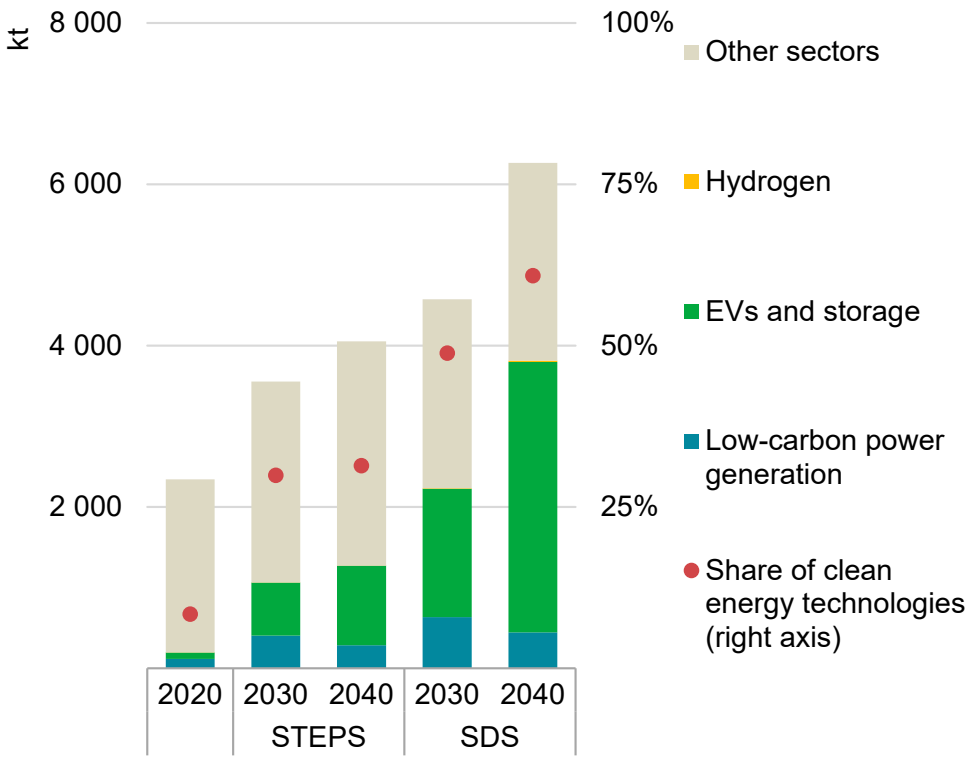
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Nickel: From resource to consumer

Nickel supply chain



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.

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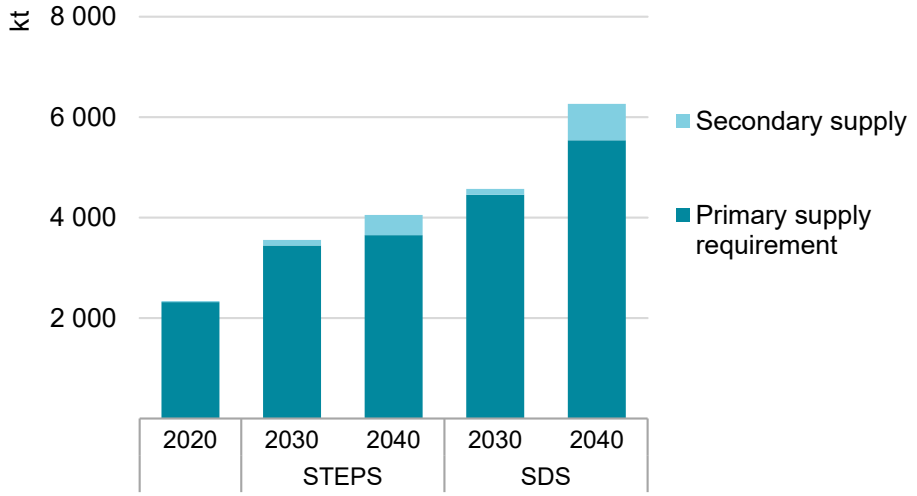
Nickel: All eyes on Indonesia

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.

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

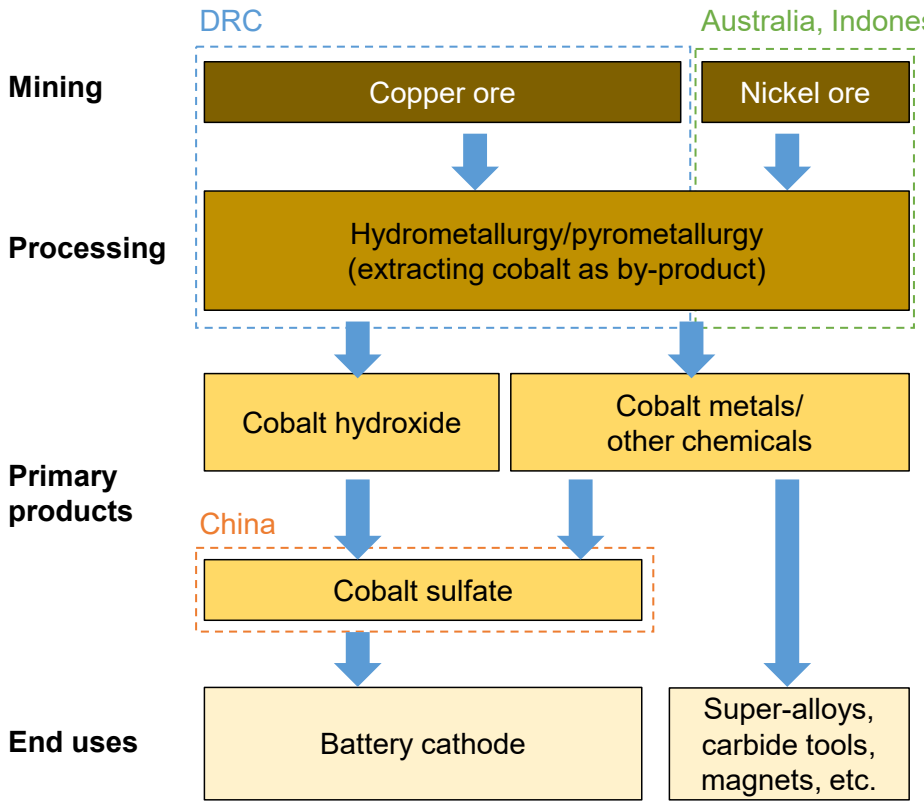
- Some of the current Class 1 consumption in the non-battery sector could be switched to Class 2, freeing up Class 1 nickel supply for batteries. Higher prices would be required to incentivise such a switch.
- Increasing stainless steel production from scrap materials would make some Class 1 supply available 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.

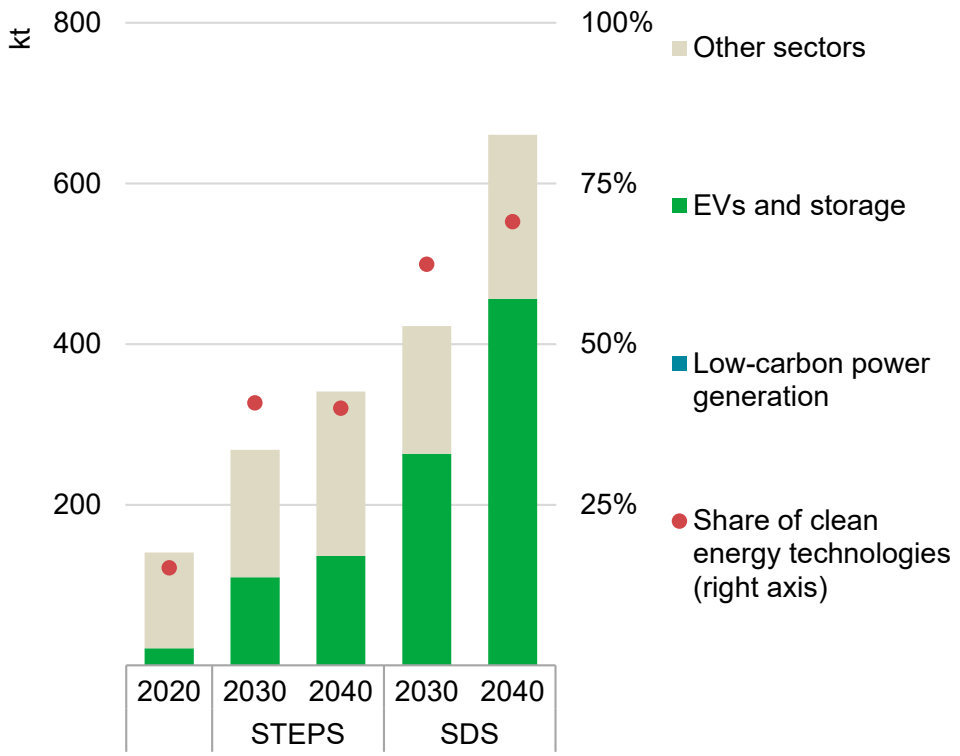
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Cobalt: From resource to consumer

Cobalt supply chain



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.

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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.

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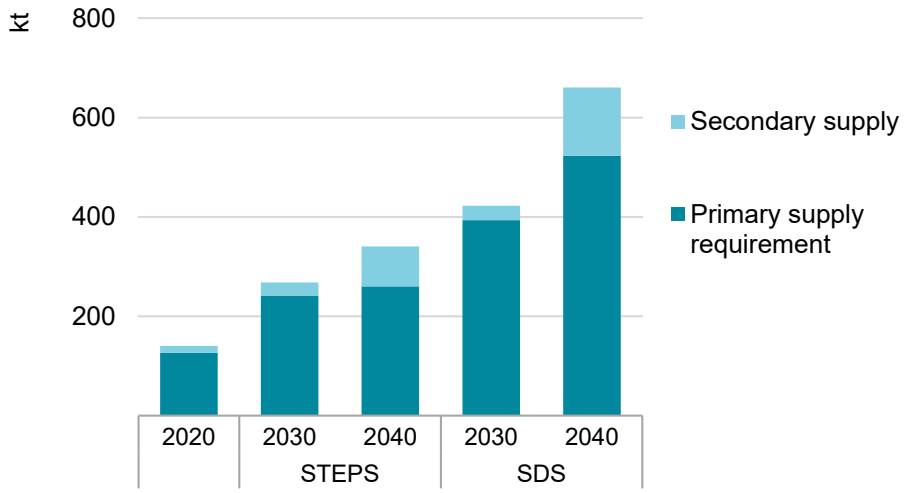
Cobalt: Production of cobalt is likely to remain concentrated in the DRC and China

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).

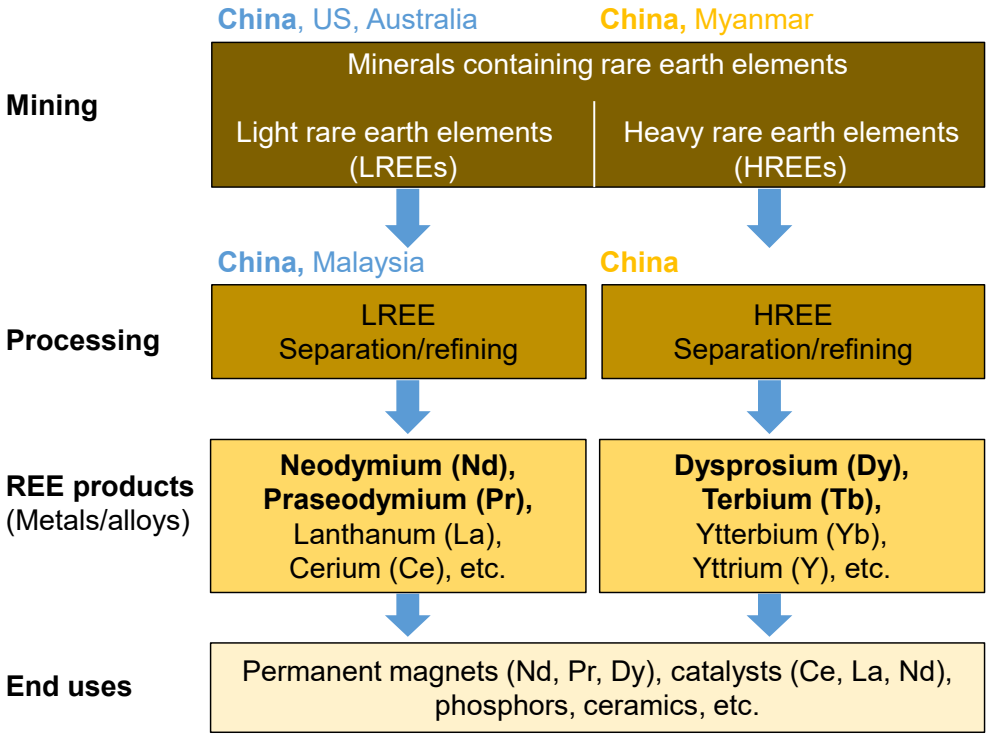
Companies and governments are also developing “on the ground” efforts to formalise the sector and prevent irresponsible practices. The DRC government has announced support for formalising ASM through the state-owned Entreprise Générale du Cobalt, and some companies have established formalised or semi-formalised 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.

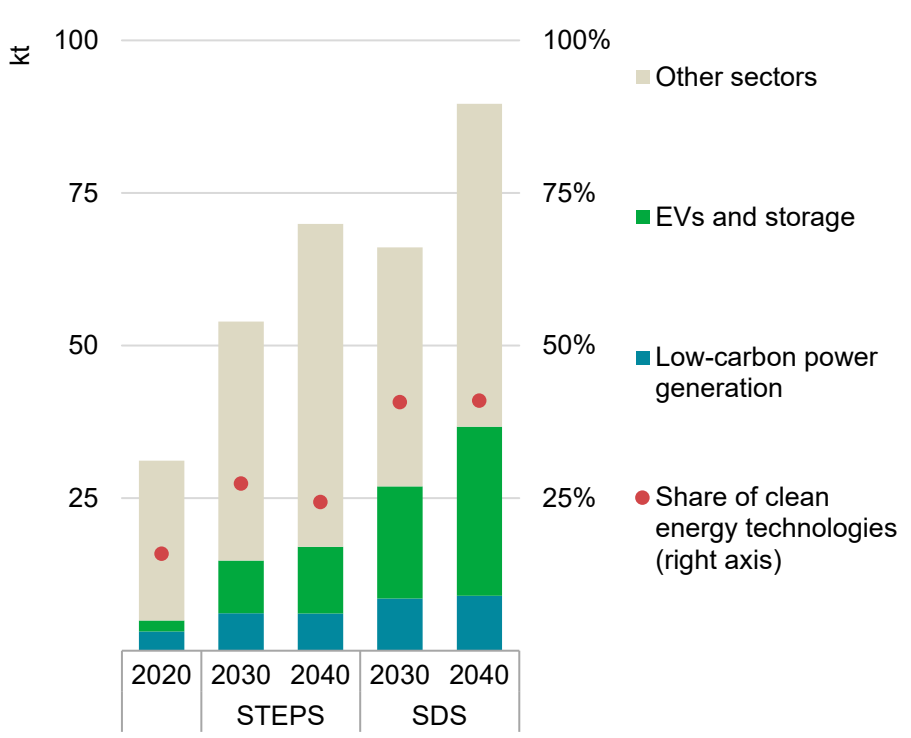
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Rare earth elements: From resource to consumer

Rare earth elements supply chain



Total neodymium demand by sector and scenario



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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).

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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.

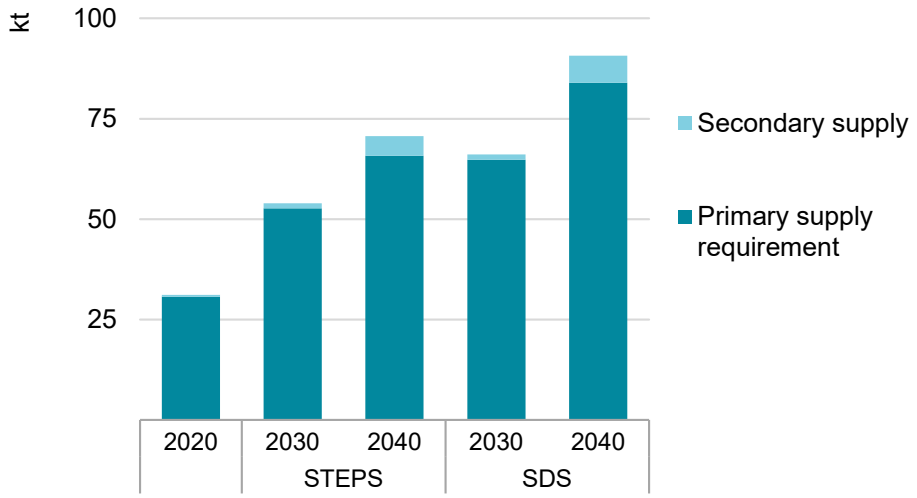
China's attempt to limit REE exports in 2010 was an alarm bell for many countries that rely on imports. In the immediate aftermath, prices spiked by more than 10 times for many REEs, although prices subsequently declined. This extreme price movement triggered many countries to consider options to reduce 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.

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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.

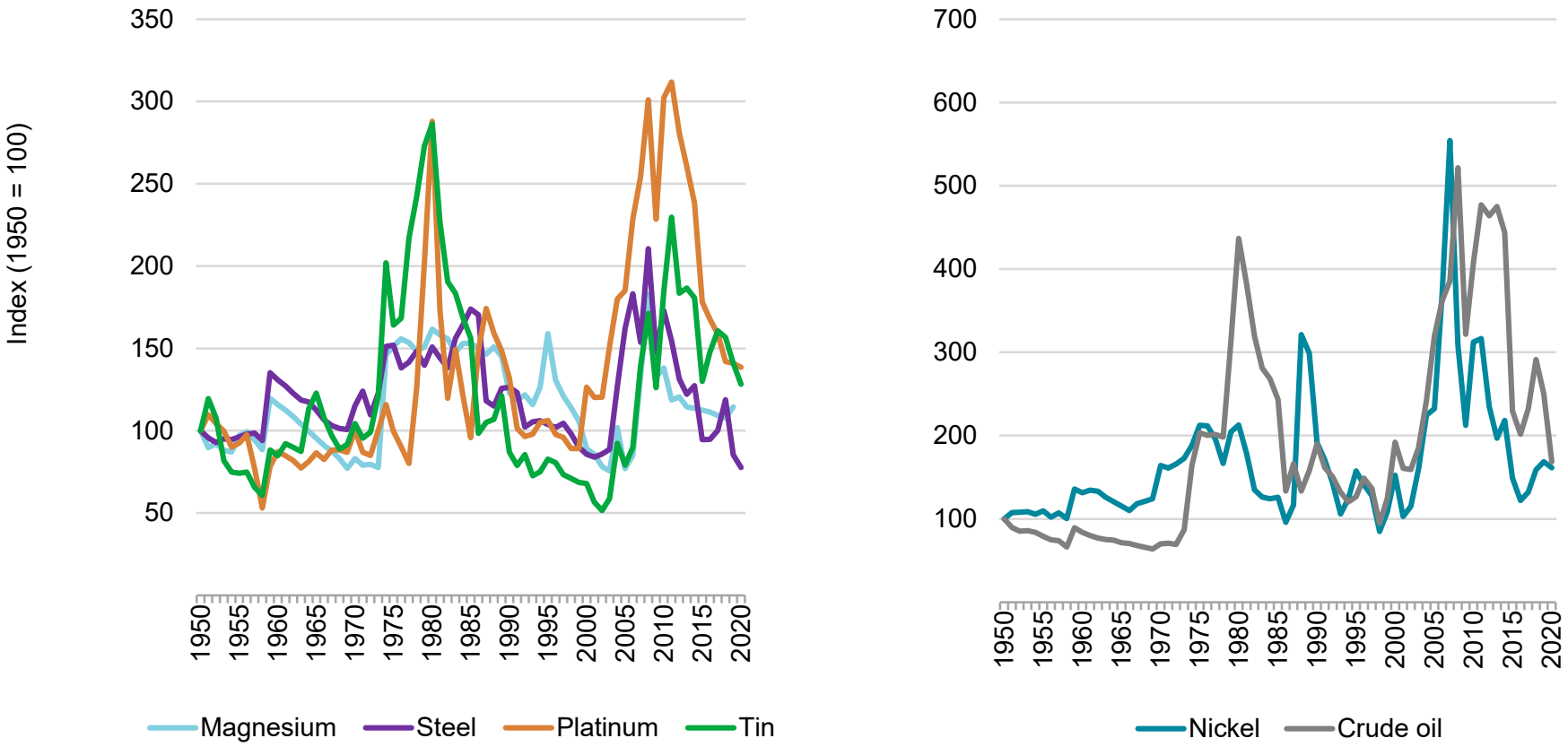
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Approaches to ensure reliable mineral supply

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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.

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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.

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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.

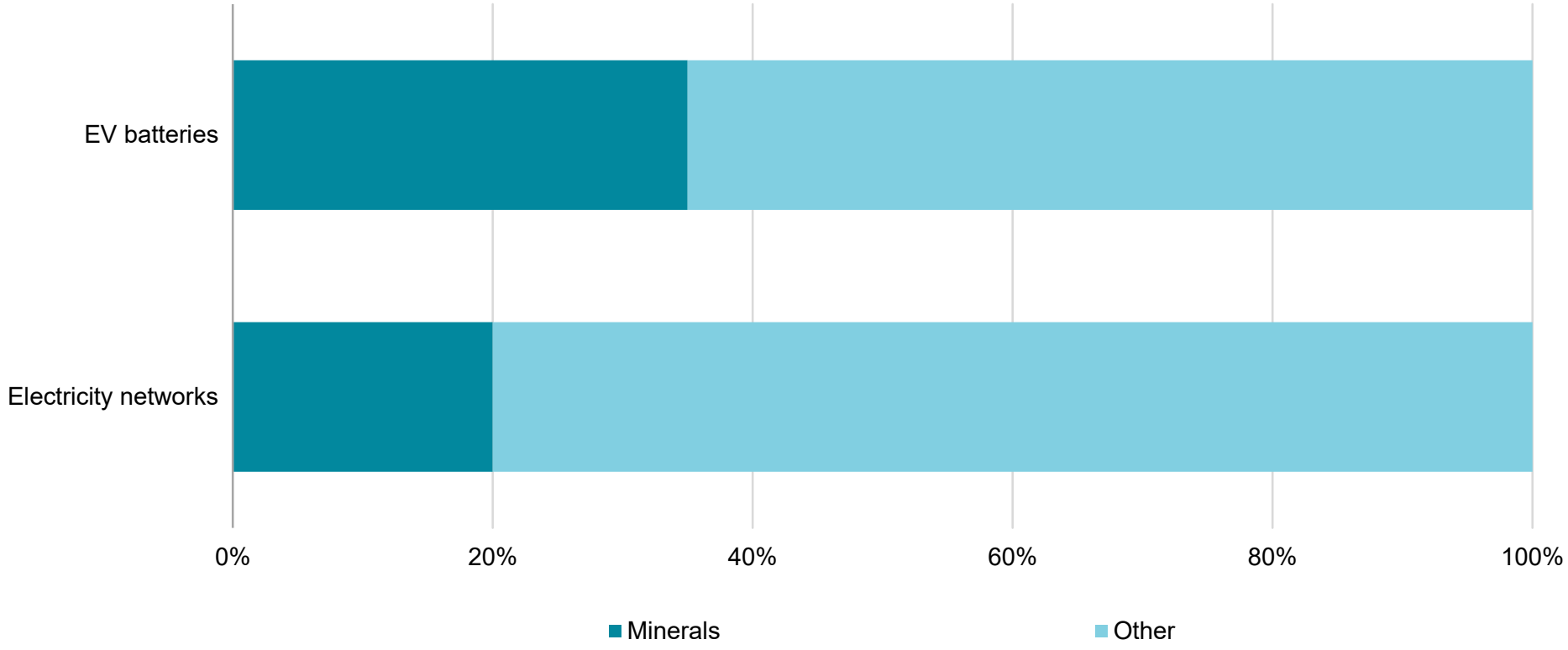
Platinum prices spurred innovation in substitution

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.

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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



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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.

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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

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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.

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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

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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 USD 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–

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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).

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IEA's six pillars of a comprehensive approach to mineral security

While each country has different motivations and approaches to the issue of critical minerals, their experiences provide useful lessons for designing frameworks to ensure reliable mineral supplies. Past approaches have varied depending on whether the country is a producer or a consumer, but this distinction is increasingly becoming blurred as producer countries strive to build a domestic industry to produce clean energy equipment, and consumer countries seek to revitalise domestic production or secure overseas production assets. This suggests that an approach to ensuring reliable mineral supplies needs to be multi-faceted, covering a wide range of aspects from supply to demand to recycling.

Based on the IEA's long-standing experience in energy security, we identify **six pillars of a broad approach to minerals security**, complementing countries' existing initiatives. They are: (i) ensuring adequate investment in diversified sources of new supply; (ii) promoting technology innovation at all points along the value chain; (iii) scaling up recycling; (iv) enhancing supply chain resilience and market transparency; (v) mainstreaming higher environmental and social standards; and (vi) strengthening international collaboration between producers and consumers.

Beginning with adequacy of supply, the supply of minerals and metals needs to keep up with the rapid pace of demand growth to ensure orderly energy transitions. This requires strong growth in investment to bring forward new supplies at the right time. Governments can take a variety of measures to attract investment into the sector, but the foremost action is to provide clear and strong signals about energy transitions. As noted in Chapter 2, the largest uncertainty around demand comes from questions about countries' real commitment to their climate ambitions. If companies do not have confidence in countries' climate policies, they are likely to make investment decisions based on much more conservative expectations. Given the long lead times for new projects, this could create a bottleneck when deployment of clean energy technologies starts to grow rapidly, as envisaged in the SDS.

Governments can also play a role in creating conditions conducive to investment in the mineral supply chain. Measures could include strengthening national geological surveys, streamlining permitting procedures to shorten lead times and, in some cases, providing financing support to de-risk strategic projects (which can be defined according to each country's own assessment of which, and how much, critical minerals they might need in the future). They can also support the unlocking of additional sources of supply by supporting enhanced metals recovery from low-grade ores and waste streams or revisiting the potential of abandoned mines. Further, governments can work together to improve data availability and comparability across regions, and raise public acceptance.

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Box 3.2. What would be the right metrics to assess mineral security?

Any efforts to improve security of supply start with understanding where we stand and what progress is being made. The rising importance of critical minerals in energy transitions raises a question about the right metrics to measure the status and progress of mineral security.

The most commonly used metrics today are (i) import dependency and (ii) the level of supplier concentration. Import dependency is calculated as the amount of imported material as a percentage of domestic consumption. The level of supplier concentration is often measured using the Herfindahl–Hirschman Index, a widely used metric to assess the level of market concentration. In some cases, these are complemented by measurement of the economic importance of a certain mineral, such as the contribution of minerals to the value added of end-use sectors. Many countries have defined a list of critical minerals using variations of this approach.

While these remain highly valuable, most of the metrics naturally focus on the sovereign boundary, and the question remains as to how these measures can trigger action to improve security of supply. Given the need for a wider security approach, there may be scope to develop metrics that encompass wider aspects of supply, demand, resilience and sustainability to complement the traditional criticality indicators.

For example, to assess the adequacy of future supply, the actual level of investment spending against the level required to meet long-term demand could be measured, as has been done for the energy sector in the IEA's *World Energy Investment* reports. This could give an indication of possible market tightness.

Public R&D spending on technologies that can reduce material intensity, allow substitution and unlock new supplies can be assessed. The IEA's *Energy Technology RD&D Budgets* report assesses this for energy technologies in IEA member countries. There is scope to track material intensity in clean energy technologies in a systematic manner. This will be crucial for a more accurate view about future material requirements.

On supply chain resiliency, the measurement of supplier concentration could be expanded to include the processing and refining value chain. Some countries assess the political and social risks of the major producers, which can be a useful complement. Finally, progress on recycling (e.g. collection rates and the share of secondary production) can be an important part of security metrics.

Both traditional and complementary metrics will require greater data transparency. Governments have a role in collecting and disseminating reliable data in this regard.

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Stepping up efforts for technology innovation and recycling can yield multiple benefits

History suggests that innovation in demand-side technology can play a major role in alleviating strains on supply and reducing material costs, which could in turn help enhance the affordability of clean energy technologies. As noted in Chapter 2, costs associated with raw materials are likely to represent a larger portion of total investment costs for clean energy technologies in the future as other cost components continue to decline thanks to technology learning and economies of scale. This underscores the important role of innovation in demand-side technology to mitigate upward cost pressure.

There are many positive examples. Efforts to reduce the use of silver and silicon in solar cells have helped to enable a spectacular rise in solar PV deployment in recent years. Technology advances in aluminium helped ease strains on copper supply in the 1950s and tin supply in the 1980s. A host of emerging technologies have the potential to reduce the use of critical minerals, if successfully commercialised (e.g. induction motors or switched reluctance motors to reduce REE consumption). There is, however, a need to assess trade-offs that substitution could trigger (e.g. all solid-state batteries reduce the need for nickel and cobalt, but require more lithium).

The possible contributions of technology are not confined to the demand side. Innovation in production and processing technologies can unlock sizeable amounts of new supplies and contribute to reducing primary supply requirements. The emergence of Sx-Ew processes in the 1970s opened up the possibility to tap into extensive copper oxide resources. More recently, emerging technologies such as direct lithium extraction, or enhanced metal recovery from waste streams or low-grade ores, could lead to a step change in future supply volumes. Technologies that help reduce water use or energy consumption can also bring additional environmental and operational benefits. In 2021 the US Department of Energy announced USD 30 million in funding research to secure domestic supply chains. Countries endowed with huge resources are naturally putting more effort into supply-side technology innovation, but consumer countries can also benefit from reduced import dependency.

Policy support to scale up recycling efforts can bring multiple benefits. It can help reduce primary supply requirements and alleviate the environmental burdens associated with primary supply. Also, the security benefits of recycling can be far greater for regions with wider deployment of clean energy technology, as they stand to benefit from greater economies of scale. Government support may be necessary to incentivise recycling at the end-of-life stage of products, support collection and sorting activities and fund R&D into new recycling technologies. In the last section of this chapter, we examine the prospects and policy approaches to scaling up recycling in more detail, with a focus on batteries and electricity network

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Governments can play a role in enhancing supply chain resilience and market transparency

Ensuring that critical minerals enable clean energy transitions requires a broad view of the supply chains, from mining to processing. Even if raw materials from mining are well supplied, a bottleneck in processing capacity could elevate prices for refined products and affect clean energy investment. In addition, a higher degree of concentration of production implies that disruption can have wider ripple impacts on the entire value chain.

Periodic stress-tests coupled with emergency response exercises can help policy makers identify points of potential weakness, assess potential impacts and devise necessary actions. For example, some European countries conduct a regular “N-1” stress test to assess the resiliency of gas supply infrastructure. The test assumes the loss of the single largest element of supply infrastructure and evaluates the impact on the country’s energy supply. Another example is the emergency response exercises the IEA regularly organises with its member countries to ensure quick and effective responses to major supply disruptions. Safeguarding security of oil supply has been the main focus so far, but the concept is expanding to encompass other areas as well. In 2016 the IEA worked with the Japanese government to conduct a gas resiliency assessment, aimed at identifying risks and challenges related to natural gas supply in Japan.

Voluntary strategic stockpiling, where applicable, can also help countries weather short-term supply disruption. Some countries have been operating stockpiling schemes for many years as a tool to ensure supply security. Such programmes need to be carefully designed, based on a periodic review of potential vulnerabilities. In general, such schemes can be more effective for minerals with smaller markets, opaque pricing and a concentrated supply structure than those with well-developed markets and ample liquidity.

There is scope to improve market transparency. Many base metals such as copper are widely traded in the market with reliable pricing mechanisms. However, this is not the case for some energy transition minerals with smaller markets, such as lithium and cobalt (see Box 3.3). These minerals have been historically regarded as “minor minerals” and traded on a bilateral basis, resulting in low pricing transparency and liquidity. Buyers need to rely on information provided by suppliers, making it difficult to manage price risks and affecting investment decisions down the value chain. However, as demand grows, end users will increasingly call for more transparency around pricing to hedge risks. Establishing reliable price benchmarks will be an important step towards enhancing market transparency and supporting market development. While this process takes time, the experience in the LNG market shows the potential benefits: the rise of hub-based pricing for LNG, alongside long-term supply contracts, has made gas markets more responsive to changes in global and regional supply-demand balances.

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Box 3.3. Towards a transparent pricing system: A story of lithium and cobalt

The predominant approach to trading lithium has not changed much over the past few years. Lithium has not been listed on an exchange and does not have a reliable benchmark price. The vast majority of lithium raw materials and chemicals are sold under bilateral long-term contracts between suppliers and end users. There is a spot price index based on Chinese custom data, but a question mark remains as to whether the index reflects market dynamics in an accurate and timely manner. It is rarely used for large-scale negotiation or hedging in practice (McKinsey, 2018).

However, there are signs of change. The duration of contracts is becoming shorter, and the London Metal Exchange (LME) introduced a tradeable price benchmark in partnership with Fastmarkets, a price reporting agency. The LME also plans to launch the LME lithium futures contract in the first half of 2021 – the first of its kind. These developments are expected to allow stakeholders to mitigate against price volatility.

There are, however, challenges. While a growing number of buyers are entering the market, only four companies supply the majority of lithium raw materials. The ambiguity of standards and classifications is another obstacle. Lithium is a speciality chemical that comes in a variety of material grades. This calls for a standardised methodology to enable comparability and accuracy of prices.

Cobalt is currently traded on the LME and the Chicago Mercantile Exchange (CME). The LME launched a physically settled contract in 2010, followed by a financially settled contract in 2019. CME launched new cash-settled cobalt futures contract in 2020. So far, the LME's physically settled cobalt contract has not been widely accepted by industry participants as a tool for hedging. The financially settled contracts faced similar issues. The major barriers to cobalt trade have been the lack of liquidity in the spot market, as well as cargo heterogeneity.

However, the situation is clearly improving with more pricing information being available. Fastmarkets releases a daily metal price and twice-weekly hydroxide payable assessment. These have been adopted into the majority of cobalt contracts. Some companies started to hedge cobalt exposure through financial swaps and banks are also getting involved.

Over time, as demand grows and more market participants enter the market, more liquid contracts are likely to be evident in the market. The development of new financial instruments will be important to provide some level of risk mitigation and increased levels of transparency (Lee et al., 2020).

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Improved environmental and social performance contributes to enhanced mineral security

As a sector, mining is often cited as having the greatest exposure to ESG risks (S&P Global, 2019b). Recognising this, investors, consumers and civil society increasingly push companies to source minerals that are sustainably and responsibly produced, with institutional investors particularly visible in these efforts. It is becoming increasingly difficult for mining companies to ignore these concerns. Higher environmental and social performance is also crucial for governments to gain public acceptance for project development.

There is a significant degree of variation in environmental and social performance in the market. This makes it challenging for consumers to exclude poor-performing minerals as there may not be sufficient quantities of high-performing minerals to meet demand. Efforts to improve environmental and social performance can therefore contribute to enhanced mineral security by increasing volumes produced with higher environmental and social standards and lowering the cost of sourcing them.

Poor environmental and social performance can also lead to supply disruption. Production sites may be shut down or disrupted due to disputes over water access or as a consequence of regulatory actions to enforce child labour or human rights violations. Meanwhile, dam failures at tailings storage facilities can lead to extended shutdowns and large remediation and repair costs. At the same time, criminal and civil liability related to environmental damage or corrupt practices can raise the cost of production, with severe reputational and financial implications for the companies concerned.

A level playing field

Environmental and social performance tends to be better for minerals produced in countries with well-developed regulatory systems, strong enforcement and institutionalised transparency practices. At the same time, some of the worst social impacts caused by mining, such as child labour, are ultimately a product of widespread poverty. To address these impacts, co-ordinated policy efforts will be needed: (i) to provide technical and political support to countries seeking to improve legal and regulatory practices; (ii) to incentivise producers to adopt more sustainable operational practices; and (iii) to ensure that companies across the supply chain undertake due diligence to identify, assess and mitigate these risks (see Chapter 4).

Establishing a level playing field may also help to support innovative strategies to address these risks, which can ultimately lead to greater diversification among supply. If strong environmental and social performance is rewarded in the marketplace, new entrants will have an incentive to develop new approaches to addressing these risks.

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International co-operation is vital for ensuring reliable and sustainable mineral supply

As noted above, many governments have developed strategies to ensure the reliable and sustainable supply of minerals. While encouraging, given the complex nature of the mineral supply chains spanning across the globe and involving multiple minerals, no individual country will be able to drive the necessary changes on its own. For example, in the case of REEs, while there is growing interest in securing diversified supply options, it would be challenging and cost-prohibitive for a single country to build a presence along the entire value chain and some efforts so far have given rise to trade disputes (see Box 3.4).

Governments can steer better market outcomes and improve the security of mineral supply by working together. For the moment, there is no overarching international governance framework for critical minerals and co-ordinated policy action is lacking. Individual efforts are often fragmented and tend to focus on narrow issues. There is a strong case for strengthened international co-operation to ensure reliable and sustainable mineral supply. To this end, the UN Environmental Programme's International Resource Panel highlighted the need for a framework to inform policy strategies and co-ordinate international efforts surrounding mineral security (IRP, 2020).

There are many ways in which a multilateral framework could play a role in ensuring reliable and sustainable mineral supply:

- Provide clear market signals on decarbonisation targets to reduce demand uncertainty and help de-risk investment decisions.
- Facilitate a dialogue between producers and consumers to identify key bottlenecks and co-ordinate investment decisions.
- Mobilise public funds to accelerate R&D efforts for technology innovation.
- Conduct regular assessments of potential vulnerabilities across the supply chains and discuss collective action to respond to potential disruption.
- Promote knowledge and capacity transfer to spread sustainable and responsible development practices to a wide range of countries.
- Strengthen environmental and social performance standards through international standardisation and other mechanisms, to maintain a social license and ensure a level playing field.
- Co-ordinate diplomatic efforts to prevent restrictive export policies.
- Collect reliable data to assess the level of risk and help informed decision-making.

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Box 3.4. Export restrictions on critical minerals

As security of supply comes into sharper focus, potential distortions to the free trade of critical minerals become increasingly sensitive. Export restrictions introduced by China, Indonesia and the DRC reflect the varying objectives being pursued, and the mixed results achieved. Quantitative restrictions are largely prohibited under GATT article XI, but may be justified under certain limited exceptions such as environmental conservation or national security.

China started introducing export restrictions on REEs in 2006, which resulted in an increase in prices and the United States filing a WTO case in 2012. Plaintiffs argued that the export controls were part of a deliberate industrial policy, and not resource conservation efforts. In 2014 the WTO Appellate Body ruled in their favour and China lifted the measures (WTO, 2015). Moves by third countries to invest in non-Chinese sourcing, the subsequent collapse in prices and the ultimate WTO ruling underline the mixed benefits of such measures. In January 2021 the Chinese government issued its draft version of the Regulations on Rare Earth Management. The regulations aim to protect national security and prohibit unsustainable practices such as illegal mining and environmental degradation. Exports would become subject to government approval through the Chinese Export Control Law (China Briefing, 2021). The compatibility of any potential measures with WTO provisions remains unclear.

Policies aimed at adding local value are also subject to economic conditions and WTO rules. For instance, while Indonesia's nickel ore export prohibition has been successful at enticing the construction of smelters (UNCTAD, 2017), it has not attracted a diverse investment profile, with mostly Chinese companies investing so far, and the European Union is now challenging it at the WTO (DG Trade, 2021). The DRC pursued a similar strategy through an export ban on copper and cobalt concentrates starting in 2013. However, this ban has largely stalled due to operators' inability to develop local processing facilities (Africa Oil & Power, 2020). This reflects the inherent challenges to interventionist trade policies in commodity-dependent countries.

These examples illustrate how growing concerns over local development and environmental conservation could lead to an increase in export restrictions. However, importing countries are likely to dispute them as a proxy for industrial or geopolitical strategies. Empirical evidence also shows that despite the limited geographic scope of production and/or processing of certain minerals, export restrictions often have limited effect in the long run due to potential diversification of supply (IRENA, 2019).

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Focus on recycling

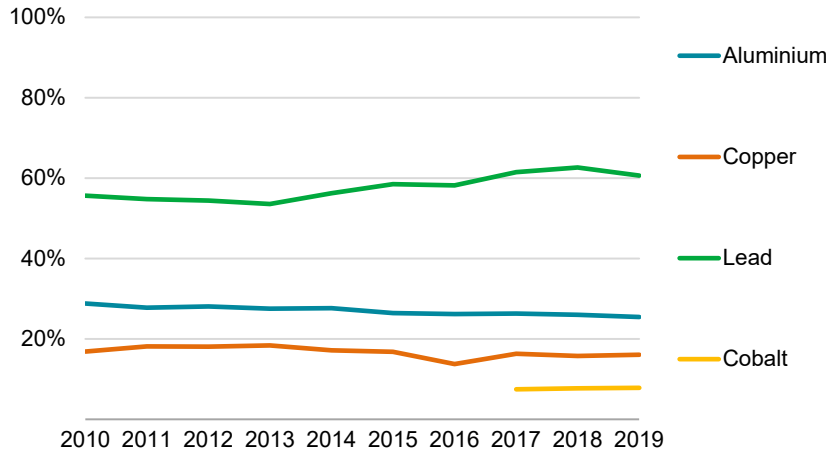
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Growing recycled volumes have only managed to keep up with demand growth

Metal recycling has the potential to be a significant source of secondary supply, although it comes with its own set of challenges. Recycling comprises the physical collection and separation of metals, and metallurgical processing to recover them. Taken together, these combine multiple pathways with a wide range of technologies and practices. Potential sources for recycling include tailings from processing, scrap used in manufacturing and fabrication and scrap from end-of-life products. For some metals, such as aluminium and copper, global stock and recycling pathways are relatively well established. However, for many metals, global stock assessments are scant or only examine discrete sub-sectoral applications, making recycling potential difficult to assess.

As noted in Chapter 1, recycling rates are typically measured by end-of-life recycling rates and recycled input rates. End-of-life recycling rates refer to the share of material in waste flows that is actually recycled, and recycled input rates assess the share of secondary sources in total supply. Both rates differ substantially by metal and region. Higher end-of-life recycling rates do not necessarily mean higher recycled input rates, as each end-use product has a different lifetime and shows a varying pace of demand growth. For example, a beverage can typically enters the waste stream within a month after consumption, whereas building materials take over 40 years to be collected. The fact that collected products are often reused in a semi-fabricated form makes an additional difference. For many metals such as copper and aluminium, recycled input rates have not changed much in recent years, meaning that improved recycling activities have only managed to keep up with demand growth.

Recycled input rates for selected metals and minerals



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Notes: Share of secondary production in total refined product consumption. Does not include scrap volumes that are reused in end-use applications.
Source: World Bureau of Metal Statistics (2020).

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Scaling up recycling can bring considerable security and environmental benefits

Physical collection is a primary limiting factor on the level of recycling. Metals such as aluminium, iron, nickel and often copper have been able to achieve high rates of recycling for simple, bulk products or for industrial applications that are easier to collect and more homogeneous in nature. As a result, these metals have a higher potential for continuous recycling and maintaining global stock.

Many new products such as personal electronics or alloyed materials make physical and metallurgical separation difficult. New iron and copper alloys, for example, bring superior functionalities but result in energy-intensive recycling pathways. Recycling of these products may require the physical, chemical and metallurgical separation of over 50 materials with different thermodynamic and metallurgic considerations from a single product.

Recycling technologies need to take into account current available stock and anticipate stock changes. Minerals that enter stock today may not be recoverable for decades depending on product life. Technologies must adapt to the stock life and the nature of the stock's evolving thermodynamic and metallurgical properties. While stock descriptions are moderately robust for copper, aluminium and nickel at a global level, most critical minerals lack information and description of stock at country, regional or global levels. For many energy transition minerals, stock descriptions and estimates are needed to inform policy measures to efficiently support the development of new markets (Nicolli et al, 2012).

But the potential for increased secondary supply from recycling, while challenging, is apparent. Recent analysis indicates that recovery of key minerals (copper, palladium, gold and silver) from printed circuit boards could require as little as 5% of the energy as compared to primary supply from mining (Seabra and Caldeira-Pires, 2020). In a world increasingly looking to reduce emissions, this is an important advantage. Critical to achieving these potential rates are increased collection rates, developing knowledge of global and regional stocks, market incentives, and collaboration, often beyond country borders, to encourage secondary market development. The digital revolution is also seeing its mark across recycling processes. Approaches span from the use of data analytics to track and understand global and regional metal stocks to the use of new sensors to improve physical collection and separation.

In addition to established waste streams (e.g. industrial applications), emerging waste streams from clean energy technologies (e.g. batteries, solar panels) could be a significant source of secondary supply after the 2030s, although they do not eliminate the need for continued investment in the primary supply of minerals.

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Enhanced metal recovery from mining and processing waste provides additional opportunities for secondary supply

Enhanced metals recovery from mining and processing waste (e.g. mining residues, slag, sludges and tailings) provides a clear opportunity to increase supply. Better treatment of waste streams can also reduce the risk of hazardous materials entering the environment. Governments are increasingly taking notice of the opportunities to improve metal recovery from waste streams, as shown by Australia's recently announced National Manufacturing Priority roadmap (DISER, 2021) aimed at increasing the country's share of critical mineral supply.

New technologies, coupled with in-depth assessments of the potential from mining and processing waste, can help generate further supply and reduce the dependence on imported materials. For example, the Kiruna iron ore mine tailings in Sweden are estimated to contain approximately 5 000 parts per million of REEs after beneficiation and are considered a new REE resource for the European Union (Peelman et al., 2016). US scientists found that waste rock from long-closed iron ore mines in the eastern Adirondack Mountains, New York, may provide valuable REEs. This is triggering further analysis of the potential of waste rock and tailings from old mines, although there are challenges associated with the proper handling of radioactive elements (e.g. thorium) (USGS, 2020). Rio Tinto is tapping an opportunity to extract lithium from waste rocks at its Boron mine in the United States (see section on lithium). Several laboratory studies demonstrated the potential of bioleaching to recover copper, cobalt, nickel and others from mine tailings and other secondary sources (e.g. electronic waste) in Germany, Spain, Serbia, Iran, China and Uganda (Schippers et al., 2014, Zhang et al., 2020).

Similarly, stockpiled and annually produced bauxite residue can be considered a resource for extracting REEs, titanium and vanadium. In the European Union the combination of enhanced metal recovery from low-grade ores, fine grained landfilled sludges, iron-rich sludges from metal production (from zinc production) and fayalitic slag (mostly from primary and secondary copper production) could yield additional volumes of zinc, nickel, copper, cobalt and others, with a combined market value estimated at EUR 2.9 billion per year (Eurometaux, 2019).

While secondary supply from waste streams is becoming increasingly cost-competitive with primary sources (Spooren, 2020), challenges remain to be addressed such as minimising emissions from recycling processes and removing hazardous substances.

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Policy intervention may be necessary to build demand for secondary supply…

In certain contexts, secondary markets for specific metals have developed in recent years even in the absence of policy support. This has occurred where market prices were high enough to encourage investment in recycling and a sizeable, readily available supply of waste stock existed. This is not currently the case for many minerals and metals that are vital for energy transitions. Barriers to further development of secondary supplies include competition from primary supply (the prices of which often do not account for negative environmental externalities), information deficits and limited waste collection (Nicolli et al, 2012; Söderholm, 2020). In these cases, a range of policy options can support the development of secondary supply markets and consequently reduce many of the environmental and social impacts associated with mining.

Support for secondary supply markets

Many countries have set overall recycling rate targets for consumer products – particularly for end-of-life vehicles and electronic waste. However, these product-specific recycling targets are less likely to encourage recycling of energy transition metals than more targeted, metal-specific policies. Weight- and volume-based metrics that are not metal-specific may allow companies to meet the targets by focusing on high-volume materials that are more readily recyclable than those found in small or trace quantities (UNEP, 2013).

Targeted policies, including minimum recycled content requirements, tradeable recycling credits and virgin material taxes all have potential to incentivise recycling and drive growth of secondary supplies (Söderholm, 2020). Alternatively, governments can consider direct subsidies for recycling. California's Covered Electronic Waste programme, for example, charges a fee to consumers on purchases of electronics, which is used to offset the cost of recovery and recycling. Each of these policy options increases the cost of using non-recycled materials vis-à-vis secondary supplies.

While these policies can, in theory, all yield similar outcomes, their impacts may vary in practice depending on the specific market dynamics (e.g. how a certain tax level would affect prices for primary products and in turn the uptake of secondary supply in each market). It is therefore crucial for policy makers to choose policy tools based on an understanding of the specific market context in order to adequately account for the costs of negative externalities.

International co-ordination will be critical because of the global nature of metal markets. If policies designed to stimulate demand for secondary supply are enacted unilaterally, they may have unintended consequences that lead only to a geographical change in use rather than a change in market supply. In addition, collaboration between countries or regions may be needed to sufficiently understand market stock, costs and dynamics.

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...and to ensure a sufficiently large waste stream to justify infrastructure investment

In addition to policies driving demand for secondary supplies, it will be important for policy makers to address other potential externalities associated with secondary supplies. They include supporting the development of collection and sorting programmes and incentivising manufacturers to develop products that are easier to recycle.

Enhanced support for collection and recycling

Economies of scale play a major role in improving the economic viability of recycling, and increasing collection and sorting rates is a crucial starting point. In this context, government policies can play a major role in facilitating waste collection. For example, although traditionally applied to drinks containers, deposit-refund schemes may have potential to increase collection rates of electronics and batteries. Denmark introduced such a system in the 1990s to increase collection of nickel-cadmium batteries (OECD, 2014). Lower-volume minerals, such as cobalt, lithium or REEs, may require collaboration across country boundaries, for example across the European Union, to drive sufficient waste streams to warrant infrastructure investment. Furthermore, concerted action may be needed to discourage waste from being exported for the purpose of avoiding recycling requirements and to ensure that products exported for secondary use are held to similar end-of-life standards in the destination country – for example, batteries contained in exported used cars.

Extended producer responsibility

Waste collection can also be encouraged by making the manufacturer responsible for the treatment or disposal of post-consumer products. In addition to incentivising collection, this encourages manufacturers to reduce waste and to adopt product designs that facilitate recycling processes. Schemes like these have been deployed across a number of different product types, including batteries, tyres, vehicles, packaging and electronic waste. Although some extended producer responsibility schemes have led to very high recycling rates, there can be major differences in performance depending on policy design (Bio by Deloitte, 2014). Therefore, it is important that policy makers set clear definitions and objectives, apply those criteria equally to all market players, and take an active role in enforcement.

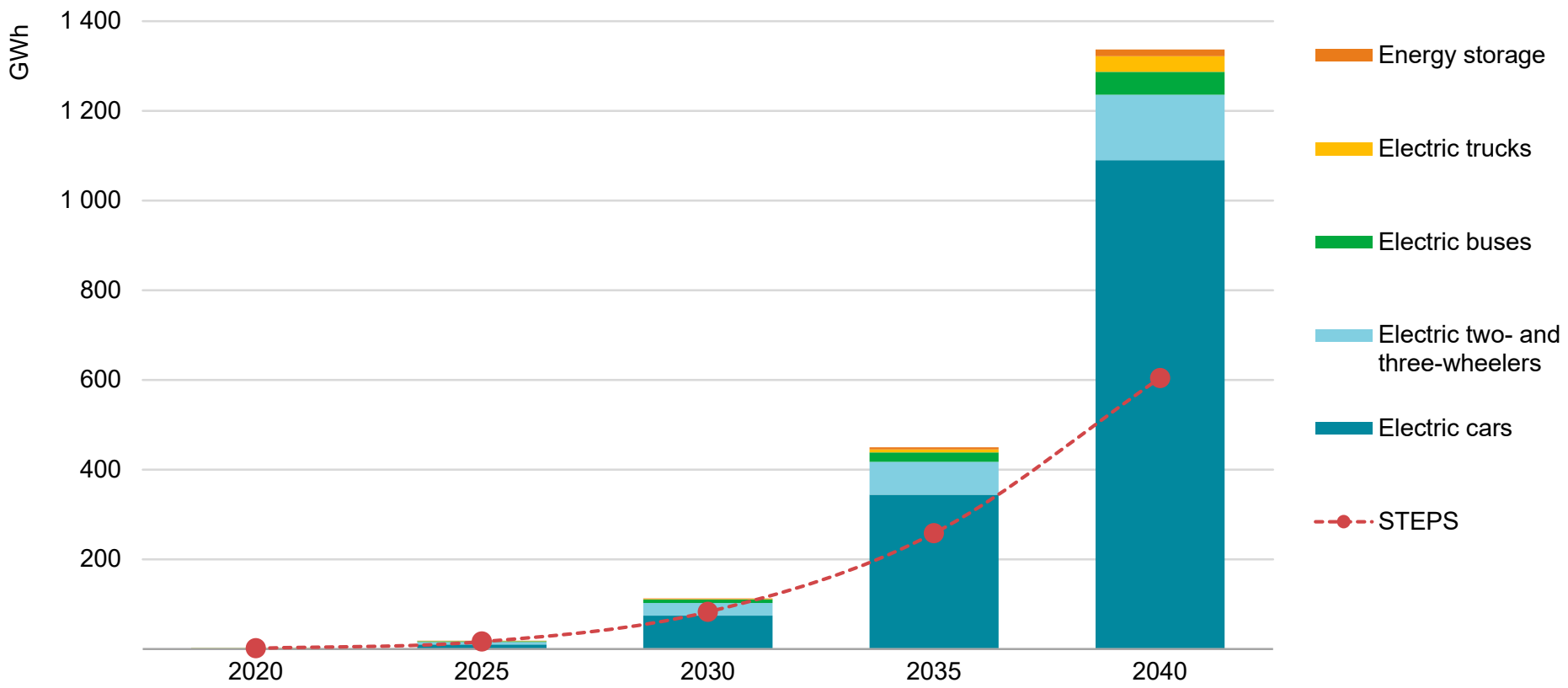
Ultimately, a mix of policies will be necessary to ensure that companies across the value chain incorporate recycling into their business activities. Depending on the market and national/regional considerations, combinations of trading credits, subsidies and other policy instruments can successfully support regional secondary supply value chains that ultimately influence global markets.

In the remainder of this section, we will consider two potential recycling cases in greater depth: batteries and electricity networks.

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Battery recycling: The amount of spent EV and storage batteries reaching the end of their first life is expected to surge after 2030, reaching 1.3 TWh by 2040 in the SDS

Amount of spent lithium-ion batteries for EVs and storage by application in the SDS



Note: GWh = gigawatt hour.

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Battery recycling: The battery recycling industry is in its nascent stages, but the picture is set to change significantly from 2030 as an influx of spent batteries arrives

Although the volume of lithium-ion batteries available for recycling or reuse today is modest and largely dominated by batteries in waste electronic products, the fast-paced growth of EV sales and the demand for energy storage are poised to alter this situation significantly by the end of the decade. As the share of electric cars in the total car stock grows from today's 1% to 18% in the STEPS and 50% in the SDS by 2040, an influx of spent batteries is expected to arrive in the market, and is likely to pose serious waste management challenges. For example, when all the electric cars sold in 2019 reach the end of their lifetime, this would result in 500 000 tonnes of unprocessed battery pack waste (Harper et al., 2019).

The total amount of spent batteries from EV and storage applications is under 2 GWh today. Under the *WEO 2020* EV and energy storage deployment trajectories, the volume reaching the end of their first life rises modestly over the period to 2030 to the tune of 100 GWh, and grows rapidly thereafter to reach 600 GWh in the STEPS and over 1.3 TWh in the SDS by 2040. This represents over 20% of new battery requirements in that year. At over 80%, the majority of these spent batteries under the SDS in 2040 come from electric cars, while over 10% will be from electric two- and three-wheelers, more than 5% from buses and trucks, and just over 1% or about 15 GWh from the energy storage domain.

There are two main ways to deal with the stream of spent lithium-ion batteries – recycling and reuse. The first route involves recycling the used batteries to recover the valuable minerals like cobalt, lithium and nickel. This approach has several advantages. Recycling materials can curb the volatility of the supply chain and prices of raw materials for battery manufacturing, and can therefore play a pivotal role in alleviating the energy security concerns of countries that are heavily dependent on imports of these minerals.

It could also reduce the environmental, social and health impacts arising from mining large quantities of these minerals that are needed to meet the expanding demand for batteries. Further benefits of recycling include reducing the energy used for and emissions from the production of lithium-ion cells. Argonne National Laboratory found that the use of recycled materials reduces both (Gaines et al., 2018). The study reported that the most sizeable reductions in energy use come from the recovery of the metals, whose initial extraction from low-concentration ores is very energy-intensive. Additionally, sulfur dioxide emissions arising from cobalt, nickel and copper develoments can be reduced by 65% to 90% depending on the recycling process employed.

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Battery recycling: The projected surge in spent volumes suggests immense scope for recycling

Several methods for recycling lithium-ion batteries are currently in use either commercially or at the pilot level. Before being recycled, battery packs must be first discharged, stabilised and then dismantled to at least the module level. Once discharged, the cell components can be separated into different material streams for further processing. Three broad categories of techniques, either employed alone or in combination, are currently used for battery recycling. These are mechanical pretreatment, pyrometallurgical processes and hydrometallurgical processes.

Mechanical pretreatment primarily involves shredding and sorting plastic fluff from metal-enriched liquid and metal solids. However, it must be combined with other methods (usually with hydrometallurgy) to recover most cathode materials, other than copper, aluminium and steel casings. Few companies focus on this process: they include AkkuSer (Finland), Retriev Technologies (United States) and Li-cycle (Canada).

Pyrometallurgical recovery uses high-temperature smelting to reduce the component to an alloy of cobalt, nickel and copper. It is a frequently used method to extract valuable metals such as cobalt and nickel, despite its environmental drawbacks (such as the production of toxic gases) and high energy costs. Hydrometallurgical recovery uses aqueous solutions to leach metals from the cathode. This could be followed by solvent extraction and/or chemical precipitation to recover lithium, nickel and cobalt. Umicore (Belgium) and JX Nippon Mining and Metals (Japan) are some of the representative companies that use both pyrometallurgical and hydrometallurgical technology, while Brunp (China) and Valdi (France) use mechanical and hydrometallurgical technology.

Additionally, an emerging recycling method known as direct recycling removes the cathode or anode from the electrode for reconditioning and reuse in a remanufactured lithium-ion battery without breaking them down into individual materials elements. Although this has the major benefit of avoiding long and expensive purification steps, there is a limitation that recovered cathodes can only be used for the manufacturing of the same battery type (Northvolt, 2019; IEA, 2020; Harper et al., 2019).

Currently, the global capacity for battery recycling is around 180 kilotonnes per year (kt/yr). China accounts for almost 50% of this capacity and it is expected to retain its dominant position given the large amount of additional capacity it has announced, amounting to 1 000 kt/y (BloombergNEF, 2019). Most of the companies involved today are independent refiners, but a broad spectrum of players from battery manufacturers, original equipment manufacturers, miners and processors are beginning to show interest in entering the market, especially in Europe.

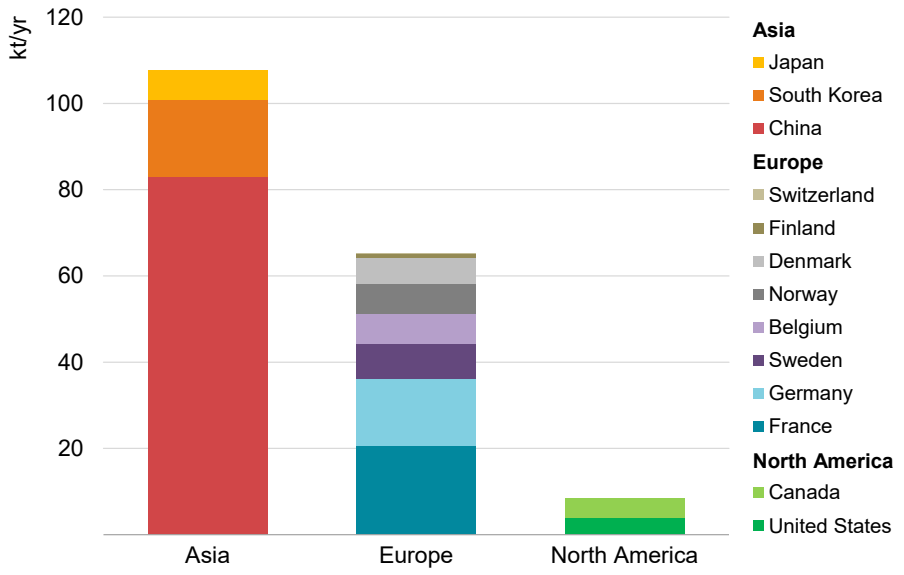
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Battery recycling: The reuse of EV batteries for second-life applications offers additional scope for reducing primary supply requirements

A complementary measure to recycling is the reuse of the rapidly growing pool of EV batteries for “second-life” applications. Spent EV batteries tend to have terawatt hours of unused energy that no longer meet the standards for usage in an EV, although they typically maintain up to 80% of their total usable capacity (IEA, 2020). Repurposing used EV batteries could generate significant value and ultimately help bring down the cost of EV charging stations, residential and even utility-scale energy storage to enable further penetration of renewable power into electricity grids. Initial trials for second-life batteries have already begun. For example, in January 2020 Nissan Motor Co. and American Electric Power launched a pilot study in Ohio that reuses expired Nissan Leaf batteries to test their stationary storage characteristics. BMW introduced a plan to sell stationary storage products for peak load reduction and backup power storage in homes by reusing batteries from the i3 EV model.

However, a number of technological and regulatory challenges remain for second-life applications to grow at scale. Chief among them is their ability to compete on price given the rapidly falling cost of new systems. Retired batteries need to undergo costly refurbishing processes to be used in new applications, and a lack of transparency regarding the state of used batteries (e.g. storage condition, remaining capacity) further complicates the economics. Clear guidance on repackaging, certification, standardisation and warranty liability of used EV batteries would be needed to overcome these challenges.

Existing and announced lithium-ion battery recycling capacity to come online by 2021 by region



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Sources: IEA analysis based on company announcements, press research and Swedish Energy Agency (2019).

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Battery recycling: Scaling up battery recycling needs to overcome various technological and commercial challenges

While many companies are active or showing interest in the field, lithium-ion battery recycling has yet to reach the maturity of technology needed to scale up sufficiently and become economically profitable. The commercial viability of recycling depends on the costs of collecting and disassembling the batteries, as well as the value of the materials recycled. Unlike the lead-acid battery recycling industry, which is already mature, the lithium-ion battery recycling industry still needs to address several challenges in order to reach scale and profitability. Some of these are technical constraints, and others involve economics, logistics and a lack of streamlined policies.

Although some companies and organisations collect spent batteries, there are no comprehensive systems that dictate and guide the material collection processes at a national level in most countries. In 2006 the Battery Directive proposed by the European Union was an important step in this direction, but not all members have reached the mandated collection targets and the directive did not include specific targets for each mineral present in spent EV batteries. In December 2020, the European Commission proposed a new Batteries Regulation as an update to the older directive, which placed a particular emphasis on lithium-ion batteries. The proposed new regulation suggests mandatory sustainability and safety requirements (e.g. carbon footprint rules, minimum recycled content, labelling and information) and end-of-life management obligations (e.g. producer responsibility, collection targets and obligations, recycling efficiency targets) (see Box 3.5).

Specific guidelines or regulations for discharging, disassembling and storing spent batteries are also lacking in most countries. China is one of the few with some technical guidelines on dismantling and restoring spent EV batteries, and retraining staff at carmakers (MIIT, 2018).

Transport logistics for end-of-life lithium-ion batteries pose another challenge. The high energy density of their cells, coupled with the presence of flammable organic electrolytes, creates a risk of thermal runaway. This requires more stringent safety measures to handle and transport spent EV battery packs.

Technology bottlenecks include the lack of standardisation of designs for battery packs, modules and cells. Different vehicle manufacturers have adopted different battery chemistries, especially for the cathode, and they tend not to disclose information on their cell designs and chemistries. This wide variety of cell types and chemistries in the market poses a major challenge to recycling, and especially to the automation of recycling processes, as each battery pack and module type requires different approaches for disassembly.

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Battery recycling: Policy can play a pivotal role in preparing for the exponential growth in volumes of waste EV and storage batteries

While there is no standard policy framework that governs the end-of-life management of lithium-ion batteries globally, several policies have been announced, mainly in the European Union, China, Japan and at a state level in the United States. Recent progress also includes the founding of the Global Battery Alliance in 2017, which aims to establish a sustainable battery value chain, from sourcing, to repurposing and recycling.

Policy makers can consider three specific actions: (i) facilitating the efficient collection and transport of spent batteries; (ii) fostering product design and labelling that help streamline the recycling process; and (iii) harmonising regulations on international movement of batteries.

Firstly, clear guidance on collection, transport and storage of end-of-life lithium-ion batteries is crucial. Policies enabling the exchange of data between key stakeholders in the process, including original equipment manufacturers, will be necessary. For example, BMW, Umicore and Northvolt have recently embarked on a joint project that aims to create a “closed life cycle loop” for battery cells. In this technology consortium, the EV maker (BMW) collects and deposits its end-of-life batteries directly at the recycler (Umicore), then the recycler uses the recovered material to produce active cathode material. This material is then shipped to the cell maker (Northvolt), which closes the loop by supplying batteries to the OEM (Umicore, 2018).

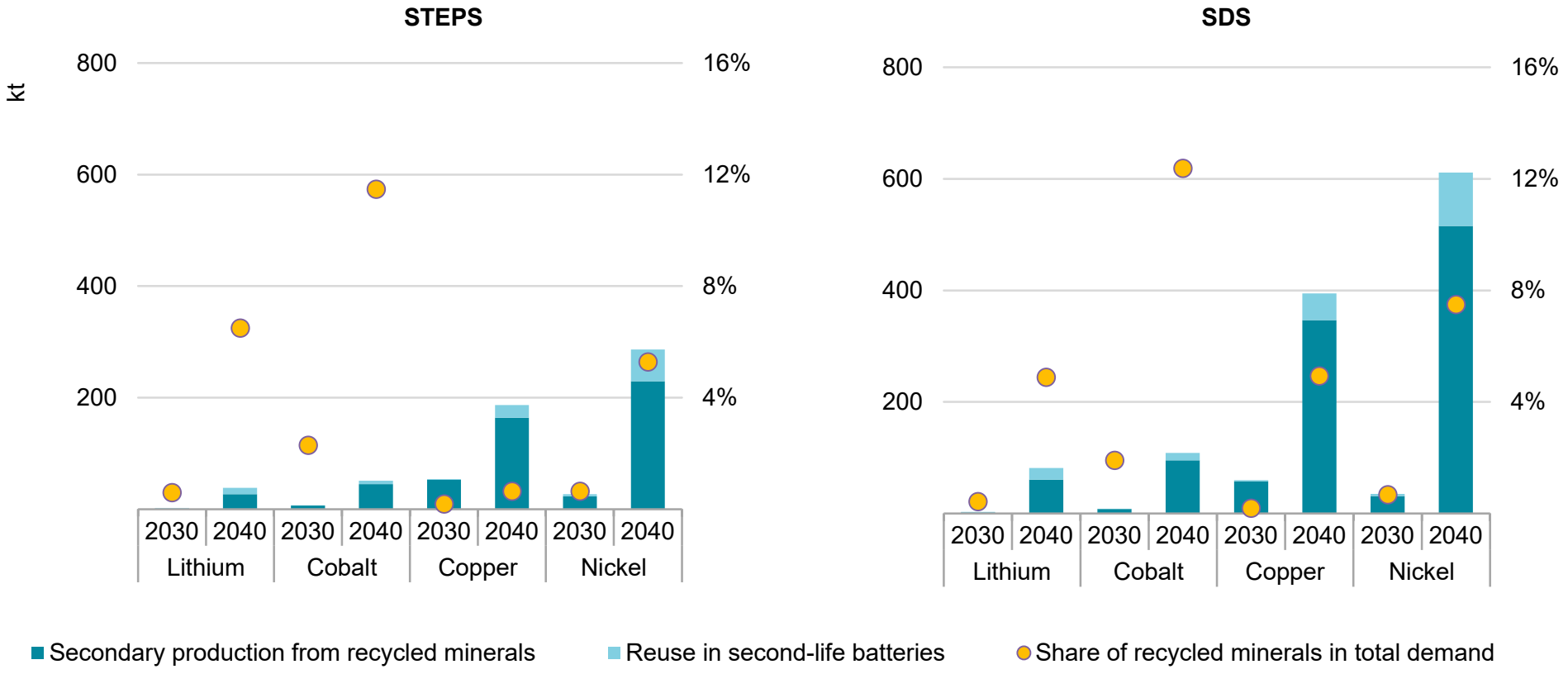
Secondly, early action in the product engineering and design phase can help facilitate an efficient recycling process. The current design of battery packs is not optimised for easy disassembly. A more standardised battery design with recycling in mind will allow easier dismantling and automation. Measures such as including labels or QR codes on battery cells or battery packs, with information on the battery components, chemistries and substructures, would not only help streamline the recycling process, but also enhance safety by better preventing fire hazards and explosions during battery disassembly and smelting (SAE International, 2016; USABC, 2014).

Lastly, concerted regulatory action across countries to ensure the safe, eco-friendly and affordable transport of batteries is essential. The Global Battery Alliance has launched the concept of a “battery passport,” which is a digital representation of a battery that contains information about all applicable lifecycle requirements of a sustainable battery, making it easier to identify and track batteries throughout their lifecycle. This could not only support data sharing on battery chemistries, origin and the state-of-health of spent batteries, but also help countries harmonise their regulatory actions on transboundary movement of spent lithium-ion batteries (WEF, 2020).

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Battery recycling: By 2040 recycling and reuse of EV and storage batteries could reduce the primary supply requirement for minerals by up to 12%

Contribution of recycling and reuse of batteries to reducing primary supply requirement for selected minerals by scenario



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Battery recycling: Recycling and reuse of batteries can bring significant security and environmental benefits, although the need for continued investment in primary supply remains

We analysed the possible contributions from recycling and reuse of spent batteries to reducing primary supply requirements for lithium, nickel, cobalt and copper under base-case chemistry assumptions. Key inputs to the model are the lifetime of the different batteries, the battery collection rate, the yield rate for each mineral, the reuse rate and the reuse efficiency. We assumed the collection rate to increase gradually to 80% by 2040, and the yield rate to vary according to the technical limitations for the extraction of each mineral using the currently available recycling methods. The reuse rates are much lower than the collection rate for recycling as the use of second-life batteries faces many technical and regulatory obstacles.

The recycled mineral volumes are negligible in the 2020s, but they start to make larger contributions to the total supply from 2030 and become much more significant by 2040. While recycling and reuse assumptions are identical in the STEPS and the SDS, the higher absolute deployment of EV and storage in the SDS makes the contribution of the recycled minerals far more sizeable than under the STEPS.

In the SDS, recycled quantities of nickel, copper, cobalt and lithium from spent EV and storage batteries in 2040 are around 500 kt, 350 kt, 100 kt and 60 kt respectively. By 2040 secondary production from recycled minerals accounts for up to 12% of total supply requirements for cobalt, around 7% for nickel, and 5% for lithium and copper. The projected contribution of reused batteries is relatively smaller, reaching only 1-2% of total supply requirements for each mineral in 2040.

This implies that the recycling of end-of-life lithium-ion batteries to recover the valuable minerals, and to a smaller extent their reuse as second-life batteries, can relieve a proportion of the burden from mining them from virgin ores. Although this does not eliminate the need for continued investment in primary supply of minerals, the contributions from recycled minerals could be even more prominent in the total supply if effective recycling policies are adopted more widely across the globe, with larger benefits particularly for the regions with higher EV deployment.

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Box 3.5. EU Sustainable Batteries Regulation

In line with the European Union's circular economy and European Battery Alliance objectives, the proposed regulation addresses the social, economic and environmental issues related to all types of batteries, including those imported into the bloc. The proposal covers the entire battery life cycle, and directly applies to lithium, cobalt, nickel and copper supply chains. The shift from a directive to a regulation is aimed at increasing harmonisation and legal certainty by giving the instrument binding legal force in all member states. The Commission states that the regulation sets out "mandatory requirements for the greenest, safest and most sustainable batteries on this planet" (EURACTIV, 2020). It is scheduled to enter into force on 1 January 2022.

Proposals for mandatory requirements range from sustainability and safety, end-of-life management, labelling, electronic exchange of information and digital passports. The aim is to enhance separate collection of portable batteries to achieve 70% collection by 2030, against less than 50% in 2018 (EUROSTAT, 2020) and prohibit any landfilling. It also places obligations on economic operators for product requirements and supply chain due diligence. The OECD Due Diligence Guidance is incorporated into the legal instrument, ensuring that sustainable batteries do not come at the expense of responsible and sustainable supply chains (see Box 4.8).

The regulation's general objective is to mitigate the environmental impact of batteries and their effects on climate change and public health by controlling toxic substances and mandating waste management. As part of the EU Sustainable and Smart Mobility Initiative, it aims to facilitate the transition to cleaner mobility by contributing to a 90% reduction in transport-related GHG emissions by 2050. The deployment of clean batteries reduces GHG emissions while improving air quality. The proposal sets out minimum levels of recycled content (12% cobalt, 4% lithium and 4% nickel by 2030) and material recovery (90% cobalt, 90% copper, 35% lithium and 90% nickel by 2026) which will gradually increase. Batteries sold in the European Union will have to carry a carbon intensity performance label and comply with carbon footprint thresholds. The carbon footprint, recycled content and responsible sourcing will be verified by recognised third-party entities. The Commission is supporting research on batteries in line with these objectives, in particular through H2020 projects receiving approximately EUR 500 million (European Commission, 2020b).

The regulation is a critical step towards achieving both clean mobility and high penetration of renewables, ensuring a fully circular economic model. By facilitating a market for recycled products and waste, it lays the groundwork for sustainable minerals development.

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Grid recycling: Unlocking copper and aluminium from today's electricity networks

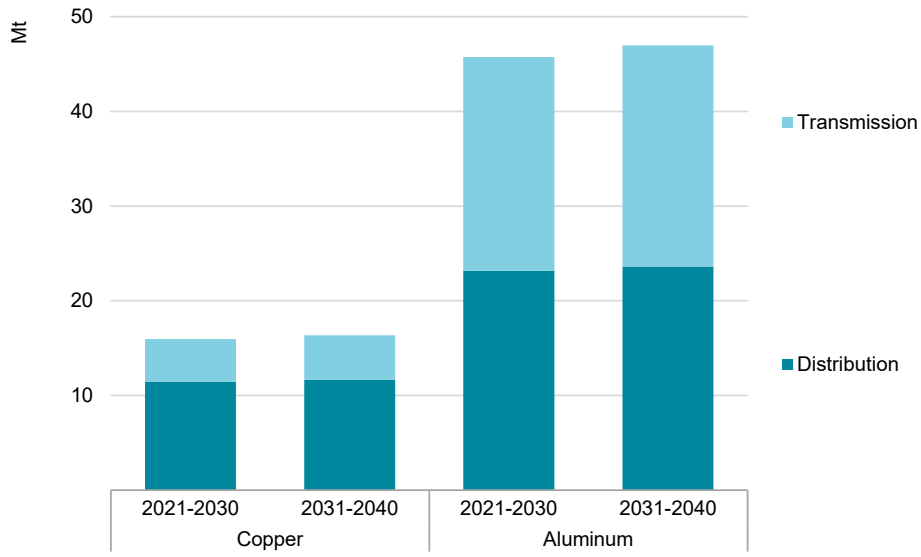
Transmission and distribution systems contain a large amount of "locked-in" copper and aluminium. Analysis of the globally installed base of overhead lines, underground cables and transformers suggests that 150 Mt of copper and over 220 Mt of aluminium are present in these grids today. These volumes are roughly seven times higher than current annual copper demand and three times higher than that for aluminium. With current technologies, the locked-in volume is projected to grow by almost 60% in the STEPS and some 75% in the SDS by 2040. When efficient collection and processing operations are put in place, these volumes can provide a sizeable source of supply to the market, via recycling or reuse.

Overhead lines, undergound cables and transformers in electricity grids have usually a design lifetime of around 40-60 years. After this period, these assets need to be replaced. The displaced grid assets can then be reused in a semi-fabricated form or the locked-in copper and alumimium can be recycled. Over 60 Mt of aluminium and copper attached to grid infrastructure needs to be replaced by 2030 and a similar amount between 2031 and 2040.

High end-of-life recycling rates are essential to reduce primary supply requirements for grid expansion and replacement. Copper has a high end-of-life recycling rate: current estimates of copper recycling from electricity grid infrastructure are around 60% (higher than the average copper recycling rates). But the potential end-of-life recycling rate of copper is over 85% (Henckens, 2021). Achieving this would reduce primary copper supply requirements by over 9 Mt in 2040 in the SDS.

Aluminium has a global recycling rate of around 40% (UNEP, 2011). The potential end-of-life recycling rate of aluminium is estimated to be around 75% (IAI, 2020). Achieving this would reduce primary supply requirements by around 32.5 Mt in 2040 in the SDS.

Copper and aluminium demand for grid replacement



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Sustainable and responsible development of minerals

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Failure to manage environmental and social impacts from minerals development will slow clean energy transitions

The growth of mineral supply not only plays a vital role in enabling clean energy transitions, but also holds great promise to lift some of the world's poorest people out of poverty. Mineral wealth can, if exploited responsibly, contribute to public revenue and provide economic livelihoods for many. However, if poorly managed, mineral development can lead to a myriad of negative consequences, including:

- Significant greenhouse gas (GHG) emissions arising from energy-intensive mining and processing activities.
- Environmental impacts, including biodiversity loss and social disruption due to land use change, water depletion and pollution, waste-related contamination and air pollution.
- Social impacts stemming from corruption and misuse of government resources, fatalities and injuries to workers and members of the public, human rights abuses including child labour and unequal impacts on women and girls.

In addition, these risks may lead to supply disruption, which could slow the pace of clean energy transitions. It is therefore imperative for both companies and governments to manage the environmental and social impacts of mineral production.

Companies have a clear business case to address these harms to reduce risk and maintain a social licence to operate. Consumers and investors are increasingly demanding that companies take these issues seriously. Failure to respond to these social demands could not only undermine reputation, but also lead to difficulties in raising capital or even to legal liability.

Companies have increasingly implemented responsible practices over the years. The adoption of corporate responsibility policies and processes at company level and via industry-wide initiatives has led to improvements throughout mineral supply chains. However, performance varies significantly among industry actors, with some segments showing limited effort and more progress being needed across the board. Challenges are more substantial where regulatory safeguards are inadequate, and where systemic issues such as labour informality, weak fiscal capacity and high inequalities are persistent, such as in artisanal and small-scale mining (ASM).

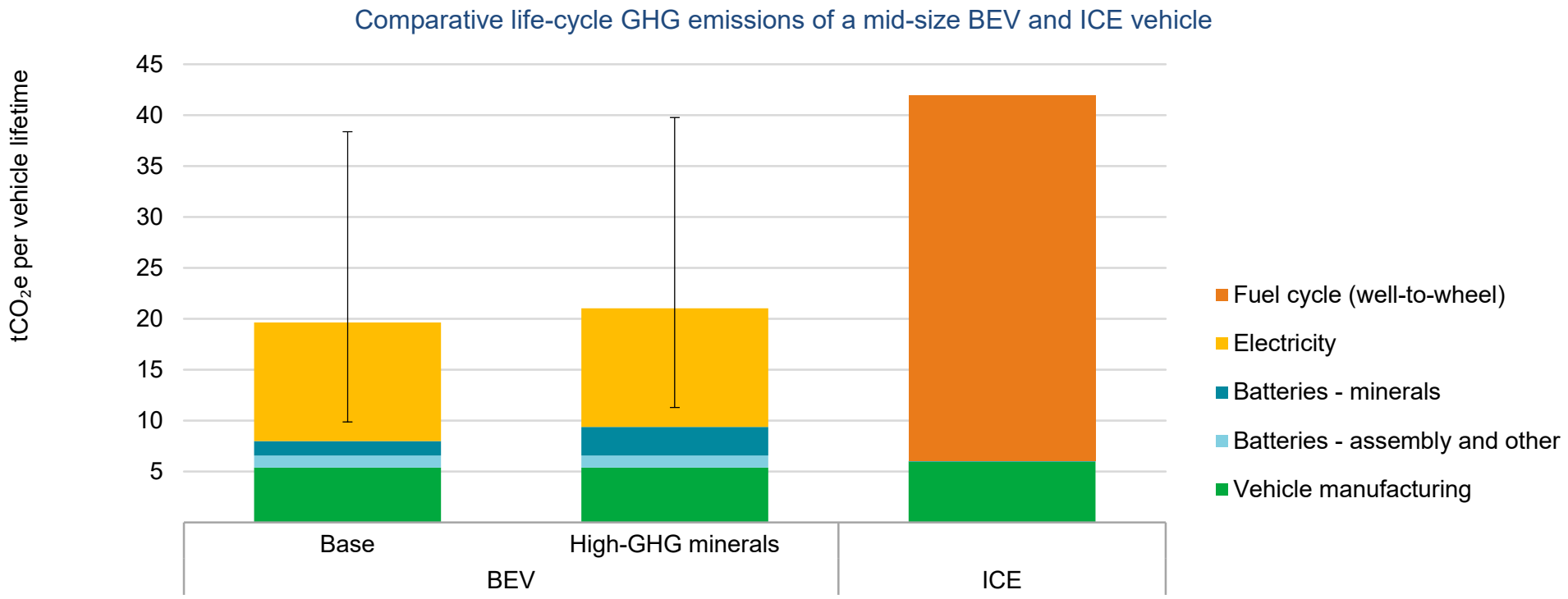
Governments play an important role in promoting improvements in environmental and social performance. As supply chains become more global, international co-operation to apply appropriate standards will be critical to ensuring that the extraction and trade of minerals are carried out sustainably and responsibly, and that the supply of energy transition minerals remains uninterrupted.

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Mineral development and climate change

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Emissions from minerals development do not negate the climate advantages of clean energy technologies



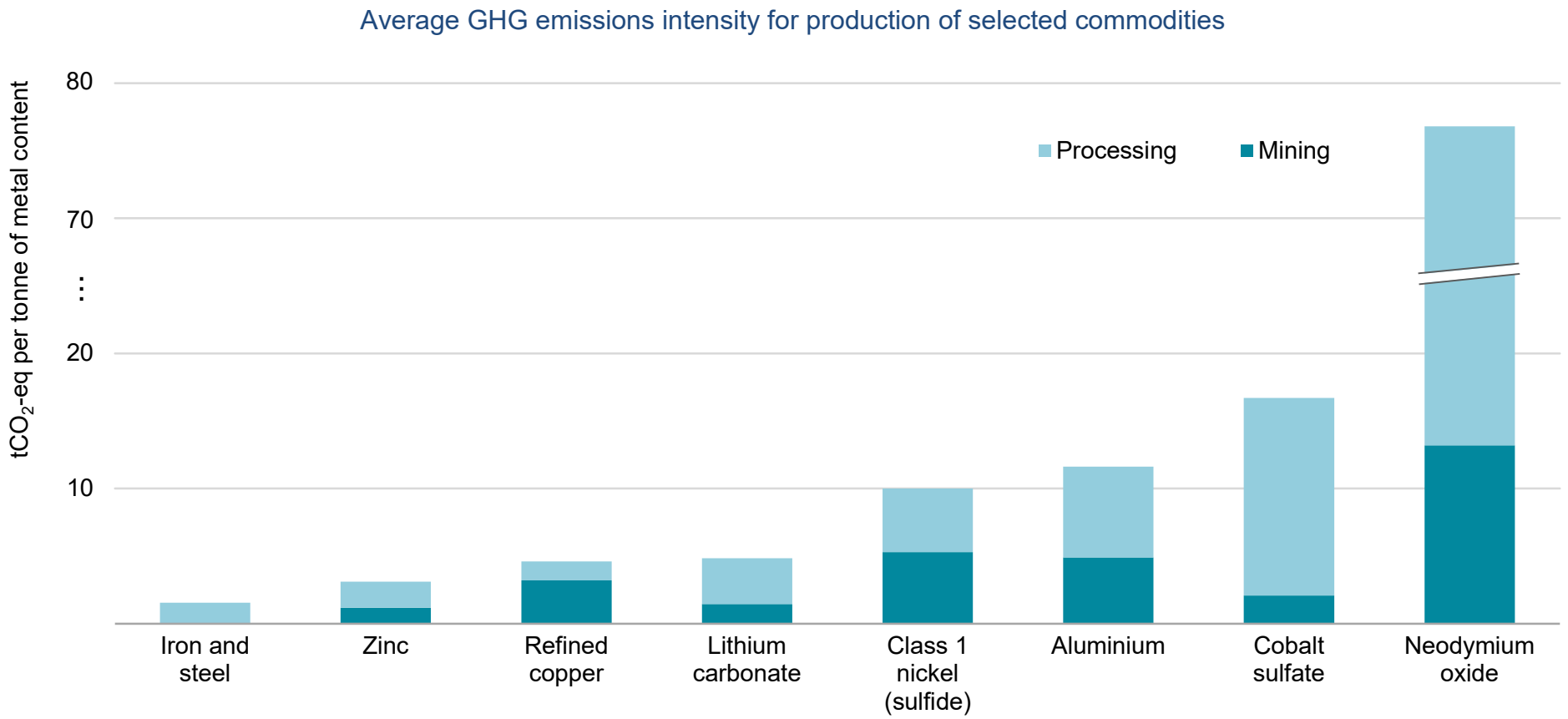
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Notes: The "High-GHG minerals" case assumes double the GHG emissions intensity for battery minerals (70 kg CO_2-eq/kWh compared to 35 kg CO_2-eq/kWh in the base case; other assumptions are the same). The values are for a vehicle manufactured from today's manufacturing lines assuming dynamic global average grid carbon intensity in the SDS (including transmissions, distribution and charging losses, weighted for mileage decay over a 20-year lifetime). The ranges shown for BEV represent cases for charging with a static low-carbon (50 g CO_2-eq/kWh) and high-carbon electricity mix (800 g CO_2-eq/kWh). Vehicle assumptions: 200 000 km lifetime mileage; ICE fuel economy 6.8 Lge/100 km; BEV fuel economy 0.19 kWh/km; BEV battery 40 kWh NMC622. BEV = battery electric vehicle; ICE = internal combustion engine; NMC622 = nickel manganese cobalt in a 6:2:2 ratio; g CO_2-eq = gramme of CO_2-equivalent; kg CO_2-eq = kilogramme of CO_2-equivalent; tCO_2-eq = tonne of CO_2-equivalent; km = kilometre; kWh = kilowatt hour; Lge = litre of gasoline-equivalent.

Sources: IEA analysis based on IEA (2020a); Kelly et al. (2020); Argonne National Laboratory (2020).

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However, there is a growing imperative to tackle emissions from mineral development as energy transition minerals involve higher GHG emission intensities



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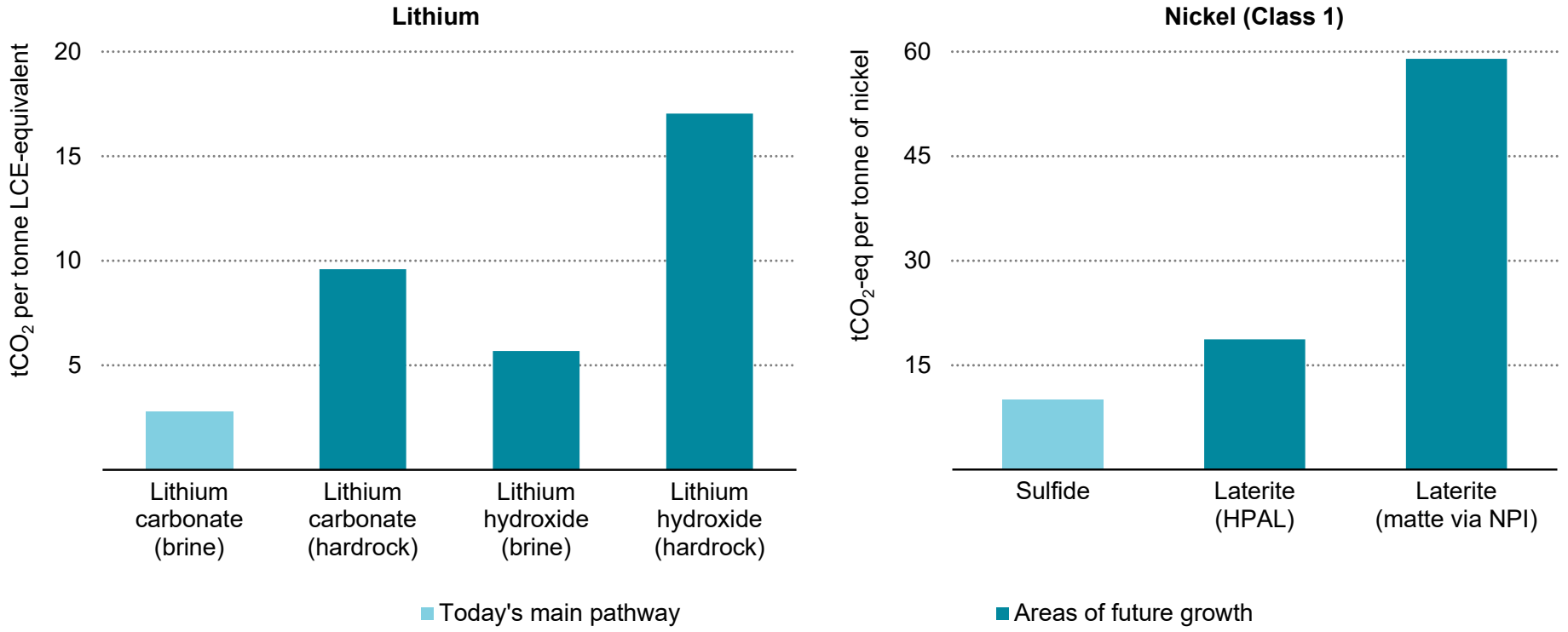
Notes: Includes both Scope 1 and 2 emissions of all GHGs (the majority of which are CO_2) from primary production. The values for lithium carbonate refer only to CO_2 emissions based on the weight average of brine and hard-rock production (denoted on a lithium carbonate-equivalent basis).

Sources: IEA (2020b) and Rio Tinto (2020) (steel); Nuss and Eckelman (2014) (zinc); data received from Skarn Associates (copper and nickel); Roskill (2020) and S&P Global (2021) (lithium); IEA (2020b) and Tost et al. (2018) (aluminium); Argonne National Laboratory (2019) (cobalt); Marx et al. (2018) (neodymium).

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Changing patterns of demand and types of resource targeted for development are set to exert upward pressure on emissions

GHG emissions intensity for lithium and nickel by resource type and processing route



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Notes: LCE = lithium carbonate-equivalent; HPAL = high pressure acid leaching; NPI = nickel pig iron. Includes both Scope 1 and 2 emissions from mining and processing (primary production). For lithium hydroxide, the value of brine is based on Chilean operations and the value for hardrock is based on a product that is mined in Australia and refined in the People's Republic of China ("China").

Source: IEA analysis based on Roskill (2020), S&P Global (2021) and Vulcan Energy (2020) (lithium); data received from Skarn Associates (nickel sulfide and laterite HPAL) and Trytten Consulting Services (nickel matter via NPI).

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Stronger action will be required to counter upward pressure on emissions from mineral production

The process of producing various commodities, such as fossil fuels and steel, is a significant contributor to global emissions. For the moment, emissions from producing minerals vital for clean energy technologies are relatively small, due to their low production volumes. However, these minerals require much more energy to produce per unit of product, which results in higher emissions intensity than other commodities. For example, emissions from producing the average tonne of lithium carbonate and Class 1 nickel are three and ten times higher, respectively, than those from producing a tonne of steel.

The higher emissions relate to the fact that most energy transition minerals have a lower metallic concentration in ore. While the metal content in iron ore is typically 50-70% (IEA, 2020c), the average ore grade for nickel is less than 2% and under 1% for copper. Lower grade ores require more energy to extract the valuable fraction, and to move and treat the waste fraction (the “gangue”).

The effects are aggravated by deteriorating ore quality. The average ore grade for copper in Chile declined from 1.25% in 2001 to 0.65% in 2017. As a result, fuel and electricity consumption per unit of mined copper increased by 130% and 32% respectively over the same period (Azadi et al., 2020). Given their large electricity consumption, refining and smelting operations are also a major contributor to emissions, especially when relying on coal-based electricity.

Future production is likely to gravitate towards more energy-intensive pathways. Lithium production has been moving from brine-based recovery (mostly in Chile) to mineral concentrate production from hardrock (mostly in Australia). The emissions intensity of hardrock-based lithium carbonate production is three times higher than that of brine production. This is due in part to higher energy requirements in mining and also in refining, the latter being mainly carried out in China where coal plays a dominant role in the power mix. In this context, several companies in Australia are looking to integrate projects within the country to lower these emissions.

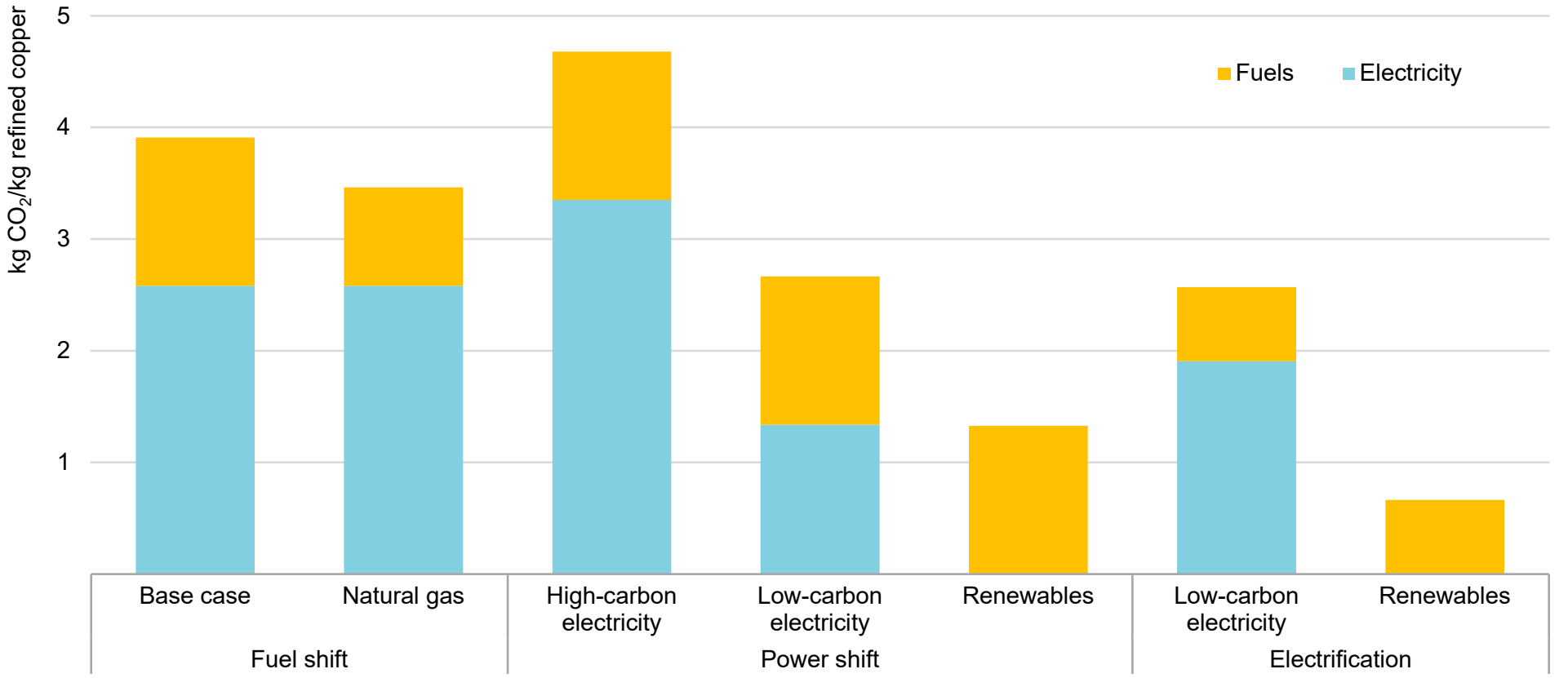
There is also additional pressure from changing demand patterns for lithium. Demand is moving from lithium carbonate towards lithium hydroxide, as the latter is more suitable for batteries with higher nickel cathode chemistries. However, lithium hydroxide involves more emissions as it requires an additional processing step to convert lithium carbonate to lithium hydroxide (when produced from brine resources).

Battery-grade nickel faces a similar situation. While sulfide resources played a major role in the past, future growth is increasingly coming from laterite resources, which require more energy to produce. These underlying pressures highlight the need for companies to take stronger action to address emissions across their value chains.

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The emissions intensity of production can vary considerably across companies and regions…

Energy-related CO_2 emissions intensity for an indicative refined copper production project under different energy consumption scenarios



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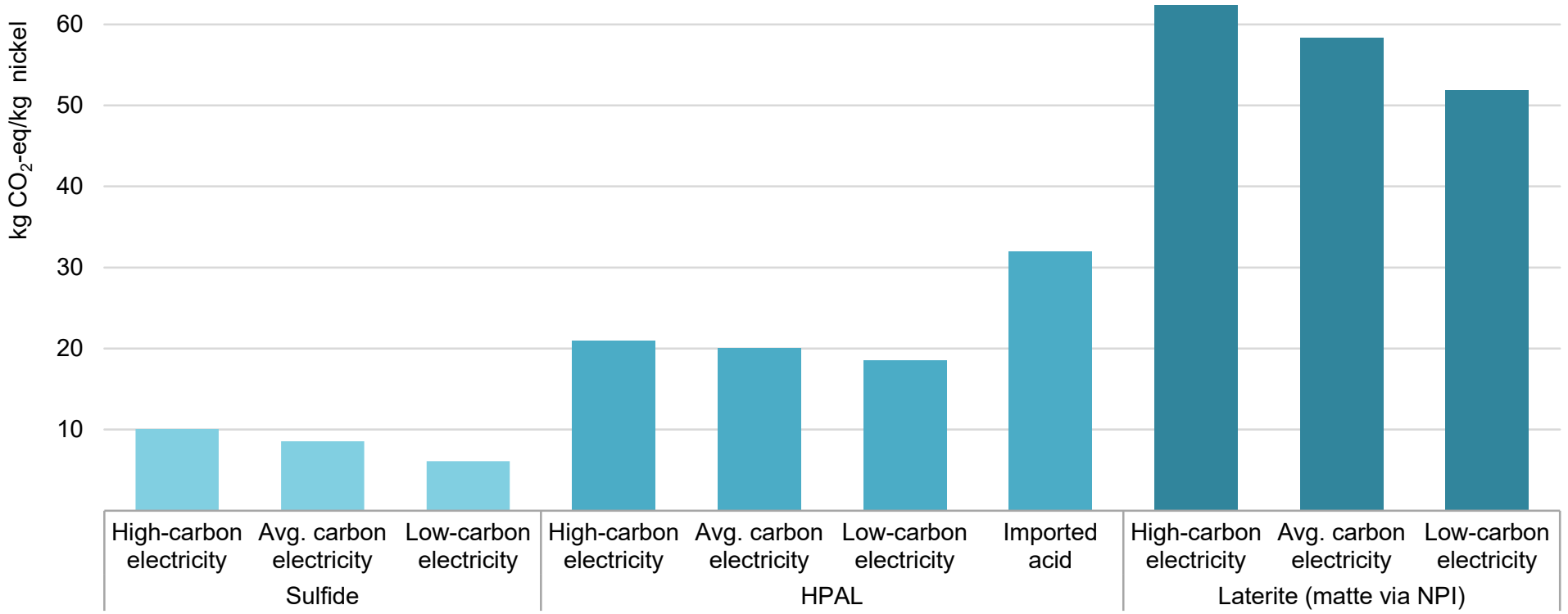
Notes: The base case assumes a fuel mix of 33% coal, 33% diesel and 33% natural gas with a global average emissions intensity for electricity (463 g CO_2/kWh). The high-carbon and low-carbon electricity cases assume 600 g CO_2/kWh and 240 g CO_2/kWh, respectively, and renewables are assumed to be carbon neutral. The electrification case assumes 50% of the energy demand from fuel consumption becomes electrified.

Source: IEA analysis based on Cochilco (2020).

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...depending on operational practices, power sources and production pathways

GHG emissions intensity for an indicative nickel production project under different grid scenarios and production pathways



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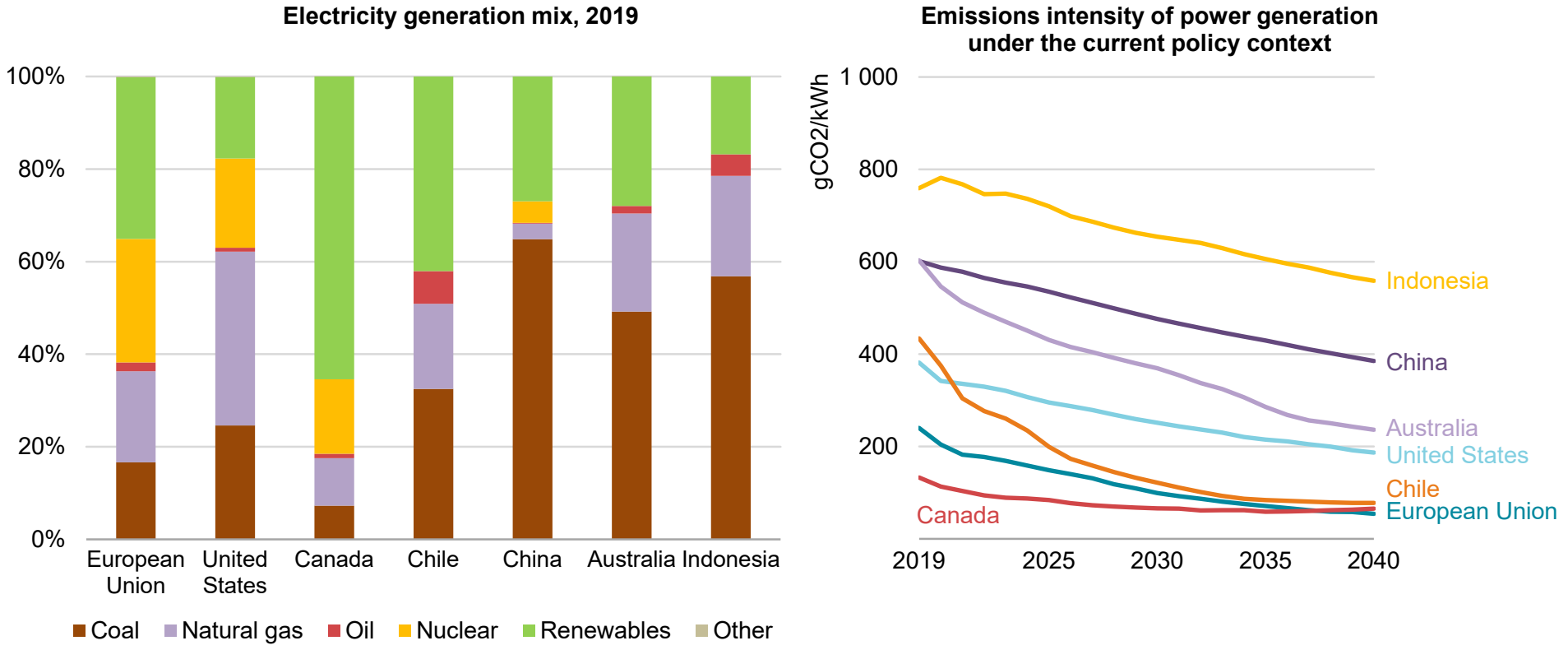
Notes: Avg. carbon electricity = global average emissions intensity for electricity (464 g/kWh). The high-carbon and low-carbon electricity cases assume 600 g CO_2/kWh and 240 g CO_2/kWh, respectively. Includes both Scope 1 and 2 emissions from mining and processing. Imported acid HPAL assumes average electricity carbon intensity.

Source: IEA analysis based on data received from Trytten Consulting Services.

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The carbon footprint of the electricity mix and the pace of future decarbonisation have significant impacts on the emissions profile of mineral production

Electricity mix and emissions intensity of power generation in selected regions



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Notes: The emissions intensity under the current policy context is based on the projections in the Stated Policies Scenario. The values for Australia also cover New Zealand as the two countries are modelled together in the World Energy Model.

Source: IEA (2020b).

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Minerals are needed for clean energy transitions, and sustainable mineral development needs clean energy

Many aspects of mineral production contribute to climate change, and foremost among these are direct and indirect sources of GHG emissions. Direct emissions, also called Scope 1 emissions, include vented CO_2 from waste rocks, emissions from fuel used in mining and refining operations and GHGs from acid neutralisation, mineral beneficiation (e.g. flotation), extraction and waste streams (e.g. tailings). Indirect emissions are either associated with the generation of purchased energy (e.g. electricity, steam and heat) (Scope 2) or any other emissions that occur in the products' value chain (Scope 3). Overall, Scope 3 emissions are the largest source of GHG emissions from the mining sector, representing well over two-thirds of the total (McKinsey, 2020), which is why many companies are taking steps to curb these emissions by partnering with end users, such as the steel industry.

Even within similar production routes, GHG emission intensities vary greatly between operators, depending on the technologies employed and mine characteristics. For instance, a time-series life-cycle assessment study, which looked at copper mining and smelting in Australia from 1940 to 2008, indicated that the carbon footprint of copper produced at all sites over the time period ranged from 2.5 to 8.5 kg CO_2-eq/kg copper (Memary et al., 2012).

In the context of Scope 1 and 2 sources, emissions from mineral production are largely driven by electricity consumption and fuel use. Electricity serves multiple purposes throughout mineral development, but refining activities are particularly electricity-intensive, representing a large share of emissions that are linked to the grid's carbon footprint. Comminution, the process of crushing and grinding solid materials, is estimated to consume up to 3% of all the electricity generated in the world (NRCan, 2016). Meanwhile, fuels are mostly used by vehicles (e.g. diesel consumption by trucks in ore hauling and loading operations) and to generate heat for processing steps.

Emissions from mineral development can be significantly reduced by a shift in fuel sources and by using low-carbon electricity. A simulation of an indicative refined copper production project under different energy consumption profiles reveals a wide variation in emissions intensity depending on the type of fuel used and the intensity of electricity supplied by the grid. Shifting all fuels to natural gas would bring emissions down by 10%, while using renewable-based electricity reduces CO_2 intensity by about two-thirds. Further reductions could be achieved through the electrification of fuel use. When combined, electrification and renewable-based electricity have the potential to reduce emissions intensity by almost 80%. Similar trends are also visible in nickel production.

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Fuel switching, low-carbon electricity and investment in energy efficiency can significantly reduce the emissions footprint of mineral production in the near term

Near-term strategies to reduce energy-related emissions include increasing the share of low-carbon electricity, acting on energy efficiency and switching to cleaner fuels.

Emissions from electricity use can be lowered by using low-carbon electricity via corporate power purchase agreements (PPAs) or on-site renewable generation. Glencore, for example, built a 3 megawatt wind turbine at its Raglan Mine in Canada to replace diesel power generation. The project received funding from the Canadian government to couple leading-edge storage technologies with an Arctic-grade wind turbine and demonstrate that such a system can operate reliably (NRCan, 2021). Meanwhile, BHP stepped out of nearly 800 million dollars in contracts for coal-fired power in Chile and established 6 terawatt hour renewables power purchase contracts (Reuters, 2019a). Of note, PPAs need to go hand-in-hand with efforts to lower the grid's carbon intensity to be more effective. For better results, low-carbon electricity can be coupled with higher power demand resulting from increased electrification of equipment and the incorporation of batteries to safeguard flexibility in operations.

Additional emission reductions can be achieved through investment in energy efficiency, for example through digitalisation, automated process management and technological improvements (e.g. using high-efficiency burners in furnaces). Glencore's Nikkelverk refinery in Norway, for example, implemented a portfolio of energy management technologies to save over 30 gigawatt hours annually (Eurometaux, 2019). The plant reduced its energy consumption by installing new tanks, electrical contacts and energy-efficient anodes. Moreover, waste heat from its sulfuric acid plant replaced previously electrically generated steam.

In the medium term, reducing or displacing diesel use in trucks is an important element of many companies' efforts. Options include optimising material handling practices, using other transport means (e.g. conveyors) or switching to electric trucks. Some companies are also exploring the possibility of using hydrogen. For example, Anglo American is partnering with ENGIE to develop a hydrogen-powered mine haul truck (Anglo American, 2019).

Companies are also increasingly reviewing options to tackle Scope 3 emissions, by shifting their business portfolio away from polluting fuels (such as coal), using low-carbon fuels for shipping and working with customers to co-invest in emission reduction measures. Another option to reduce emissions is to scale up secondary production. An assessment of current copper production routes in China shows that producing copper from scrap has the potential to reduce GHG emissions intensity to about a quarter of conventional routes (Dong et al., 2020).

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An increasing number of mining companies are committing to reduce emissions...

Net CO_2 emission reduction pledges for top 20 mining companies

Company	Scope 1 and 2		Scope 3	
	2021-2030	Long term	2021-2030	Long term
Vale	33%	100%	-	15%
BHP	30%	100%	30-40% [i]	-
Rio Tinto	30%	100%	15%	-
Glencore	40%	100%	40%	100%
Freeport-McMoRan	15%	-	-	-
Codelco (Corporación Nacional del Cobre)	70%	-	-	-
Fortescue Metals Group	26%	100%	-	-
Norilsk Nickel	25% [i]	-	-	-
Barrick Gold	10%	-	-	-
Southern Copper	-	-	-	-
Newmont	30%	100%	15%	100%
Hancock Prospecting	-	-	-	-
KGHM Polska Miedź	-	-	-	-
Teck Resources	33%	100%	-	-
AngloGold Ashanti	-	-	-	-
First Quantum Minerals	-	-	-	-
Zijin Mining Group	-	-	-	-
Anglo American	30%	100%	-	-
Sibanye-Stillwater	27%	-	-	-
Mitsui	50%	100%	50%	100%

Notes: Reductions can account for CO_2 removal (e.g. through afforestation or direct air capture) and emission credits (generated by emission reductions in other sectors). Long-term targets include pledges to be fulfilled in 2035, 2040 or 2050. i = intensity target.

Source: IEA analysis based on company filings or websites.

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... but a wider range of companies needs to come on board if overall emission levels are to follow a sustainable development path

With mounting pressure from investors, governments and other stakeholders, the industry is increasingly aware of its environmental footprint. The Responsible Mining Index reports that the vast majority of companies track their performance on Scope 1 and 2 GHG emissions, with over half disclosing comprehensive tracking data against publicly stated targets. However, fewer companies review the effectiveness of measures taken to manage emissions, and fewer still take actions to respond to such reviews.

Announced emission reduction targets have proliferated in recent years among major mining companies. Two-thirds of the top 20 mining companies have established Scope 1 and 2 emissions reduction targets for 2030. A further one-third have extended targets to include long-term and Scope 3 reductions, with Glencore, Mitsui & Co. Ltd, and Newmont Corp. setting full net-zero targets.

While encouraging, companies with emission pledges account for only a small proportion of global mining output – 25% for cobalt, and less than 20% for copper and nickel. Greater pressure from governments, investors and end-use customers is needed to expand emission reduction initiatives across sectors and regions, to include junior miners, refiners and Chinese players. Major companies, via their influence in non-operated ventures, can also influence the performance of the sector as a whole.

Mineral development can also contribute to clean energy transitions in other sectors. It can act as an anchor consumer for renewable power, support demand response and export residual energy to nearby users. In Chile, copper mines consume substantial amounts of electricity in an area with one of the world's highest levels of solar irradiation. This, coupled with the declining cost of renewables, has led to an increase in renewable power capacity, which contributed to reducing the carbon footprint of the grid (OECD, 2019a). Moreover, in the refining sector, many electricity-intensive facilities provide services to the power grid (e.g. grid stabilisation and peak attenuation) by allowing for temporary interruption of power supply or demand reduction in instances of lower supply. Automated process management helped these services become competitive in many countries, such as France and Germany, particularly for aluminium, zinc and copper production (Eurometaux, 2019).

To achieve net-zero targets, mining companies will have to address all GHG sources in their value chain, including those hard-to-abate sources. In this context, carbon offsets may complement direct emission reduction measures. However, for offsets to be effective, mining companies must verify that they result in permanent, additional, real and verified emission reductions.

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Industry and market-driven disclosures are starting to improve transparency on sourcing and sustainability…

Industry sustainability initiatives have pushed companies towards voluntary environmental impact disclosures, bridging the gap between consumer and investor expectations and regulatory processes. For example, the Mining Association of Canada's Towards Sustainable Mining (TSM) initiative has developed an assessment tool, the TSM Energy and Greenhouse Gas Emissions Management Protocol, which calls for companies to develop a comprehensive GHG emissions management system, track and report GHG emissions metrics and set reduction targets. The Initiative for Responsible Mining Assurance's GHG emissions requirements in their Standard for Responsible Mining similarly encourage companies to quantify and report emissions and to develop specific emission reduction strategies.

Market mechanisms

Trading platforms and metal purchasers can also play an important role in encouraging companies to adopt voluntary approaches to reduce emissions. The London Metal Exchange (LME) trading platform is aiming to provide consumers with greater transparency of the carbon footprint of traded metals, building on recent efforts to incorporate responsible sourcing standards into its brand listing requirements. The new voluntary disclosures will be introduced in 2021 starting with aluminium, in the form of an "LME passport" and a spot-trading platform so that producers can substantiate their carbon emission claims. This digital passport will then be phased in for all LME's physically settled metals requiring certificates of analysis, including cobalt and nickel from 2023 (LME, 2020). Public disclosure of sustainability metrics can incentivise producers to measure emissions in a credible manner, and ultimately lower their carbon footprint to meet consumer demands. This in turn may eventually support a price premium for low-emission metals. It can also act as an indicator to policy makers to assess industry and consumer buy-in (IGF, 2018a).

These industry initiatives actively support greater disclosure of emissions data, but it will take time for them to mature enough to provide consistent data and indicators. Moreover, further effort is needed to develop standardised accounting frameworks to ensure emissions data is comparable across companies. So far, industry sustainability standards remain voluntary, and thus their impact is limited to companies that choose to implement them. Although governments can encourage companies to adopt these standards – as Canada does for TSM – policy support will be needed to provide incentives for further uptake of transparency norms.

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…while regulatory approaches to reduce mining emissions are often incomplete

Once an industry standard is broadly accepted, governments can play a key role in turning voluntary commitments into legal requirements. For example, the EU Batteries Regulation will mandate disclosure of key sustainability metrics already reported on a voluntary basis under industry standards (see Box 3.5). Voluntary climate-related financial disclosures, such as the Task Force on Climate-related Financial Disclosures, are also being progressively incorporated into law, for instance in the United Kingdom and New Zealand (Davies et al., 2020).

Inconsistent reporting frameworks

Governments also have a role to play in driving standardisation among emissions accounting frameworks. Although companies are increasingly expected to disclose GHG emissions, including any indirect emissions in the value chain (Scope 3), the lack of consistency in reporting makes it challenging to compare data. Even under the Greenhouse Gas Protocol, which is designed explicitly to create a corporate standard allowing comparable reporting, companies are free to choose which values to report, emission category boundaries and relevant categories. Empirical research on the copper supply chain demonstrated that GHG accounting protocols were often lacking and differed dramatically between companies (Lee et al, 2020). As such, policy support to standardise accounting principles is necessary to bolster emission disclosures.

A suite of policy options for mining emissions

Government policies can drive companies to adopt emission reduction strategies across their operations, including fuel switching and investing in low-carbon electricity and energy efficiency. These can be addressed through a suite of policies such as renewable portfolio standards, energy efficiency mandates, emission regulations and carbon pricing. In particular, allowing independent power producers to enter the market could facilitate less emission-intensive power generation. For instance, in 2015 Chile mandated power distribution companies to conduct tender processes to provide energy to regulated customers, thus facilitating the successful development of renewable-powered mines (CCSI, 2018).

R&D and innovation support is also key to lowering emissions in mining. For instance, in the context of the European Battery Alliance, the European Union financially supports a “Zero Carbon Lithium” project in Germany to find less water- and carbon-intensive ways to extract the mineral (Energy Storage News, 2020). The Australian Renewable Energy Agency and other government entities also provided financial support for solar-powered energy generation at the DeGrussa copper mine in Western Australia, which has the potential to meet up to 90% of the mine’s daytime demand (CCSI, 2018). Clean fuel standards can also impact mining operations given their use of liquid fossil fuels and freight services (Government of Canada, 2020).

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Carbon pricing can complement other policies by providing incentives to reduce emissions

Carbon pricing holds potential to become an important component of climate governance, at both national and international levels. Carbon taxation and emissions trading schemes can be an effective tool for driving reductions in emissions in line with the “polluter pays” principle while encouraging innovation. However, so far the impact of carbon pricing mechanisms on the minerals sector has been limited to only a handful of contexts.

In many cases, the impact of carbon pricing mechanisms on minerals has been limited to the indirect effects of carbon pricing applied to electricity or fuel use. This indirect effect is small as long as carbon prices remain low. The carbon tax in Chile is a good example of these limits. The tax applies to power generation, which may ultimately be passed on to mineral producers in electricity contracts. The actual impact is minimal due to the low level of the price: USD 5 per tonne CO_2-eq (ICAP, 2021). Further, the mining sector has sometimes been exempted or received free allocation of allowances due to carbon leakage and competitiveness concerns.

However, there are encouraging efforts to apply carbon pricing directly to mining and mineral processing operations. Canada’s output-based pricing system, which applies to provinces and territories that do not have their own carbon pricing systems with comparable stringency and coverage, targets large industrial emitters. Among the sectors covered, the system puts a price on emissions occurring from mining and refining base metals such as nickel, copper, zinc, lead and cobalt, in addition to a charge on fossil fuels (Government of Canada, 2019). By combining direct and indirect carbon pricing, such schemes can provide further incentives to lower emissions.

For carbon pricing to have a more widespread impact on the mining sector's emissions, rigorous implementation will be needed and governments should send clear policy signals to this effect. For instance, the Canadian government has proposed increasing the federal carbon price by CAD15 per year from 2023, reaching CAD170 per tonne CO_2-eq in 2030 (Government of Canada, 2021a). Such policies can incentivise investment in emissions reduction measures in project planning. However, uncertainty over carbon pricing in different jurisdictions complicates the picture for companies.

Some companies have established an internal carbon price within corporate account systems. For instance, BHP has established a “shadow” carbon price ranging from USD 10 to USD 110/t CO_2-eq. It uses the price in scenario modelling to determine the competitiveness of fuels across sectors, to inform investment decisions and asset valuations (BHP, 2020). The use of shadow prices within company decision-making is a positive step to track and reduce emissions, but clear signals from governments on carbon pricing remain crucial.

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Sustainable minerals development

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A holistic approach can help integrate sustainable practices in mineral development

Mineral development affects the local and regional environment in different ways. Related interactions must be managed carefully to mitigate negative impacts and reduce associated risks. In this section, we focus on three chief challenges that are present throughout the mining value chain:

- Land use change – This is the main source of direct and immediate impacts on people, biodiversity and ecosystems. It can result in the displacement of communities and the loss of habitats that are home to endangered species.
- Water use – Mining generally requires large volumes of water for its operations. It can also be a source of water contamination, be it through acid mine drainage, wastewater discharge or the disposal of tailings.
- Waste generation – Mineral development results in massive amounts of residues, both during extraction and after utilisation, some of which are hazardous to human health.

Mineral development also entails other environmental aspects and impacts, including air pollution from particulate matter (e.g. mine dust) and gaseous emissions (e.g. sulfur and nitrogen oxides), and noise pollution due to blasting and transporting activities.

Experience suggests that it is possible to manage these impacts effectively via a combination of policy measures, robust project management and technological solutions. In particular, integrating environmental concerns at the early stages of project planning can go a long way to ensuring sustainable practices do not come at a high cost.

In this context, employing a holistic approach enables an integrated assessment of the drawbacks and benefits of different project alternatives. Often there are trade-offs between different environmental objectives. Open-pit mining, for example, has lower energy requirements than underground mining, generally leading to lower emissions, but results in more land use change. However, there are also cases where an alternative presents synergistic outcomes. The recovery of minerals from waste streams (e.g. reclaimed copper production) illustrates this, as it can reduce the amount of waste that needs to be disposed of, lessen the ecotoxicity of effluents and lead to lower GHG emissions (Hong et al., 2018).

Furthermore, taking an integrated approach to sustainability can enable better resource use and systemic innovation, often resulting in lower overall energy needs (Lèbre and Corder, 2015). For example, extracting multiple minerals from the same ore or reworking tailings to maximise recovery rates are ways to increase production, reduce pollution and often minimise other risks in parallel.

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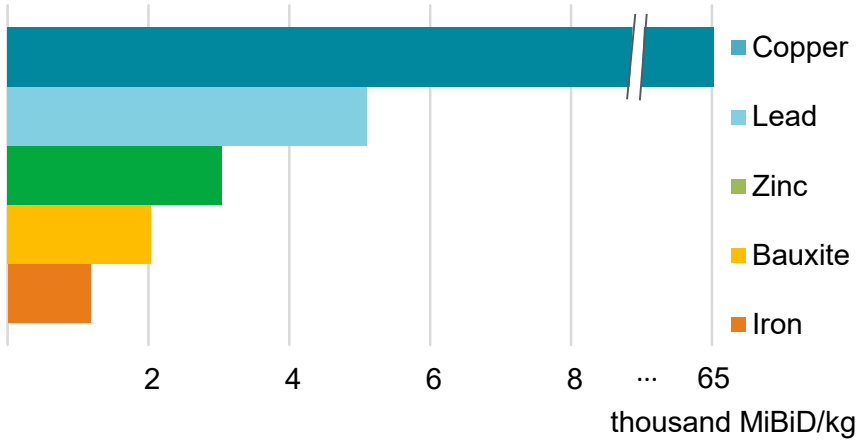
Land use: Mining can displace communities and threaten natural habitats

Mining brings major changes in land cover. Open-pit mines, in particular, can spread across several kilometres and usher in dramatic changes to the surrounding environment. Underground mines have a lower surface impact, but still generally require areas for processing, waste management and transport systems that have a sizeable aboveground footprint. Furthermore, mining activities can have spillover effects in nearby regions, such as increased urbanisation or the conversion of land to plantation forestry, which is used in the supply chain of related industries (Sonter et al., 2014). Global estimates for the area disturbed by mining activities lie between 0.3% and 1% of total terrestrial land surface (Tost et al., 2018).

The amount of land needed for mining varies significantly according to the technologies employed, the minerals produced and project characteristics. A recent study used satellite image analysis to assess land use change at three copper mines, showing results ranging from below 5 to about 20 hectares of built-up land needed per thousand tonnes of copper ore extracted (Murakami et al., 2020). The highest values were tied to an open-pit mine in a mountainous and forested location in Indonesia, which aggravated spatial requirements and related impacts, whereas the lowest values came from an underground mine in a Chilean desert. Other influencing factors included mine productivity, ore grade and afforestation initiatives.

Impacts from land use change have a cumulative nature and can cause far-ranging repercussions. In sensitive areas, such as habitats of endemic species or traditional indigenous territories, engaging in new mining developments might present a lower societal value than maintaining healthy ecosystems.

Intensity of mining pressure on biodiversity for selected minerals



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Note: MiBiD is a non-dimensional index based on data regarding land cover, protected areas and mining operations.
Source: Kobayashi, Watando and Kakimoto, 2014.

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Land use: The effects of mining projects on people and biodiversity

Activities, impacts and risks of mineral development related to land use change

Segment	Activities	Impacts	Risks
Production	• The installation of a mine involves the clearing of an area for exploration, initial processing and logistics • Open-pit mines expand as production progresses, while underground mines remain mostly with the same superficial area throughout their development • Tailings (waste materials left over after target minerals are extracted from the ore) are often stored in large dams	• Noise pollution from operating machines and the transport of materials • Habitat reduction and fragmentation, resulting in the loss of fauna, flora and ecosystem services • Potential displacement of communities in the area of the project • Landscape change and labour migration with impacts on local social settings and lifestyles	• Biodiversity loss, sometimes increasing endemic species' vulnerability to extinction • Loss of cultural heritage sites • Soil erosion can lead to changes in topography, soil quality and water pollution • Failure of underground mine excavations can lead to surface subsidence
Processing	• Refining involves large facilities and substantial material flows	• Landscape change • Noise pollution from trucks and machines	• Spills of hazardous materials or the deposition of toxic dust can lead to soil contamination
Distribution and use	• Railways and waterways are the main means of transporting minerals	• Habitat fragmentation • Noise pollution (both in land and aquatic environments)	• Accidents during transport can harm people and fauna

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Land use: Appraisal and management systems can ensure projects follow a sustainable profile

Mitigating the damage from land use change requires the potential land use issues to be considered before a project is approved. Integrated management of environmental and social impacts can help ensure projects conform to regulatory requirements.

Environmental and social impact assessments (ESIAs), which evaluate project alternatives with regard to their environmental impacts, can support decision making by providing an understanding of present environmental conditions and future consequences of proposed actions. Thus, ESIAs may identify areas that should remain untouched or options to reduce environmental impacts. For example, the Carajás S11D iron-ore project in Brazil is a case where the ESIA and project appraisal process led to reduced impacts on a national reserve, the use of technologies that do not require tailings dams and a transportation system without trucks (IBAMA, 2016).

ESIAs are now mandatory for most mining developments; however, their implementation still faces major challenges related to poor integration in project planning, monitoring and community engagement (IGF, 2019). The Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development has released a guidance document for governments on improving ESIA-related legal frameworks. Project appraisal can also provide an avenue for public participation and enable conflict resolution at an early stage of the development process. To support citizen engagement, the Environmental Law Alliance Worldwide published a guidebook for evaluating mining project ESIAs.

A major component of ESIAs is a set of measures addressing both the mitigation of impacts and their eventual compensation, such as the provision of alternative settlements for displaced populations. These are consolidated in environmental management plans (EMPs), which integrate regulatory requirements and company mitigation efforts, such as pollution control, environmental monitoring, compensation projects and risk management. EMPs commonly take a continuous improvement approach to ensure that problems are identified, corrected and procedures improved to prevent similar occurrences in the future. These plans should be present in all project phases. For example, before the start of an activity, they may provide for wildlife relocation. During operations, EMPs can address issues such as fugitive dust emissions control and the management of hazardous materials. Lastly, a major concern for mining undertakings is closure and relinquishment. There are hundreds of thousands of abandoned mines across the world, posing multiple hazards – from collapsing tunnels to soil and water contamination – with entities in charge of site clean-up often either foregoing remediation or restricting actions to highly affected areas (Gutierrez, 2020). Closure plans are a part of EMPs that help mitigate these risks by outlining costs, strategies and activities related to decommissioning.

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Box 4.2. Mine closure: Australia's Leading Practice Sustainable Development Program

Australia is a major mineral resources holder, with over 300 mining projects in operation and the world's second-largest reserves of cobalt, copper, nickel and lithium (Australia Minerals, 2021). It is also home to biodiversity hotspots and reference environmental management initiatives. One of these is the Leading Practice Sustainable Development Program for the Mining Industry, a series of handbooks developed by experts, industry, government and non-governmental representatives to serve as a reference both to mine operators and regulators.

Australia has about 60 000 abandoned mines and often it falls to the authorities to address these sites, such as in 2015, when the Western Australian government took on responsibility for a recently abandoned nickel mine (Campbell et al., 2017). The mine closure handbook sets out approaches on how to prevent or minimise adverse long-term impacts from mining. It states that most Australian jurisdictions require mine closure planning as part of the approval process for mining activities. Moreover, regulators usually have significant enforcement powers over company commitments, often linked to financial securities. Post-mining land use planning is thus incorporated in project design, including measures to minimise disturbance, establish stable non-contaminated landforms, ensure progressive rehabilitation and enable subsequent use.

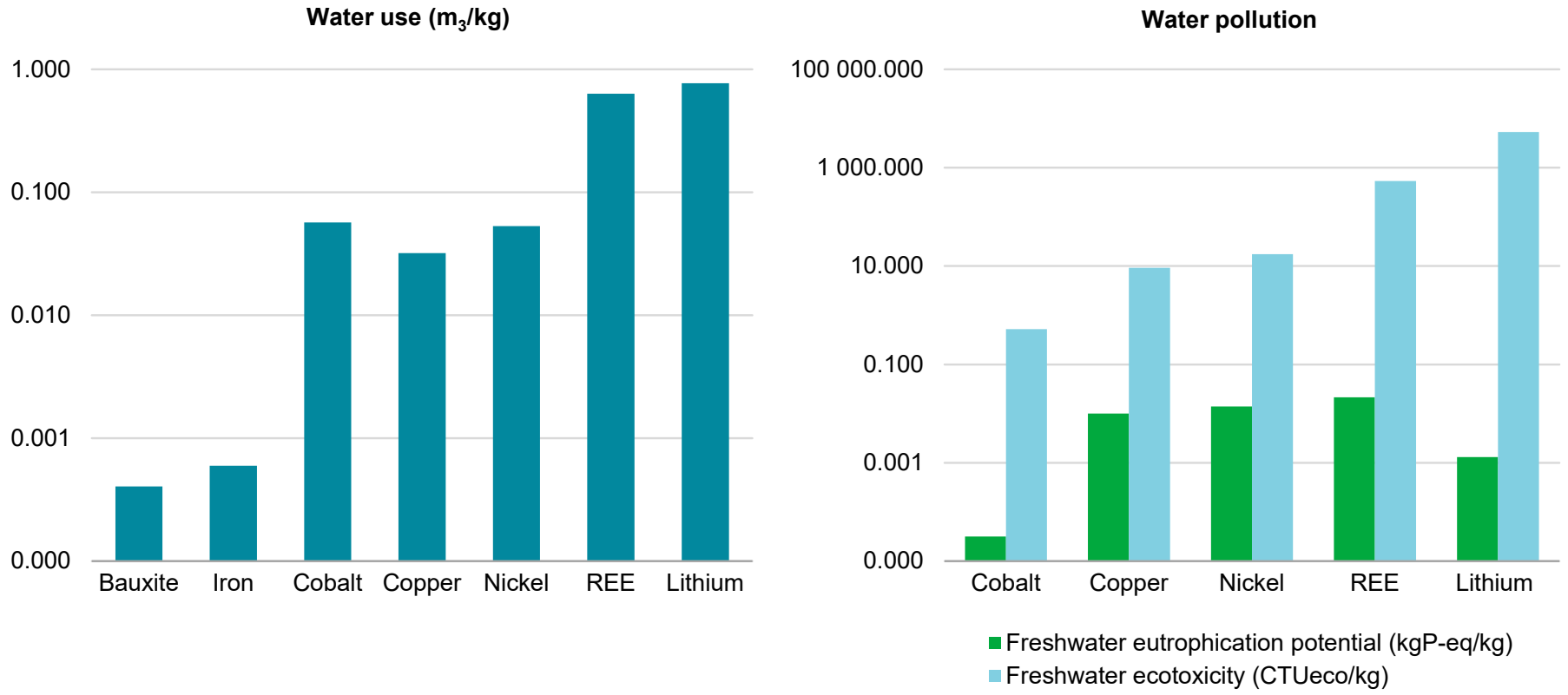
Closure plans should reflect local circumstances and build on local strengths, which are often a key factor for a successful transition after relinquishment. Future uses may comprise agricultural activity, industrial development, ecosystem conservation or community use. In this sense, planning for mine closure and rehabilitation requires a holistic approach and stakeholder engagement. Furthermore, it is an essential part of the various phases of a mining development's life cycle, from feasibility studies to project design throughout operations and decommissioning. This involves: continuous planning efforts; progressive allocation of financial resources, asset review and divestment evaluations; and implementation of closure, including remediation and monitoring, until agreed-upon completion criteria are met.

Even after infrastructure removal and site rehabilitation, there is still a need for ongoing management and monitoring until final relinquishment is approved and new users take ownership and responsibility for the land. Poorly closed and derelict mines provide a negative legacy for governments, communities and companies, while also leaving lasting environmental impacts. Best practice recognises that the mining sector is a temporary user of land and that sites should be returned to a state that enables the sustainable development of present and future generations.

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Water management: Energy transition minerals have high water requirements and pose contamination risks

Indicators for water use and water pollution for selected minerals



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Notes: REE = rare earth element; CTUeco = comparative toxic unit for ecosystems; kgP-eq/kg = kilogramme of phosphorous-equivalent per kilogramme; m^3/kg = cubic metres per kilogramme. Lithium data is for brine-based resources. REE refers to neodymium iron boron (NdFeB) magnet.

Source: IEA analysis based on Farjana, Huda and Mahmud (2019) (cobalt, copper, nickel); Jiang et al. (2020) (lithium); Marx et al. (2018) (REE); Tost et al. (2018) (bauxite and iron).

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Water management: Mining is a major water user and can cause long-lasting water pollution

Mining is a water intensive activity. Copper facilities alone withdrew over 1.3 billion cubic metres of water in 2006 (Gunson et al., 2012). Water is used along the production value chain, from exploration to processing (e.g. flotation uses water to concentrate mineral ores) and transport. It is a major input of many standard operations, such as cleaning, cooling, dust control and pumping. Energy transition minerals often have higher water needs than other commodities, although this varies according to the production process. Water consumption levels for nickel and copper production, for example, are more than double in hydrometallurgy compared with the more common pyrometallurgical method (Northey et al., 2014).

However, the most long-lasting impacts from mining do not come from water consumption. Acid mine drainage, resulting from water flows coming into contact with sulfide-rich materials, can persist long after a mine has been closed. Moreover, tailings ponds pose a risk of contamination to downstream water bodies, including extensive damage resulting from potential dam failure. Meanwhile, mines that employ dewatering operations (when groundwater inflows are pumped out to maintain access to the site) can cause a decrease in the surrounding water table or contaminate communicating aquifers.

Water pollution is particularly worrisome in the processing stage, where grinding, milling and concentration methods generate toxic effluents loaded with heavy metals and chemicals.

The associated contamination potential varies significantly among different resources, processing routes and means of disposal. Lithium production involves the highest eco-toxicity risks, mostly due to its leaching process. Moreover, the shift from traditional brine-based production to rock-based lithium leads to an almost tenfold increase in eco-toxicity values (Jiang et al., 2020). Water pollution is especially problematic in China, where REE production was conducted illegally or in unregulated small-scale activities until recently. There are numerous wastewater ponds, formerly used for leaching activities, abandoned near mining sites. China is taking steps to change this picture by remediating polluted areas and enacting stricter regulations to prevent new sources of contamination.

Mineral development can also affect the marine environment. Seabed mining can lead to significant water pollution through the release of dewatering waste or side cast sediment with fine particles and heavy metals (Miller et al., 2018). Deep-sea tailings placement, which involves the dumping of tailings in the ocean, also poses high contamination risks. Indonesia is one of the few remaining countries with mining activities that still use this disposal method. Legislation from 2001 outlawed marine tailings disposal, but two copper developments that already used deep-sea disposal before this remain in operation and a new nickel project is applying for a permit despite the existing regulatory framework (BloombergNEF, 2020).

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Water management: The effects of mining projects on water resources

Activities, impacts and risks of mineral development related to water

Segment	Activities	Impacts	Risks
Production	• Water is required for exploration (e.g. drilling), extraction, initial processing (e.g. ore crushing) and related operations • Mining frequently encounters water resources, such as aquifers, creating the need for mine dewatering • Mining often encompasses a large area subject to rainfall and related drainage • Tailings with high water content are typically stored in artificial ponds	• Reduced availability for other uses due to increased overall demand or lower quality of sources • Pollution of water bodies by discharged effluents, including leachate, process water and other effluents • Acid mine drainage and sediment build-up in nearby waterbodies	• Increased water stress in the area and depletion of groundwater resources • Contamination of aquifers or downstream water by acids, sulfates and metals • Reduced surface water storage capacity
Processing	• Water is used to separate and concentrate minerals as well as for operational needs such as dust control	• Processing operations reduce water availability and generate effluents rich in chemicals and metals	• Increased water stress in the area • Contamination of freshwater bodies
Distribution and use	• Water is used in pumping and to transport minerals through pipelines	• Pollution of water bodies	• Spills can occur during the transport of minerals by ship, rail or pipeline

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Water management: An integrated approach can help to address water needs sustainably

Water availability and demand depend on geographical conditions, the number of users and their different needs. That is the reason why water management increasingly requires an integrated catchment approach, addressing water systems at a basin level to better co-ordinate water uses and flows. This generally involves engaging stakeholders to address two major topics in a participatory manner.

Fulfilling water needs

There are several policy options to regulate surface and groundwater use, including the control of withdrawal through permits, economic instruments – such as pricing and setting a market for water rights – and defining standards for efficiency of use. These regulations often rely on monitoring systems that cover related flows and reservoir levels, to both verify compliance and ensure the sustainability of water sources.

Mining can improve its water footprint by reducing its water needs or by using alternative sources. Efficiency can be gained by reducing losses (e.g. minimising wet areas, filtrating tailings, monitoring pipelines), using dry processing technologies and by replacing evaporative cooling with less water-intensive methods. Furthermore, mining operations can often use water that has lower quality, such as water from mine dewatering and surface runoff, as well as recycled process water, treated wastewater or desalinated seawater. The Mining Association of Canada's TSM initiative has a Water Stewardship Protocol and Framework that sets benchmarks for company water management programmes.

Ensuring water quality

Effluents from the mining industry contain toxic substances, such as residual metals and chemicals used for extraction and processing. Comprehensive standards for the discharge of wastewater are a way of guaranteeing that polluting substances remain within acceptable limits, with acidity and metal toxicity being two key parameters to address (Opitz and Timms, 2016). These can be complemented by quality norms for water bodies, which align uses with required conditions and support the monitoring of affected ecosystems.

To reduce the load of pollutants discharged and meet established standards, mining facilities can reduce the volume of water that is contaminated (e.g. by managing runoff or covering waste rock and ore piles) and prevent it reaching waterbodies (e.g. implementing a drainage system or designing the project to avoid contact with groundwater). Furthermore, multiple treatment technologies allow the industry to remove the different contaminants present in its effluents. These include both simple measures (e.g. pH correction and the use of coagulants to precipitate metals) and advanced technologies, such as membrane filtration or photochemical oxidation.

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Box 4.3. Managing groundwater: Lessons from Chile, where copper mines stand next to earth's driest non-polar desert

Chile is the world's largest copper producer, responsible for about 28% of global supply in 2019. It is also the most water-stressed country in the Americas, ranking 18th globally in terms of baseline water stress (WRI, 2021). Moreover, most of its copper mines are located in the Andean mountain range in the dry northern part of the country, with approximately 54% of copper production occurring in the Antofagasta province (Lutter and Giljum, 2019), which lies next to the Atacama desert.

In this region, groundwater faces competing interests from agricultural, domestic and industrial activities, including mining. The development of copper, in particular, not only demands water for dust control and the extraction, separation and transport of ore, but can also potentially contaminate the scarce water resources due to acid mine drainage, dewatering and the disposal of tailings.

However, until the mid-2000s Chile did not have a specific legal framework to regulate groundwater use. The Water Code of 1981, which implemented a water permit trading scheme, was designed to address surface water use. In 2005 this legislation was amended to include procedures related to groundwater management (Donoso, Lictevout and Rinaudo, 2020).

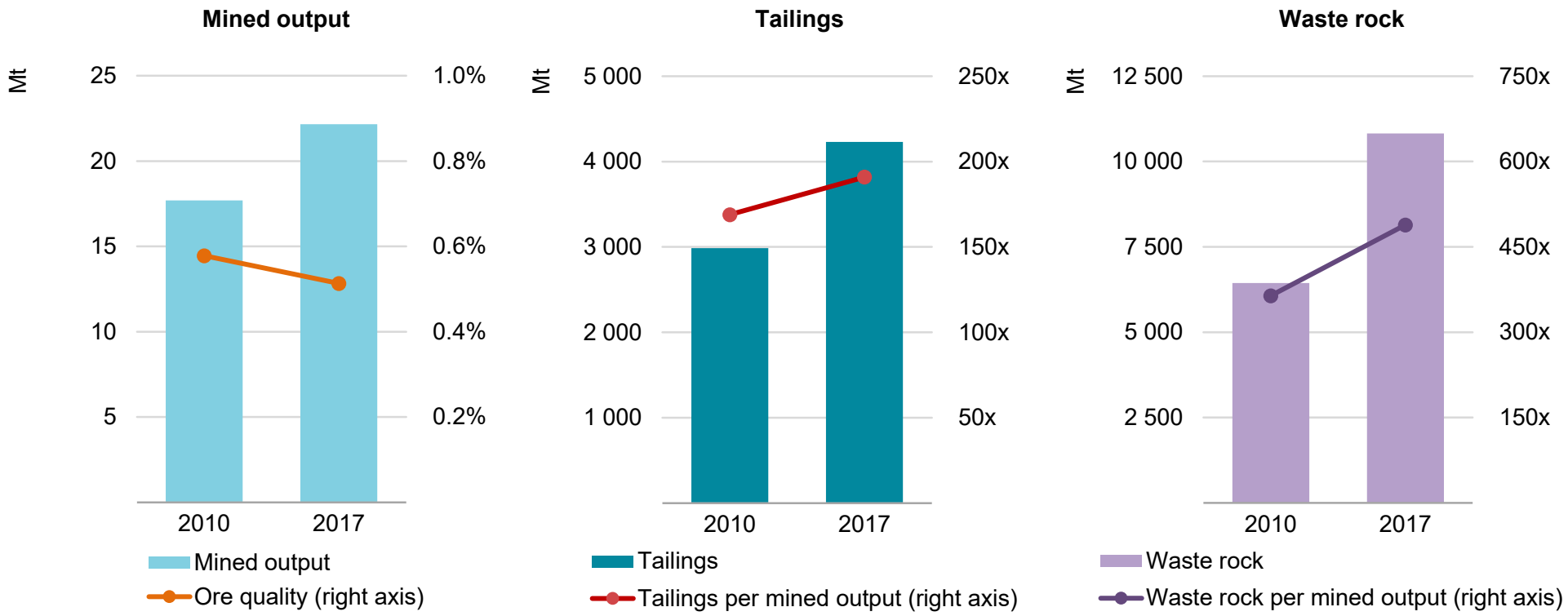
These included defining and allocating groundwater property rights, regulating its use, establishing user associations and enabling the reallocation of rights through market mechanisms. Restrictions on use apply when there is a decline in reservoir levels, exploitation generates a risk of contamination, and to safeguard water flows for sensitive ecosystems. The industry has been looking to keep pace with these developments. Anglo American, for example, took measures to allow its Los Bronces mine to recycle over 78% of the water it uses, upgrading a water transport system and using an automated circuit for recirculation (Copper Alliance, 2021).

Chile has put in place new legal instruments to address water stress. However, it could still benefit from a more integrated approach to water management, as it is not able to manage resources at river basin level or involve multiple stakeholders in co-ordination efforts (Donoso, 2018). Moreover, it faces a number of implementation challenges, such as inadequate monitoring and enforcement, often leading to the over-allocation of use rights (Donoso, Lictevout and Rinaudo, 2020). This is aggravated by the fact that many reservoirs were already overexploited before the relevant legislation came into place, highlighting the importance of regulating groundwater at the early stages of its use.

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Waste: Growing production volumes and declining ore quality are leading to a substantial increase in waste volumes from mining operations

Waste generation from copper and nickel mining



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Source: IEA analysis based on data updated and expanded from Mudd and Jowitt (2016).

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Waste: Mineral development generates vast volumes of residues that have, on more than one occasion, led to large-scale environmental disasters

Mining is generating increasing volumes of waste. This includes overburden (materials covering mineral resources), waste rock (uneconomic materials removed in ore extraction), and tailings (fine-grained materials left after separating the valuable fraction of the ore). The total amount of residues generated during mining can vary depending on the extracted commodity, methods employed and resource conditions (e.g. ore grade), but is usually quite significant. In 2018 the mining and quarrying sector accounted for over a quarter of the total waste generated in Europe (Eurostat, 2021).

Typically, the volume of waste rocks is governed by the stripping ratio, which refers to the amount of material removed to extract one unit of ore. This ratio spans from 2:1 to 8:1 in surface extraction and is much lower in underground mining (EC JRC, 2018). Waste rocks are often stored close to the mine, in piles or heaps. Meanwhile, the amount of tailings is related to the ore grade (i.e. the share of valuable minerals in the ore). For copper and nickel, of which ore grades are low, the waste rock and tailings generated to produce one tonne of product amounted to almost 700 tonnes in 2017, 30% more than in 2010 due to deteriorating ore quality and the predominance of surface mining. Tailings are usually transported through pipes to a tailings storage facility. The number of these facilities are estimated at around 32 000 globally – among active, inactive and abandoned facilities – containing around 223 billion tonnes of tailings (World Mine Tailings Failures, 2020). The most common type is an embankment dam that is designed to retain tailings and the associated water.

These facilities pose contamination risks for nearby soil and water bodies and the hazard of dam failure. The locally called Rare Earth Lake, for example, covers over 10 square kilometres of Bayan Obo, a mining town in China, and the soil surrounding it is highly enriched with heavy metals (Pan and Li, 2016). In 2019 the collapse of the tailings storage facility at Vale's mine in Brumadinho, Brazil, led to mining waste surging across the surrounding areas and the death of over 270 people (see Box 4.6). In 2015 Brazil had already seen the collapse of the Fundão dam, which released 43 million cubic metres of iron ore tailings, polluting 668 km of watercourses from the Doce River to the Atlantic Ocean (Carmo et al., 2017).

Mining and mineral processing also generates hazardous waste, an output related not only to the metals and chemicals handled in these activities, but also to the presence of naturally occurring radioactive material (NORM) in some ores. NORM can be further concentrated during mineral processing and end up in waste, with the highest activity concentrations having been found in scales from wet chemical processes and in precipitator dust from high-temperature processes (IAEA, 2005).

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Waste: The impact of mining operations on residues

Activities, impacts and risks of mineral development related to waste

Segment	Activities	Impacts	Risks
Production	• Excavation removes overburden, while initial processing generates waste rock and tailings • Seabed mining might discharge plumes of contaminated waste sediments and slurry in the seafloor	• Formation of waste piles, often with the potential to result in acid drainage • Generation of hazardous waste, including heavy metals and, in some cases, radioactive material (NORM)	• Soil contamination due to the leaching of waste piles • Pollution of downstream water bodies, including adjacent aquifers
Processing	• The beneficiation of minerals frequently requires the use of chemicals and the comminution of ores (e.g. grinding) • Processing equipment can concentrate NORM, resulting in technically enhanced substances (TENORM)	• These processes generate waste streams with fine metal particles and, in many cases, high toxicity • Waste with higher radioactivity (TENORM) generally must be disposed of through permanent storage in specialised facilities	• Hazardous waste poses health threats to workers as well as environmental contamination potential
Distribution and use	• Products that reach their end of life are discarded by users	• Generation of hazardous waste, often with mixed substances, such as a combination of plastics and metals	• Improperly managed waste can end up being handled in unsafe environments or contaminating ecosystems

Note: TENORM = technologically enhanced naturally occurring radioactive material.

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Waste: A robust waste management framework can ensure that companies take steps to reduce waste generation and handle waste safely

Sustainable waste management can ensure that instead of causing environmental harm, mining residues are used as resources and support economic development. This usually follows a "reduce, reuse and recycle" hierarchy, with disposal as a last resort.

Policies and plans to manage waste

Effective waste management policies ensure that companies take action to reduce the risks to the environment and public health from waste streams, take steps to reduce waste generation and undertake proper disposal or recovery. The European Union's Directive on Management of Waste from Extractive Industries, 2006/21/EC, for example, requires the use of best available techniques, including techniques to reduce the volume of extractive waste and use of residues for backfilling or construction purposes. In addition, the EU directive requires operators to develop waste management plans that cover all aspects of waste management, including waste reduction, storage, transport, monitoring and reporting, for each phase of production.

Waste management plans typically involve establishing procedures for each type of residue. The International Finance Corporation indicates measures for management of key mining waste categories in their Environmental, Health and Safety Guidelines for Mining.

Dewatering tailings to reduce waste volumes and risks

Tailings dewatering techniques offer several benefits, including less land use, lower risk of dam failure and reduced scope for acid drainage. Thickened or dried tailings can be disposed of as a paste or through dry-stacking, both of which create more stable disposal structures and allow water recovery. Many methods exist to dewater tailings, including pressure filtering and thickening agents, but until recently, these methods had been used primarily at high-grade, low-throughput operations due to technical limitations and high capital costs. However, a recent pilot project in the Escondida copper mine in Chile demonstrated their feasibility at higher-throughput projects, indicating that the economics of these technologies are improving. Furthermore, increasing water scarcity and safety requirements created in the wake of the Brumadinho disaster may provide the push needed to scale up tailings dewatering (Leonida, 2020).

Thickened tailings can also facilitate tailings reprocessing and support a more recovery-focused management strategy. This enables waste reduction while also increasing mineral supply. Most types of waste generated by mining can be used by other sectors, for example, in cement production. Moreover, metals contained in products that reach their end of life can generally be recycled, even if this potential is still widely underexplored (see Chapter 3).

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Box 4.4. Managing tailings: Challenges for a Global Industry Standard

An analysis of tailings incidents showed that about 80% of the root causes of dam failures are related to controllable factors (e.g. slope stability), while only the remaining 20% result from uncontrollable failures, such as earthquakes (Accenture, 2019). The most common cause identified was overtopping (i.e. when water flows over the dam) as a result of overfilling. This suggests that improving tailings management can mitigate associated risks. Best practice benchmarks are a step towards better management, even if companies' actions often face shortcomings. In the Brumadinho case, the German TÜV SÜD had certified the dam as safe months prior to the collapse, and Vale's automated monitoring equipment had displayed worrying signs days before the event (BBC, 2019).

The Global Industry Standard on Tailings Management aims to provide global best practices for tailings storage facilities and enable zero harm to people and the environment. It is the result of a joint effort of the International Council on Mining and Metals, the United Nations Environment Programme, and the Principles for Responsible Investment. Underpinned by an integrated approach to tailings management, the standard's goal is to prevent catastrophic failure and enhance the safety of mine tailings facilities worldwide. It is directed at operators and will be supported by implementation protocols that provide detailed guidance for certification.

The standard comprises six key topics and related principles:

1. Respect the rights of project-affected people and meaningfully engage them at all phases of the tailings facility life cycle.
2. Develop and maintain an interdisciplinary knowledge base with associated technical, environmental and social information.
3. Design plans and criteria for the tailings facility to minimise risk for all project phases – including closure and post-closure – and implement a related monitoring system.
4. Establish systems and accountabilities to support the safety and integrity of the tailings facility.
5. Prepare for emergency response to accidents and long-term recovery in the event of catastrophic failure.
6. Publicly disclose and provide access to information about the tailings facility to support public accountability.

As is often the case, managing impacts can help mitigate related risks and vice versa. The use of tailings for backfilling, for example, can lower water consumption and minimise land use impacts, as well as reduce subsidence or dam failure risks.

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Air quality: Tailored solutions for tackling air pollution

Sources of air pollution are concentrated in mine exploration and development, but also present further down the value chain during smelting, refining and distribution. The main sources of air pollution include (ELAW, 2010):

- Particulate matter mobilised due to excavations, blasting, ore crushing, transport of materials and wind erosion. It is also present in fugitive dust from tailings facilities, stockpiles, waste dumps and haul roads – as well as in exhaust emissions from mobile sources (e.g. trucks).
- Gaseous emissions from fuel combustion in stationary sources (e.g. drying and smelting operations) and mobile sources, explosions and mineral processing.

Particle emissions contribute to the majority of air quality problems at mines, whereas gaseous emissions can affect a broader area and be more problematic in smelting and refining. Gaseous emissions include sulfur, nitrogen and carbon oxides; photochemical oxidants; volatile organic compounds and hydrocarbons. These pollutants have detrimental health effects and cause environmental impacts, such as those associated with acid rain. Of note, some pollutants present in mineral deposits are released into the air during mining activities, such as heavy metals and radioactive emissions in REE extraction, posing occupational hazards.

Typically, each source of emissions requires a different control technology. Dust control can be addressed during mine planning with the aid of air dispersion modelling and the development of wind barriers. During operations, dust management may involve the use of containment measures, including soil stabilisation and vegetation growth, as well as moisture control (e.g. by spraying water onto stockpiles and roads).

Stationary sources can reduce emissions by using filters, wet scrubbers, electrostatic precipitators and other treatment technologies. Meanwhile, mobile sources can benefit from increased electrification and the use of clean fuels (e.g. low-carbon hydrogen), which enable both lower gaseous emissions and a reduced overall carbon footprint.

Air pollution can be tackled by many of the same policy instruments presented earlier in this section. For example, ESIAs and EMPs can affect project design and ensure the implementation of measures to control particulates and stationary sources. Additionally, jurisdictions often set requirements for pollutant emissions, define overall air quality standards and monitor pollution levels. In this context, the Initiative for Responsible Mining Assurance outlines requirements related to the management of air contaminants in its Standard for Responsible Mining and references the European Union's Air Quality Standards.

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Responsible minerals development

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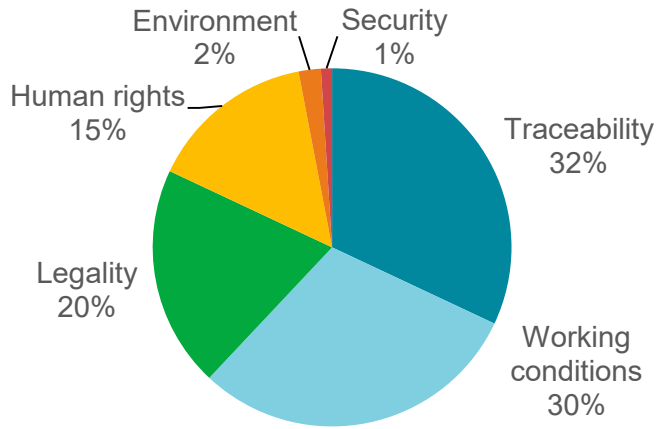
Mineral wealth has great potential to bring social and economic benefits to the local population, but many challenges remain to ensure responsible development of energy transition minerals

In most countries, mineral deposits are public resources and the government is charged with managing them in a manner that brings a public benefit. As demand grows for energy transition minerals, so does the potential for these public resources to contribute to economic growth and deliver just outcomes for national governments, companies and communities. Unfortunately, there are myriad examples where development of resources has not led to sustainable economic growth or has caused corresponding social harm.

There are many causes for this so-called “resource curse”. In many cases, public officials may act to subvert entrusted power over public resources into private gain – i.e. corruption. These problems may be particularly problematic in countries where mineral extraction contributes a large share of fiscal revenues. In addition to corruption, mining operations may have negative impacts on people and communities due to environmental damage, inadequate safety and health protections and human rights violations. Downstream consumers also contribute to these problems.

Some forms of harm are more attention grabbing than others, particularly child labour concerns. However, other impacts may ultimately be more widespread than child labour. Governments and companies increasingly cannot afford to ignore any of these impacts.

Incidents at mine sites in the Democratic Republic of the Congo categorised by type of risk



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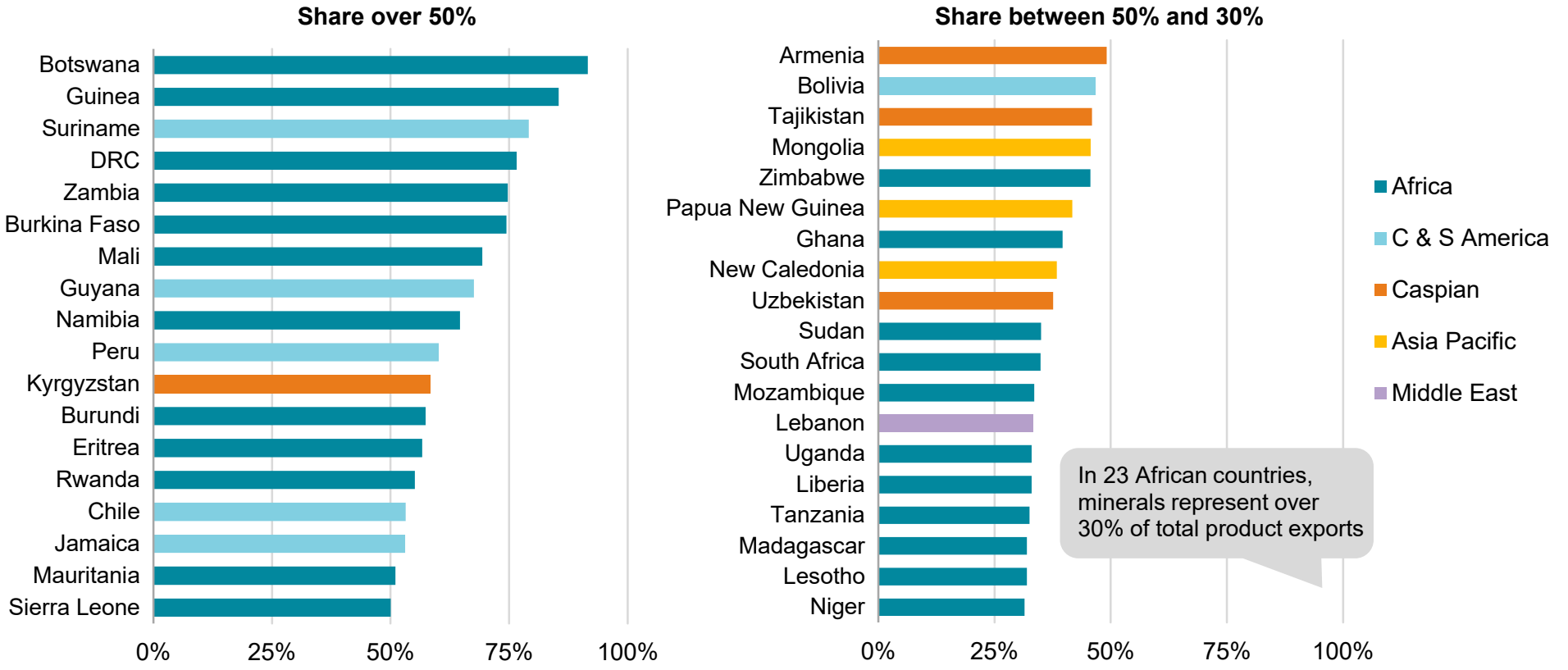
Notes: The data reflects the proportion of registered incidents fitting the risk category at artisanal and small-scale mine sites.
Source: RCS Global Group (2019).

This section begins with a discussion of the potential for mineral development to contribute to economic growth and create sustainable jobs. Then, it turns to the primary forms of social harm associated with energy transition minerals, including public corruption, risks to public safety and health, child labour and gender discrimination, with a focus on policy and regulatory strategies to mitigate these risks.

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Many mineral-producing countries rely heavily on revenue from mineral extraction, underscoring the need for transparent management of mineral wealth

Share of minerals and metals in total product exports for mineral producing countries, 2019



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Notes: The chart shows countries whose share (based on monetary value) is above 30%. Standard international trade classification codes 27, 28, 68, 667 and 971 were included in the minerals and metals category. C & S America = Central and South America.

Source: IEA analysis based on UNCTAD (2021).

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The economic benefits of mining must be managed with carefully designed legal frameworks

Although mineral production contributes to economic development in many ways, the most direct contribution is through tax and royalty revenue. In many countries this revenue source can be significant. In Chile, for example, revenue from copper production averaged around 10% of the fiscal revenue between 2010 and 2019 (Cochilco, 2020). However, without careful management, translating mining revenue into economic prosperity can be a daunting task. Volatile commodity prices often lead to procyclical public spending, which undermines the effectiveness of government expenditure in promoting economic growth. In addition, a high reliance on export revenue from minerals could lead to underinvestment in other sectors, making the economy more vulnerable to changes in global commodity prices. This underscores how fiscal revenues from mining must be used wisely to support diversification of the national economy.

The relationship between companies and communities

While mining brings in large amounts of revenue, the contribution to labour demand may be relatively small and may vary throughout the project life cycle. Governments have used various strategies to define expectations for the relationship between companies and communities and to foster “links” to other aspects of the domestic economy, such as the development of a local supplier industry to support mine operators (GIZ, 2016) (see Box 4.5).

Clear expectations for each phase of the project will help to ensure a sustainable relationship between the project developer and the local community and to enable the community to prepare for expected shifts in economic activity. Further, if the economic contribution is stable throughout these phases, it is likely to contribute to the project developing a social license to operate.

Mine operators often contribute to local communities by developing local infrastructure, providing training opportunities or making direct financial payments to community institutions. Given these contributions, companies and governments often negotiate “community development agreements” either voluntarily or pursuant to legislative requirements (Otto, 2018). In Canada, for example, there is a well-developed practice of developing impact and benefit agreements between companies and indigenous communities (NRCan, 2020). Provided that community development agreements are implemented in an inclusive and transparent fashion, they can create a structured framework for stakeholder engagement and define expectations for community investment.

Separately, governments may require companies to assess socio-economic impacts of mining projects and develop appropriate mitigation plans prior to obtaining approval. This can take place alongside assessment of environmental impacts where already required.

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Box 4.5. Fostering local "linkages" in Chile

Resource-rich countries often adopt policies designed to facilitate inter-sectoral "linkages" that create jobs, transfer technology, encourage entrepreneurship and increase local equity (Ramdoo, 2016). In many cases, the role of local suppliers is difficult to assess due to inconsistent or limited data. Initiatives like the Local Procurement Reporting Mechanism aim to provide better data for governments and companies to manage the economic impacts and benefits of local procurement.

Rule-based numerical local content requirements, although common, can be difficult to implement if not clearly defined – in Zambia, for example, an earlier law had no definition for "local" (IGF, 2018b) – and may give rise to trade disputes (Korinek and Ramdoo, 2017). As an alternative, countries may pursue horizontal policies targeted at fostering industrial development, innovation and skills training (OECD, 2019b). Chile, for example, directs revenues from mining to support innovative projects through a government-funded partnership, Fundación Chile, which operates like a venture capital firm. This funding is not limited to the mining sector and has helped to develop the salmon and wine industries. Chile has also established royalty-supported funds to support science and technology R&D and to provide local entrepreneurs with seed capital and technical support (IGF, 2018c).

Chile also supports local suppliers directly through programmes such as the World Class Suppliers Programme, which identifies and funds innovative local suppliers to address specific operational challenges. Suppliers are supported throughout the implementation phase to allow testing of ideas within real-time operations, and eventually to scale up to international markets (Navarro, 2017).

Despite some successes, Chile has not yet developed a competitive cluster of mining services suppliers. Critics have noted that the scale of supplier support programmes is too small to have the desired impact, and that a comprehensive industrial policy is needed to support the transition of the sector towards higher-value products and services (Lebdioui et al., 2020).

Although intended to foster the development of a local industry that can support economic livelihoods and drive economic development, it is clear from these examples that policies designed to increase local linkages can stumble without robust policy co-ordination. As there are many drivers of local industrial development, including access to capital, innovation funding and skilled labour, policy makers must develop a comprehensive approach that addresses the barriers to local industry without creating unintentional market distortions.

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Corruption and bribery pose major liability risks for companies, but can be managed with supply chain due diligence policies

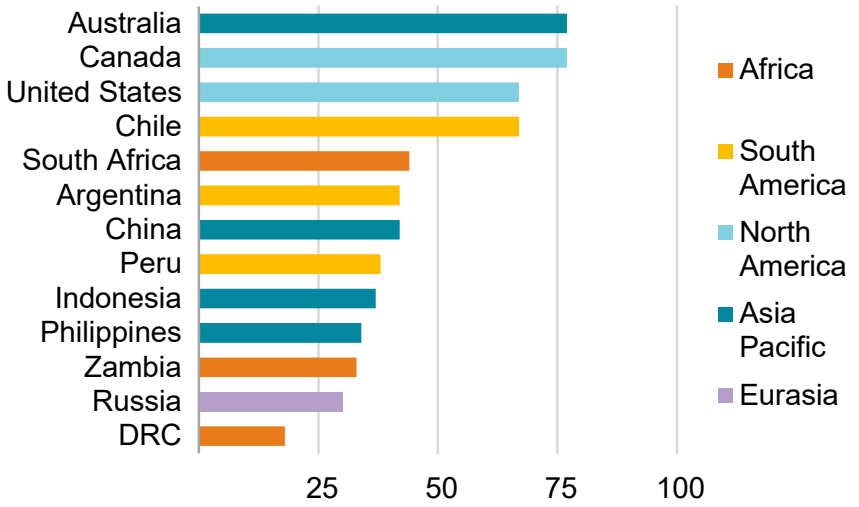
Mining operations are exposed to higher risks in locations with political instability, weak institutions and weak rule of law. The risk that mineral revenues may be used to finance armed conflict has received particular attention recently, with regulations coming into force requiring mandatory supply chain due diligence (see Box 4.8).

Although conflict-related risks are currently low for energy transition minerals, corruption and bribery risks remain high. A survey of foreign bribery enforcement actions by the Organisation for Economic Co-operation and Development (OECD) found that almost 20% of cases occurred in the extractive sector, a category that includes oil and gas production as well as mining (OECD, 2014). Further, energy transition minerals are often produced in countries that score below average in measures of perceived corruption risk.

Companies cannot afford to ignore the risk that their employees and business partners may engage in bribery. In many countries, corporations can be prosecuted for failing to prevent bribery within their overseas operations. The potential liability can be enormous, with fines reaching hundreds of millions of dollars and potential imprisonment for executives. Even short of prosecution, responding to an investigation can be extremely costly. The average investigation under the US Foreign Corrupt Practices Act lasts 38 months and costs USD 1.8 million per month (Stanford Law School, 2020).

Most major mining companies prohibit bribery among their employees, but in order to be effective, such policies must be backed up with additional measures, including risk assessments, training for employees and investigation mechanisms (RMF, 2020a). Critically, given the risks involved, companies should implement processes to identify, prevent and mitigate risks across their full supply chains, including risk-based due diligence (OECD, 2021a).

Corruption Perceptions Index for selected countries, 2020



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Note. The index ranks perceived levels of public corruption where 100 is “very clean” and zero is “highly corrupt”.
Source: Transparency International (2021).

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Governments in both producing and consuming countries can do more to mitigate corruption by increasing transparency and supporting development of institutions and the rule of law

Corruption leads to numerous pernicious effects, including decreased fiscal revenue, reduced economic growth and erosion of the rule of law (OECD, 2021a). Policy makers in both producing and consuming countries are increasingly recognising these impacts as negative social externalities that must be addressed through expanded support for legal institutions, transparency and the rule of law.

Transparency is often presented as a critical tool for addressing corruption. If governments publicly disclose contracts and payment and expenditure data, the argument goes, the public will be able to hold governments accountable for their actions, which can reduce corruption and ensure that mineral wealth actually translates into public benefit.

To support development of transparency practices, a coalition of supporting governments, companies and civil society organisations established the Extractive Industries Transparency Initiative (EITI) to help countries improve governance in the sector. In order to receive support, countries must apply to become an "implementing country", and in turn must agree to international oversight, including regular assessment of progress and adherence to specific reporting requirements. EITI has developed a global standard setting out transparency principles for governments with respect to licensing and contracting, managing extraction operations, collection of revenue and government expenditure.

EITI reports that most implementing countries are making at least "meaningful progress" against key metrics (EITI, 2020a). For example, following EITI recommendations, Madagascar changed its practices regarding publication of data about mining revenues owed to local governments (EY, 2019). This has led to constructive dialogue between the government and local officials, and EITI has rated Madagascar's progress on the issue as "meaningful" (EITI, 2020b).

EITI has been particularly successful in calling attention to vulnerabilities that increase the risk of corruption and in increasing the availability of data (Sahla et al., 2021). However, scholars have noted that simply adopting transparency processes may not necessarily reduce corruption. In order to have a meaningful impact on corruption, this type of information must actually reach the public and the public must be able to sanction corrupt conduct (Lindstedt and Naurin, 2010). Thus, further effort is needed to support the distribution of information in a format and language the public can understand, and to further develop local institutions to reduce corruption risks and ensure that corrupt officials are held to account.

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Minerals workers and the public face various health and safety risks, including accidents and exposure to toxic chemicals

Although it is difficult to compare countries, existing evidence indicates that mineworkers are subject to significant health and safety risks. In the United States, for example, the extractive sector has among the highest fatality rates – 14.6 per 100 000 workers, compared to 9.7 for the construction sector (US BLS, 2020).

Types of risk to the health and safety of mine workers

Category	Examples
Safety	Accidents involving machinery, vehicles or rockfalls in underground mines
Chemical	Exposure to acids, carbon monoxide or particulate matter such as silica dust
Biological	Insect bites or contact with animals
Physical	Loud noise, radiation or heat
Ergonomic	Frequent weight lifting or exposure to vibration
Psychological	Sexual harassment or workplace violence

Practices vary among companies

According to the Responsible Mining Foundation, most companies show a commitment to ensuring safe and healthy working conditions (RMF, 2020a). However, only two-thirds of these back this commitment with resources, including staff or financial capital. Furthermore, only a few engage with workers' representatives on the identification of occupational health and safety risks or have systems in place to ensure their operations provide gender-appropriate safety equipment. Even fewer have systems in place to protect women workers from sexual harassment and violence.

Adopting clear risk management policies can help companies to reduce potential harm, both to workers and to the public at large. Risk is a function of the frequency of an event and the magnitude of its potential consequences, and policies can act on both inputs to this equation. Prevention policies include work permit systems, which assess and set requirements to ensure the safety of work procedures, and the installation of monitoring equipment (e.g. flammable gas detectors). In parallel, policies can help to mitigate the consequences should an incident occur by requiring personal protective equipment (e.g. helmets and gloves) and developing and exercising emergency response plans.

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Box 4.6. Tailings dam collapses at Brumadinho (Brazil)

On 25 January 2019 a dam failure at an iron ore mine operated by Vale S.A. near the city of Brumadinho, Brazil, released an enormous wave of mud that flowed for nearly 10 km, killing over 270 people (Watson, 2020). This disaster has led to major pressure on mine operators across all minerals from regulators and investors alike, especially as it came on the heels of high-profile dam failures in the same state in Brazil in 2015, which killed 19 and caused vast environmental damage, and at the Mount Polley copper mine in Canada in 2014 (Cornwall, 2020).

Much of the commentary following the Brumadinho failure has centred on the method of construction – known as upstream construction. Some evidence suggests that liquefaction (when the solids in the tailings pond act as a fluid, allowing material to flow downstream as the dam collapses) is more likely with upstream construction (Kossof et al., 2014). However, commenters have also noted that poor management and operational practices are more likely to blame (Santamarina et al., 2019).

Within days of the Brumadinho disaster, the government announced a ban on new "upstream" dams and ordered existing dams to be decommissioned by 2021 (Reuters, 2019b). This prohibition was subsequently enshrined into legislation. It is not yet clear whether these laws will lead to safety improvements given the history of weak enforcement and relaxation of environmental laws (Fernandes et al., 2016). Despite having been established in 2017 with the aim of increasing regulatory autonomy and budgets, the National Mining Agency has had continued budgetary difficulties and limited resources for inspections, with just 34 inspectors responsible for nearly 800 dams (Jucá, 2019).

There are signs that these high-profile disasters have been a wake-up call for the industry. Faced with potentially enormous liability, Vale has created a new safety executive board, updated emergency plans and begun de-characterising nine dams built using the upstream method (Vale, 2020). A number of other companies have adjusted their safety practices as well, including Glencore, which has committed to upgrade 17 dams that could pose stability concerns under certain conditions (Glencore, 2019). As discussed above, the industry pushed for the development of a new Global Industry Standard on Tailings Management in August 2020, designed to enhance safety at tailings facilities. Though these actions are promising, the response has not been uniform. Since 2019 the Church of England Pensions Board, a major institutional investor, has requested information about tailings dams from 726 companies. Of these companies, only about 50% responded (Church of England, 2020).

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Health and safety protections are not uniform between large and small-scale mines

Operators of large-scale mines, smelters and refineries are typically subject to occupational and public health and safety regulations, and evidence indicates that effective regulation can lead to a reduction in risks to workers from accidents and other adverse working conditions (Holland, 2019). The International Labour Organization has developed many international labour standards and voluntary codes of practice that can reduce the risks to workers in these operations.

To a certain extent, companies can be expected to address safety risks through voluntary action to avoid accidents that may incur costs from lost productivity, civil liability and damage to public relations. As companies pay increasing attention to maintaining a social licence to operate, they may take greater effort to adhere to such voluntary safety standards. Many international standards on safety already exist, such as the Mining Association of Canada's Towards Sustainable Mining safety and health protocol and framework.

However, industry may not be capable of self-regulating for all types of safety risk – particularly where large-scale risks are involved or where there is a lack of investor pressure. In these contexts, effective enforcement or regulatory standards will be critical. For example, weak enforcement may have played a role in the Mariana and Brumadinho dam collapses (see Box 4.6).

Artisanal and small-scale mining risks remain high

Conditions are usually worse where regulatory protections are unenforced or non-existent. The problem is particularly acute for ASM, where workers are typically paid only for what they produce and lack access to health care or compensation in the event of an accident (OECD, 2019b). A 2019 survey of cobalt ASM workers in the Democratic Republic of the Congo (DRC) found that the working conditions of most miners were "unacceptable". Conditions in ventilation shafts and underground mines tended to be hazardous and all workers used protective equipment at only 2 of 58 mine sites. The survey also found that the preceding year had seen more than 60 fatal accidents and over 100 accidents involving injury (BGR, 2019).

Efforts to "formalise" ASM activities may improve health and safety conditions to the extent that formalisation allows the application of safety practices. A study of one such site in the DRC showed that the co-operative responsible for the site removed overburden to allow workers to access deposits safely, provided personal protective equipment for workers, and carried out weekly briefings on safety and other aspects (WEF, 2020). However, the long-term viability of this model remains in question as the site closed down in 2020 (Reuters, 2020a).

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Artisanal and small-scale mining of cobalt gives rise to child labour concerns

The International Labour Organization has estimated that over a million children work in mines and quarries (ILO, 2019). Child labour primarily occurs in ASM activities and is associated most closely with the mining of gold and cobalt. The problem is particularly acute in the DRC, where 10-20% of supply comes from ASM (Roskill, 2021). Although there is no reliable data on the prevalence of child labour, surveys have found children present in about 30% of the visited ASM sites in the DRC (BGR, 2019).[4] Studies have shown that children working outside the home in the DRC is directly linked to poverty, as children take on work to earn additional income (Faber et al., 2017).

The DRC has signed international conventions prohibiting child labour, including ILO Conventions No. 138 on the Minimum Age of Employment and No. 182 on the Worst Forms of Child Labour, and its labour and mining codes generally meet international standards in prohibiting child labour, forced labour and child trafficking (US DOL, 2019). However, child labour persists where ASM activities take place outside the legal structure.

Following the publication of a major report by Amnesty International calling attention to this issue (Amnesty International, 2016), some companies initially committed to sourcing ASM-free cobalt in order to mitigate child labour practices. However, in the years since, companies have evolved their thinking in recognition of the fact that ASM provides a critical source of income for many people. Removing that source of income could paradoxically exacerbate the problem (OECD, 2019b). This evolution is represented by the LME's decision to adopt a policy of non-discrimination between large-scale mining and ASM (LME, 2019). Current industry initiatives such as the Fair Cobalt Alliance and the Responsible Minerals Initiative now emphasise formalisation of ASM sites to ensure that standards are upheld and actions taken to address the root causes of child labour.

There is some evidence that ASM formalisation can be successful at reducing child labour concerns (WEF 2020; OECD, 2019b). However, successes have so far been limited in scale (BGR, 2019), and the DRC's efforts in particular have been limited by regulatory ambiguity in the mining code (OECD, 2019b). Continued multi-stakeholder engagement is needed, bringing together governments, companies and civil society to improve the situation. In this regard, the recent announcement that the DRC Minister of Mines is joining the Cobalt Action Partnership is a positive step.

[4] The simple presence of children at a mine site does not necessarily indicate a human rights violation. The ILO Convention on the Worst Forms of Child Labour applies to work that is by its nature "likely to harm the health, safety or morals of children".

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Inclusive legal frameworks and voluntary industry action can reduce the prevalence of the worst forms of child labour

Existing legal and regulatory frameworks do not always differentiate between large-scale mining and ASM, essentially applying the same requirements and limitations to all mines. This generally means that ASM activities will be "informal" or "illegal", as individuals will not be able to obtain an exploitation permit via a system designed for large companies. Even where there are special provisions for ASM, there may still be obstacles that discourage workers from working at formalised ASM sites. If enforcement is lax, or if the legal regime is burdensome, workers may continue to work at unregulated sites (IGF, 2017; IMPACT, 2018).

To be effective, policy and regulatory measures must address the root cause – i.e. poverty – and create an alternative to mining for poor children and families. While investment and technical support to develop new formalised mine sites is needed, community development and support for education and other social programmes will be important complementary strategies. The IGF has developed guidance on establishing a comprehensive ASM strategy to aid policy makers in improving the legal framework.

Industry initiatives can be scaled up

For their part, companies can do more to address the worst forms of child labour in the mineral supply chain. It is not necessarily a good solution for companies to adopt blanket "ASM-free" policies as a mitigation strategy because complete disengagement may exacerbate the causes of child labour. As an alternative, companies can seek to engage with formalised ASM and to work together with multi-stakeholder groups to promote formalisation (OECD, 2019b).

Separately, companies should seek to apply enhanced due diligence measures to their operations. Although supply chain due diligence remains voluntary for energy transition minerals, they are being increasingly adopted into regulations and market rules, and a mandatory due diligence requirement for all companies is currently under discussion at the European Parliament (European Parliament, 2021). The OECD has developed a set of practical actions that companies can take to address child labour based on the existing OECD Due Diligence Guidance, discussed in the next section.

Several industry initiatives already exist that combine several of these elements, including the Responsible Cobalt Initiative, launched by the Chinese Chamber of Commerce for Metals, Minerals and Chemicals and the Fair Cobalt Alliance. While promising, the proliferation of initiatives may cause some concern as they are not necessarily co-ordinated and risk overlapping. Thus, continued engagement throughout the value chain is needed, particularly to ensure consistency and interoperability of standards.

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Box 4.7. Formalising artisanal and small-scale mining in the DRC

Despite longstanding recognition of the potential for formalisation, as of 2019 the DRC had no more than five active formalised (or semi-formalised) ASM cobalt sites (OECD, 2019b). The government has promised reforms that may support formalisation. In November 2019 the government mandated that all ASM cobalt be sold to the newly formed Entreprise Générale du Cobalt, a subsidiary of the state mining company. In March 2021 it released a responsible sourcing standard designed to support establishing new ASM sites in the DRC (EGC, 2021), although the impact of the standard remains to be seen.

There are currently two models for formalisation of projects in the DRC. In the first model, a registered co-operative can establish an ASM site within an area designated by the government for ASM – known as a Zone d'Exploration Artisanal (ZEA). The DRC currently has 92 ZEAs in the cobalt producting region. However, these are mostly in geologically underexplored areas with less developed mining infrastructure, and a 2019 study found only two producing sites within these zones (BGR, 2019).

In the second model, the concession holder enters into an agreement with a registered co-operative to operate the site, with the concession holder setting standards for production and purchasing all material (OECD, 2019b). It is unclear how many such agreements exist, but there have been at least two documented projects so far – both initiated by buyers. A 2020 study found mixed results. While both sites had eliminated child labour and made improvements in safety practices, workers did not routinely use protective equipment and critics have noted that the sites have not led to economic or social benefits for workers (WEF, 2020). Since that study, one of the two sites has shut down (Reuters, 2020a), while for the other, the buyer announced that it would suspend purchases until it could confirm that it was free of human rights abuses (Reuters, 2020b).

From these examples, it is clear that long-term engagement with the buyer is critical to ensure that the mines are economically viable. Even with buyer support, structural barriers remain to scaling up this approach. Significant up-front investment is needed for geological analysis and to purchase the necessary infrastructure, including fences, machinery and protective equipment. In parallel, there is a need for community development to provide alternative options for children (WEF, 2020). While formalisation has the potential to improve conditions for ASM workers, a long-term commitment from buyers and mining companies alike will be necessary to ensure that it actually leads to the expansion of opportunities for ASM workers.

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Government and industry can do more to address persistent, unequal impacts on women

Historically, women have been largely excluded from large-scale mining. In the United States, women make up only about 14% of the mining workforce (US BLS, 2021). IEA analysis shows that this figure is similar in the European Union (IEA, 2020d). Although data is poor, there is little reason to think the situation is different in developing countries.

Women's participation may be greater at ASM sites, as some estimates place women at around 30% of the workforce (IGF, 2018d). However, women are most often employed in less lucrative "auxiliary activities" at these sites due to cultural barriers and gendered assumptions that mining is "man's work" (OECD, 2019b; IGF, 2018d). Women also may lack access to finance to invest in equipment and often remain fully responsible for domestic responsibilities, which limits the time and energy they have available for work. Worse, they are subject to increased risk of sexual and gender-based violence (GIZ, 2020) and can be driven to engage in sex work by financial exploitation (IGF, 2018c).

Changes in the community associated with mining may also have a disparate impact on women, even if they do not engage directly in mining activities. For example, women may be marginalised from community outreach by companies (RMF, 2020b), and the move from a subsistence to a cash economy may also give rise to family disputes and increased risk of domestic violence (GIZ, 2020).

Industry responses have so far been lacking. The Responsible Mining Foundation found that the mining sector ranked low in respect of Sustainable Development Goal 5 on gender equality (RMF & CCSI, 2020). Similarly, the foundation found in 2020 that among the 38 companies it surveyed, none had a system to regularly assess the company's impact on women (RMF, 2020b).

Creating an inclusive environment for women

The industry can do more to create an inclusive environment for women, both in their operations and in stakeholder consultations concerning community impacts and working conditions. As a first step, companies can conduct dedicated assessments of the impact of their activities on women and seek to improve gender-disaggregated data.

Governments can also play a role in promoting the inclusion of women miners and community members in multi-stakeholder consultations, as recommended by EITI (EITI, 2018). Regulatory authorities can also implement training for government and law enforcement personnel to ensure that they are prepared to intervene and address rights violations. Governments may also fund programmes designed to reduce the barriers for women to work, including providing reliable access to finance and social services to assist with childcare and domestic responsibilities.

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International co-ordination

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International co-ordination on sustainable and responsible extraction already exists

Selected initiatives categorised by activity area

Name	Climate	Sustain-ability	Responsible sourcing	Rights of workers	Fairness and inclusivity	Governance	Security of supply
World Bank Climate Smart Mining Initiative	●	●				●	●
European Battery Alliance							●
European Raw Materials Alliance							●
Extractive Industries Transparency Initiative						●	
Global Battery Alliance	●	●	●				
Energy Resource Governance Initiative		●	●	●		●	
Fair Cobalt Alliance				●	●		
International Council on Mining & Metals	●	●	●	●	●	●	
Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development		●	●	●	●	●	
Initiative for Responsible Mining Assurance		●	●			●	
Towards Sustainable Mining	●	●	●	●	●		
OECD Responsible Business Conduct			●	●	●	●	
Responsible Minerals Initiative			●	●			
Responsible Minerals Foundation	●	●	●	●	●	●	
Women's Rights and Mining			●		●		

Note: Primary activity type: ● = Technical assistance. ● = Industry standardisation. ● = Investment/funding. ● = Research and analysis.

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International co-ordination continues to play a critical role in encouraging companies to identify and address risks across their entire supply chains

Growing demand for energy transition minerals entails the expansion of supply chains and an increase in associated environmental and social risks for upstream and downstream companies alike. Identifying and addressing risks across jurisdictions with a patchwork of legal frameworks and local contexts is indeed technically challenging and resource-intensive. But ignoring supply chain risks is increasingly costly in light of pressure from consumers, investors and regulators. For instance, mining companies and traders have faced criminal probes and financial sanctions due to corrupt practices in their supply chains in the DRC (OECD, 2019c).

A prime strategy to mitigate risks is enhancing traceability, accountability, audits and other measures that allow companies to assess their supply chains. These efforts are supported by international frameworks for due diligence, such as the OECD Guidance (see Box 4.8). The operationalisation of these frameworks can be tailored to specific supply chains through industry standards. The growth of an entire industry catering to the needs of companies looking to implement these frameworks speaks to their broad uptake. Certain industry initiatives are calling attention to a broader set of risks beyond conflict financing, serious violations of human rights and economic crime, with increasing attention paid to environmental concerns. For example, the Responsible Minerals Initiative, the Cobalt Industry Responsible Assessment Framework and the Copper Mark adhere to the principles set out in the OECD Guidance, but go beyond the risks explicitly covered by its Annex II. The expanding coverage of due diligence frameworks and legislation reflects a broader trend of investors, consumers and civil society increasingly calling on companies to look more closely at their supply chains and reduce environmental and social harms through proactive engagement, rather than “de-risking” by exiting fraught supply chains altogether.

Innovation and due diligence

Innovation can also play a role in enhancing supply chain transparency. For example, shifting internal management systems from paper-based to digital documentation facilitates traceability and public access. The European Union, the Global Battery Alliance and the LME are all looking at increasing traceability through digital “passports” attached to individual batteries or metals. Market players are also considering distributed ledger technologies (blockchain) to ensure integrity of mineral supply chain data. While technological solutions alone cannot replace a company’s due diligence obligations, they can play an important role in streamlining these efforts.

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Box 4.8. OECD due diligence guidance for responsible supply chains

The *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas* (OECD Guidance) aims to help companies achieve responsible sourcing of minerals and avoid contributing to conflicts, human rights violations and economic crime. It serves as a global reference for public and private stakeholders. Although it initially focused on minerals from conflict-affected and high-risk areas, e.g. tin, tantalum, tungsten and gold, the scope is much broader: it can be applied to all minerals and all types of upstream and downstream risks. It covers both ASM and large-scale mining and is applicable globally, making it increasingly difficult for companies to "opt out". The OECD is working on a complementary tool addressing environmental risks to enhance coverage of supply chain issues.

The OECD Guidance facilitates the prevention and mitigation of human rights abuses, support to armed forces, and other risks such as tax evasion, fraud and bribery. This is achieved through a five-step framework involving establishing internal management systems, identifying and assessing risks, developing a mitigation strategy, carrying out independent audits and annual reporting. Supply chain stakeholders must establish traceability or a chain of custody system to track minerals and undertake on-the-ground assessments for "red-flagged" supply chains. Critically, companies are instructed to remedy shortcomings in supply chains rather than disengage. In energy transition mineral supply chains, the OECD Guidance has *de facto* become a core component of countries' legal frameworks for responsible sourcing. Responsible sourcing requirements based on the OECD Guidance are incorporated into the EU Regulation on Conflict Minerals (currently only applicable to tin, tantalum, tungsten and gold) and the proposed Batteries Regulation. Similar requirements were implemented through the U.S. Dodd-Franck Act and in several African countries (OECD, 2021b). The shift from a voluntary approach to mandatory legal frameworks or market rules reflects broad global consensus regarding enhanced supply chain due diligence.

In 2016 the OECD launched an Alignment Assessment project aimed at measuring the extent to which recommendations had been incorporated into industry standards and effectively implemented. This first exercise revealed significant gaps between the standards under review and OECD Guidance, which were subsequently largely remedied (OECD, 2018). Uptake studies are now underway to evaluate implementation at a company level. While these exercises alone cannot drive full compliance, they ensure a measure of accountability in the rapidly expanding world of industry initiatives, and highlight implementation gaps for policy makers.

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The international trade and investment regime is key to maintaining reliable mineral supplies, but policy support is needed to improve application of environmental and social regulations

The global trade and investment regime has helped to reduce tariffs, subsidies and other barriers to trade, enabling companies to weave global supply chains to meet the market's needs. At the same time, this regime can be seen as limiting the policy options available to governments to address environmental and social issues. Although the trade system recognises governments' authority in these areas, for example through exceptions to Article XX of the General Agreement on Tariffs and Trade, progress on incorporating sustainability norms into the international trade regime has been limited and debate continues about including enforceable standards in free-trade agreements (Bronckers and Gruni, 2021).

Governments are therefore looking to update their trade policies in line with civil society's expectations and to balance this goal with stability of supply and national security considerations. Export controls, subsidies to state-owned enterprises in the mining and processing sectors, or carbon border taxes could also lead to distortions in free trade. Such measures reflect the potential tension between international trade disciplines and the mainstreaming of environmental and social concerns.

Further, the international trade regime remains largely deadlocked at the World Trade Organization level, notably in respect of industrial subsidies reform. Due to the lack of impetus for global trade agreements, countries are increasingly shifting to bilateral or regional agreements to secure supplies of raw materials. EU trade policy strongly favours including environmental and social standards in such agreements. For example, agreements under negotiation with Chile, Australia and China, and the completed Comprehensive Economic and Trade Agreement with Canada, all include commitments to multilateral labour and environmental agreements and responsible business conduct. Apart from the draft agreement with China, they all include specific language on supporting uptake of the OECD Due Diligence Guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. They reflect the important role of international trade to promote consistency in standards. However, these commitments remain largely unenforceable as they are not subject to the agreements' dispute settlement chapter.

Although international trade undoubtedly plays a role in ensuring the stability of energy transition mineral supplies, governments must achieve both security aims and a just transition. Encouragingly, responsible and sustainable sourcing of energy transition minerals is increasingly perceived as a pillar of security of supply, and not as a necessary trade-off. As such, trade policies should reflect these standards rather than rely on them to erect new trade barriers.

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Enhancing capacity building and knowledge sharing can address critical resource gaps between countries…

Capacity building and knowledge transfer can be a particularly fruitful area of co-operation, as experience and capacity varies greatly between countries. Australia, Canada and the United States, all of which have well-developed regulatory systems addressing environmental and social concerns, are increasingly offering technical assistance to countries with nascent regulatory regimes.

Role of multilateral initiatives

At a government-to-government level, countries work together through institutions like the World Bank and the OECD to support sustainable mining and supply chain practices. Separately, governments have set up extraction-specific initiatives such as the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) and the Energy Resource Governance Initiative (ERGI) to provide technical assistance.

The IGF provides a platform for more than 75 member countries to discuss issues related to mineral resource governance and promote sustainable mining practices. In particular, it provides technical capacity building and shares best practices through its Mining Policy Framework. Similarly, ERGI shares best practices on mining governance through its ERGI Toolkit, which is primarily designed for mineral-producing economies and focuses on responsible and sustainable mining. In particular, these high-level initiatives can help ensure consistent communications with all relevant ministries in resource-rich countries, and more generally ensure issues receive appropriate levels of attention. To harness this potential, synergies between initiatives could be better exploited, and new areas for knowledge sharing could be explored beyond mining frameworks.

Public-private collaboration

Some companies have achieved high levels of sustainability performance, and governments can facilitate sharing of these experiences and good practices. For example, the Mining Association of Canada's TSM standard covers issues such as tailings management, worker safety, child labour and relationships with indigenous communities. The Canadian government actively promotes the TSM standard and supports uptake by other countries (Government of Canada, 2021b). The World Bank's Climate Smart Mining initiative also brings together public and private actors across the mineral sector to facilitate collaboration. Industry and governments have thus stepped in to facilitate knowledge sharing on a significant scale, but more is needed to achieve a comprehensive minerals governance framework.

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...but there is scope for better alignment and co-ordination

To be sure, the proliferation of international initiatives has led to encouraging success stories, including the global adoption and implementation of the OECD Due Diligence Guidance, the LME's responsible sourcing criteria and sustainability initiative, and continued improvement of transparency standards in producer economies via the EITI. However, uncoordinated efforts can lead to potential duplication – where multiple initiatives form around the same issue with different membership – or discontinuity when competing standards follow different approaches. Even where a harmonised approach emerges, to the extent that initiatives are voluntary, some important players may opt out.

As discussed in Chapter 3, a high-level forum for co-ordination could be pivotal in standardising environmental and social standards and co-ordinating activity on security of supply. There has been some success at co-ordinating competing efforts, but only on certain issues, for instance due diligence practices through the OECD Guidance. Generalised organisations like the G7 and G20 have also played this role in the past. For example, the Brisbane 2014 G20 Principles of Energy Collaboration reflected the need to make minerals governance an integral part of countries' energy security policies. New or long-standing fora such as the Climate Smart Mining Initiative or the IGF can also play an important role in channelling discussion and co-operation on energy transition minerals.

An international governance framework

Despite increasing levels of global adherence to environmental and social standards, they generally offer few avenues for collective action among governments. Policy integration through the European Union or other regional blocs alone is also insufficient to ensure consistency on a global scale. Therefore, a systemic approach is needed to ensure countries take action not only in certain notoriously fraught supply chains or in specific regions, but also for all minerals that underpin the energy transition and across jurisdictions.

A governance framework for minerals should provide countries with the tools they need to address GHG emissions, local and regional environmental impacts and social and human rights risks. It could ultimately contribute to maintaining a reliable supply of minerals necessary for the energy transition. As such, the UN Environment Programme's International Resource Panel has underlined that "[t]here is a need for an international body with a similar role to that of the International Energy Agency in the energy sector" (IRP, 2020, 131). The IEA's energy security framework could thus serve as a template for international minerals governance, underpinned by data sharing, co-ordination mechanisms and collective actions, fostering sustainable and responsible supply chains that contribute to a low-carbon economy.

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Annexes

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Scope

This report assesses the mineral requirements for the following clean energy technologies:

- **Solar PV** (utility-scale and distributed)
- **Wind** (onshore and offshore)
- **Concentrating solar power** (parabolic troughs and central tower)
- **Hydropower**
- **Geothermal**
- **Bioenergy for power**
- **Nuclear power**
- **Electricity networks** (transmission, distribution, and transformer)
- **Electric vehicles** (battery electric and plug-in hybrid electric vehicles)
- **Battery storage** (utility-scale and residential)
- **Hydrogen** (electrolysers and fuel cells).

All of these energy technologies require metals and alloys, which are produced by processing mineral-containing ores. Ores – the raw, economically viable rocks that are mined – are beneficiated to liberate and concentrate the minerals of interest. Those minerals are further processed to extract the metals or alloys of interest. Processed metals and alloys are then used in end-use applications. While this report covers the entire mineral and metal value chain from mining to processing operations, we use "minerals" as a representative term for the sake of simplicity.

Minerals are not only used in the clean energy sector, but are also used widely across the entire energy system, in technologies that improve efficiency and reduce emissions. For example, the most efficient coal-fired power plants require a lot more nickel than the least efficient ones in order to allow for higher combustion temperatures. However, here we focus specifically on the use of minerals in clean energy technologies, given that they generally require considerably more minerals than fossil fuel counterparts. Our analysis also focuses on the requirements for building a plant (or making equipment) and not on operational requirements (e.g. uranium consumption in nuclear plants).

Our report considers a wide range of minerals used in clean energy technologies listed in the table below. They include chromium, copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), molybdenum, platinum group metals, zinc, rare earth elements and others.

Steel is widely used across a broad range of technologies, but we have excluded it from the scope given that it does not have substantial security implications and the energy sector is not a major driver of growth in steel demand. Steel and aluminium are widely used across many clean energy technologies, but we have excluded it from the scope of this analysis. Steel does not have substantial security implications and the energy sector is not a major driver of

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growth in steel demand. Aluminium demand is assessed for electricity networks only as the outlook for copper is inherently linked with aluminium use in grid lines, but is not included in the aggregate demand projections. Overall aluminium demand projections are regularly assessed as part of the *WEO* and *Energy Technology Perspectives* series.

Projection results are available for download from the report webpage: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Minerals in scope

Focus minerals	Other minerals	
Cobalt	Arsenic	Niobium
Copper	Boron	Platinum
Lithium	Cadmium	Praseodymium
Nickel	Chromium	Selenium
Rare earth elements	Dysprosium	Silicon
	Gallium	Silver
	Germanium	Tantalum
	Graphite	Tellurium
	Hafnium	Terbium
	Indium	Tin
	Iridium	Titanium
	Lanthanum	Tungsten
	Lead	Vanadium
	Magnesium	Yttrium
	Manganese	Zinc
	Molybdenum	Zirconium

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Methodology

Demand

For each of the clean energy technologies, we estimate overall mineral demand using four main variables:

- clean energy deployment trends under different scenarios;
- sub-technology shares within each technology area;
- mineral intensity of each sub-technology; and
- mineral intensity improvements.

Clean energy deployment trends under the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS) are taken from the projections in the *World Energy Outlook 2020*, complemented by the results in the *Energy Technology Perspectives 2020*.

Sub-technology shares within each technology area (e.g. solar PV module types; EV battery chemistries) are also taken from the *World Energy Outlook 2020*, complemented by the *Energy Technology Perspectives 2020* and other sources.

Mineral intensity assumptions were developed through extensive literature review (see Table) and expert and industry consultations, including with IEA Technology Collaboration Programmes.

The pace of mineral intensity improvements varies by scenario, with the STEPS generally seeing minimal improvement over time as compared to modest improvement (around 10% in the longer term) assumed in the SDS. In areas that may particularly benefit from economies of scale or technology improvement (e.g. silicon and silver use in solar PV, platinum loading in fuel cells, REE use in wind turbines), we applied specific improvement rates based on the review of underlying drivers.

The report assesses demand from other sectors for the five focus minerals using historical consumption by end-use applications, relevant activity drivers (e.g. GDP, industry value added, vehicle activities, steel production) and material intensities.

Supply

Annual mineral production estimates are based on the analysis of the individual project data provided by S&P Global (2021) and BloombergNEF (2020), and supplemented with public data sources.

Operating projects are defined as mines of which development stage is operating, expansion or limited production due to some reasons. Under-construction projects are taken to be mines of which development stage is commissioning, construction planned, construction started or preproduction.

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Secondary production is estimated with two parameters: the average recycling rate and the lifetime of each end-use sector. The recycling rate is the combination of the end-of-life collection rate (the amount of a certain product being collected for recycling) and the yield rate (the amount of material a recycling process can actually recover). For existing waste streams (e.g. industrial applications), we assume only marginal improvement in collection rates, while for emerging technologies such as lithium-ion batteries, we assume collection rates increase at a faster pace. For batteries, the collection rates gradually increase from around 45% in the early-2020s to 80% by 2040. For batteries, the yield rate is assumed to vary according to the technical limitations for the extraction of each mineral using the currently available recycling methods. The reuse rates are much lower than the collection rate for recycling as the use of second-life batteries faces many technical and regulatory obstacles.

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