The Role of Critical Minerals in Clean Energy Transitions

World Energy Outlook Special Report

INTERNATIONAL ENERGY AGENCY

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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, 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

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, 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 requirements for these minerals, meaning that the energy sector is emerging as a major force in mineral markets. Until the mid-2010s, the energy 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.

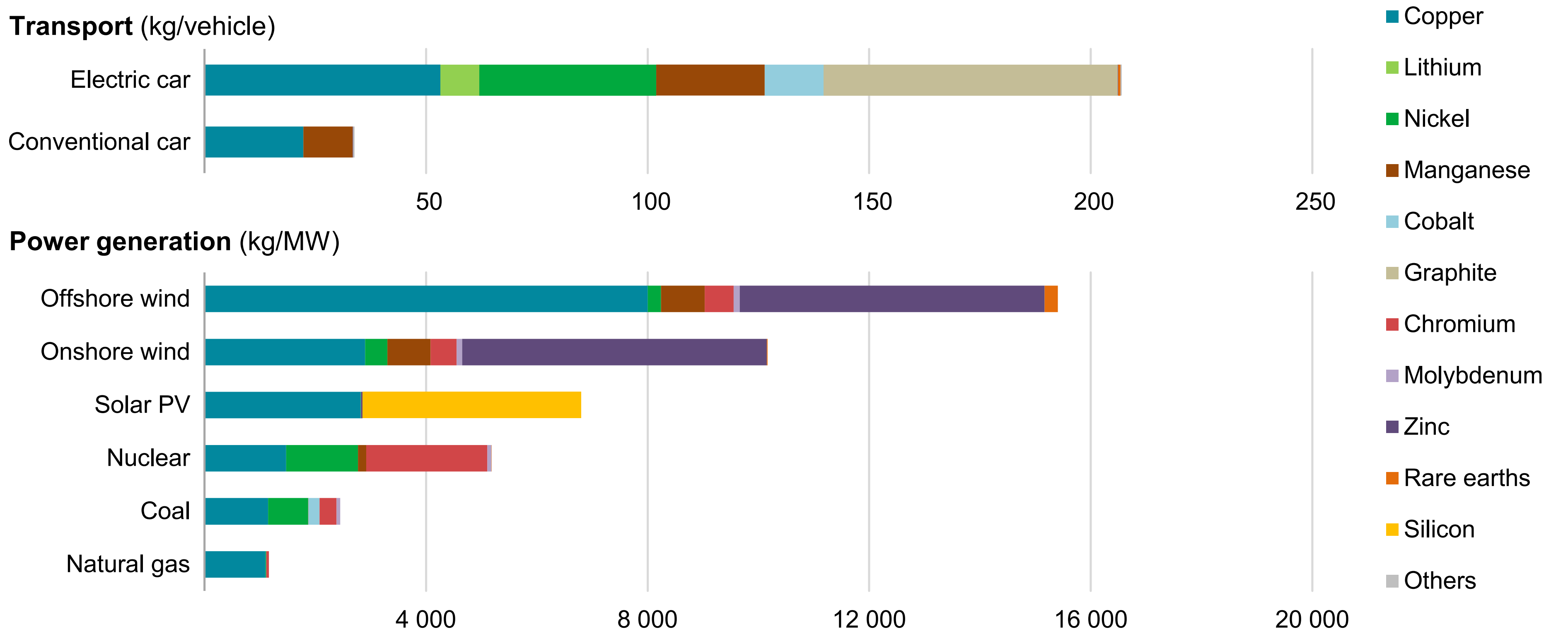
In a scenario that meets the Paris Agreement goals, clean energy technologies' share of total demand rises significantly over the next two decades to over 40% for copper and rare earth elements, 60-70% for nickel and cobalt, and almost 90% for lithium. EVs and battery storage have already displaced consumer 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.

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

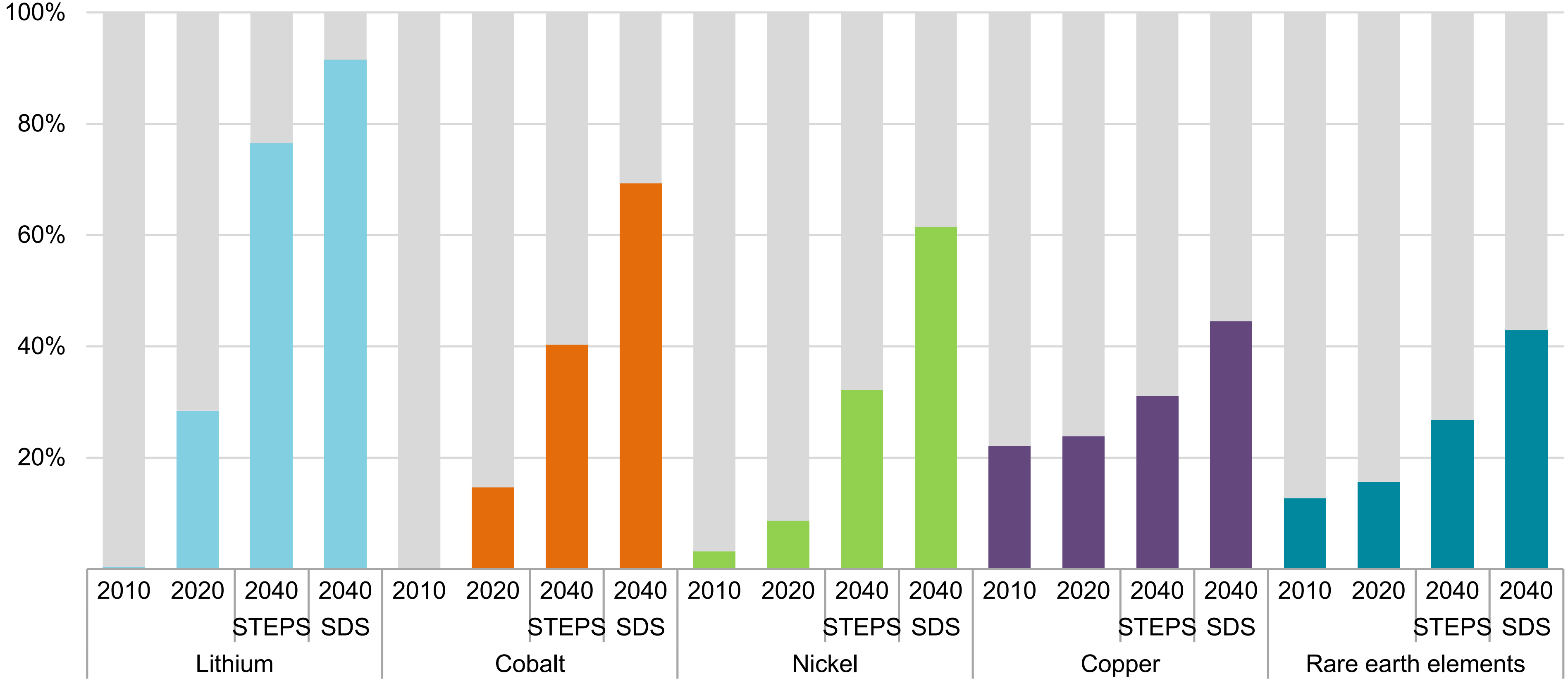
Minerals used in selected clean energy technologies



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

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

Share of clean energy technologies in total demand for selected minerals



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.

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.

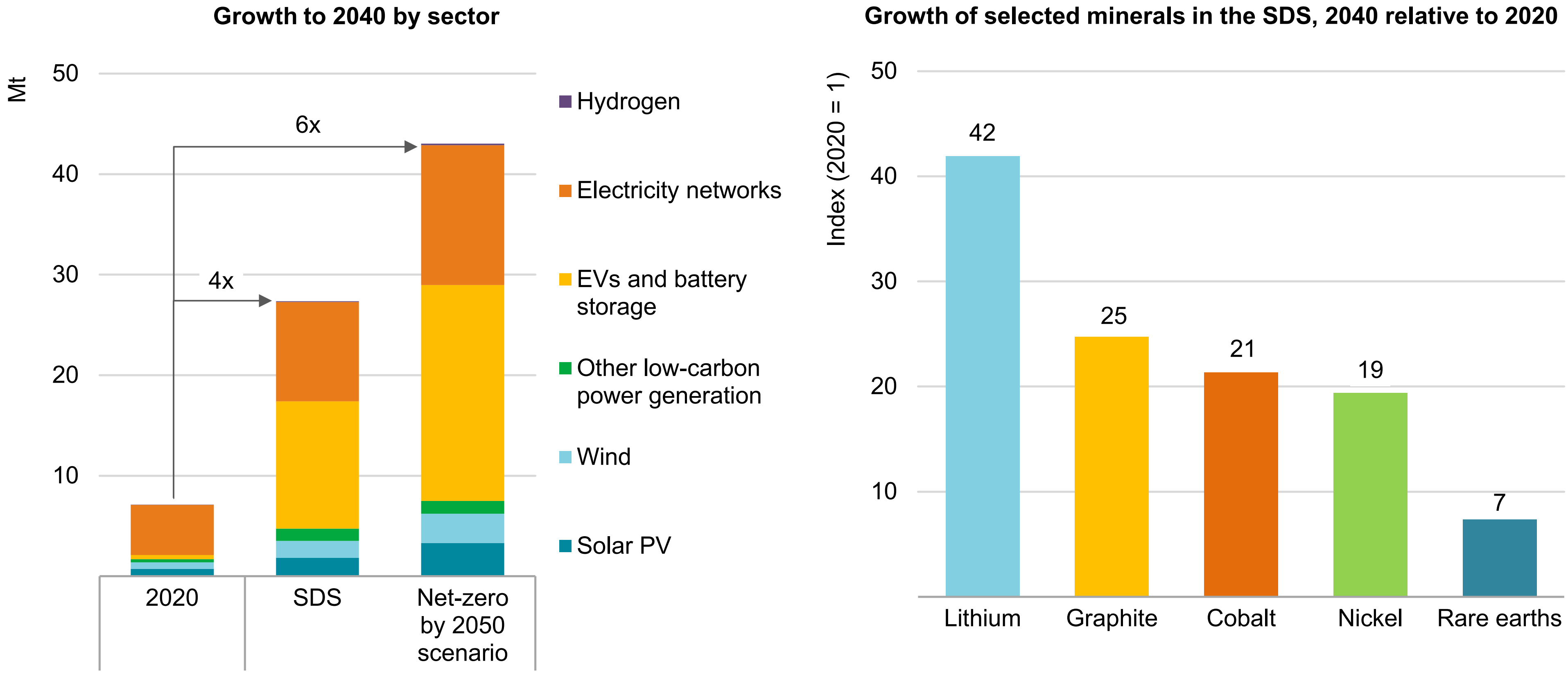
The rise of low-carbon power generation to meet climate goals also means a tripling of mineral demand from this sector by 2040. Wind takes the lead, bolstered by material-intensive offshore wind. Solar PV follows closely, due to the sheer volume of capacity that is added. Hydropower, biomass and nuclear 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.

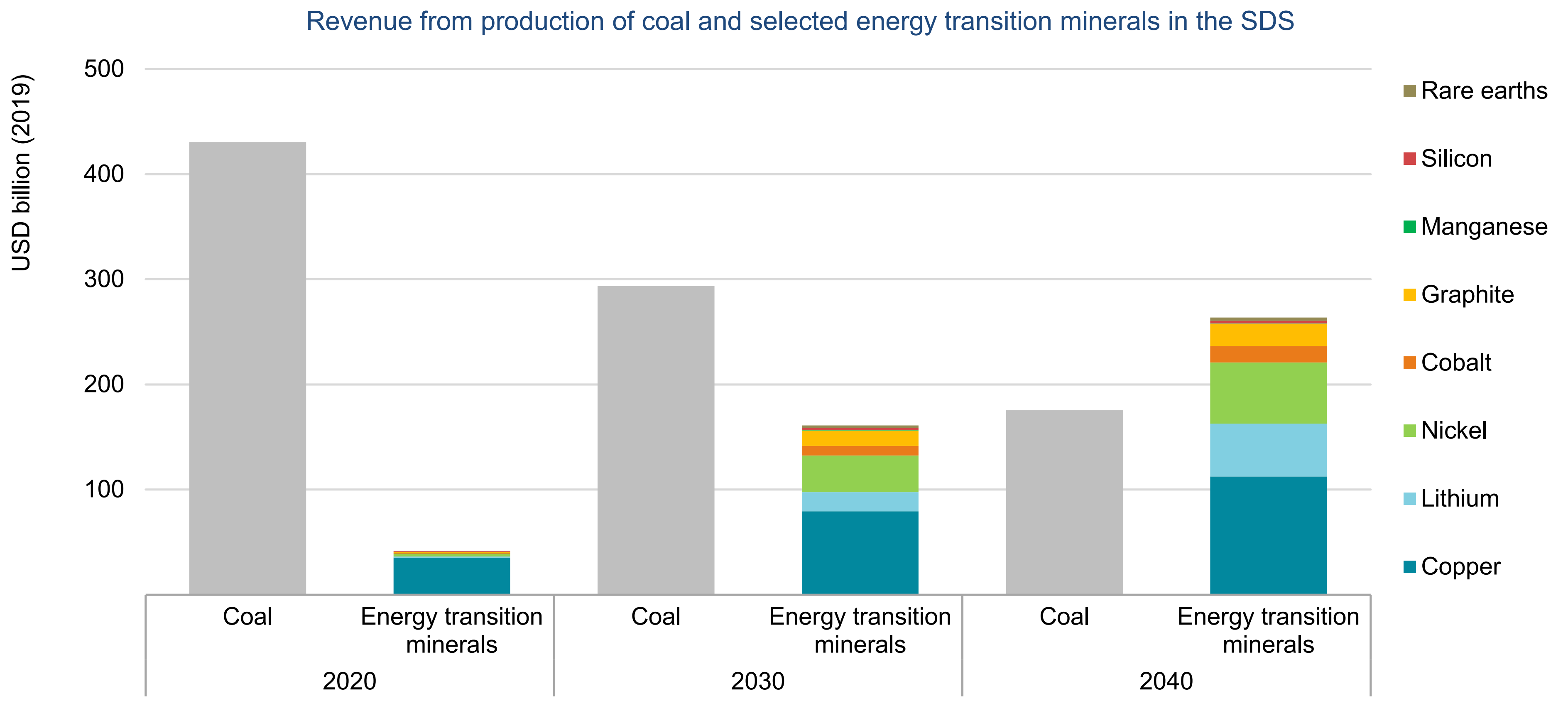
Mineral demand for clean energy technologies would rise by at least four times by 2040 to meet climate goals, with particularly high growth for EV-related minerals

Mineral demand for clean energy technologies by scenario



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.

Changing fortunes: Coal vs energy transition minerals



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).

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 are 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-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 People's Republic of China (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.

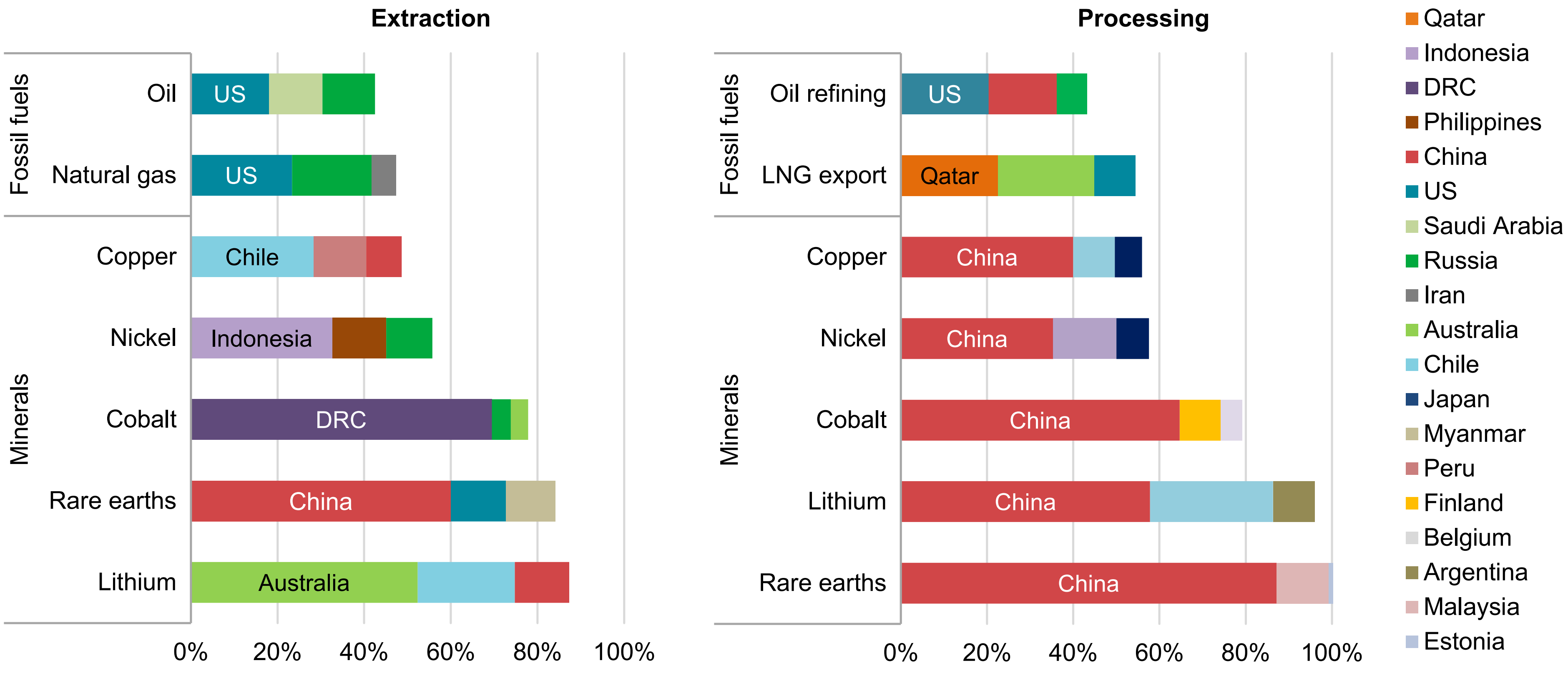
- **Growing scrutiny of environmental and social performance:** Production and processing of mineral resources gives rise to a variety of environmental and social issues that, if poorly managed, can harm local communities and disrupt supply. Consumers and investors are increasingly calling for companies 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.

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



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).

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.

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.

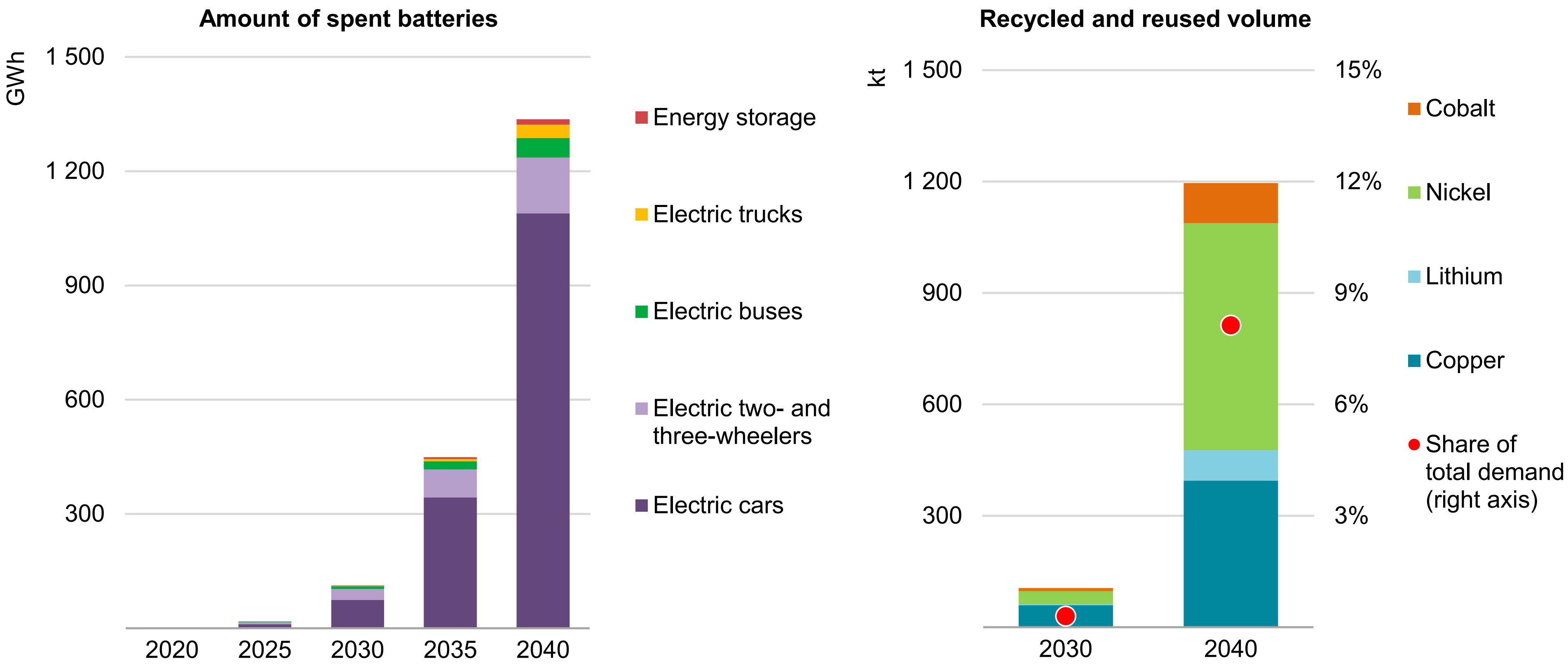
Regular market assessments and periodic stress tests, coupled with emergency response exercises (along the lines of the IEA's existing emergency response programmes), can help policy makers identify possible weak points, evaluate potential impacts and devise necessary actions. Voluntary strategic stockpiling 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.

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

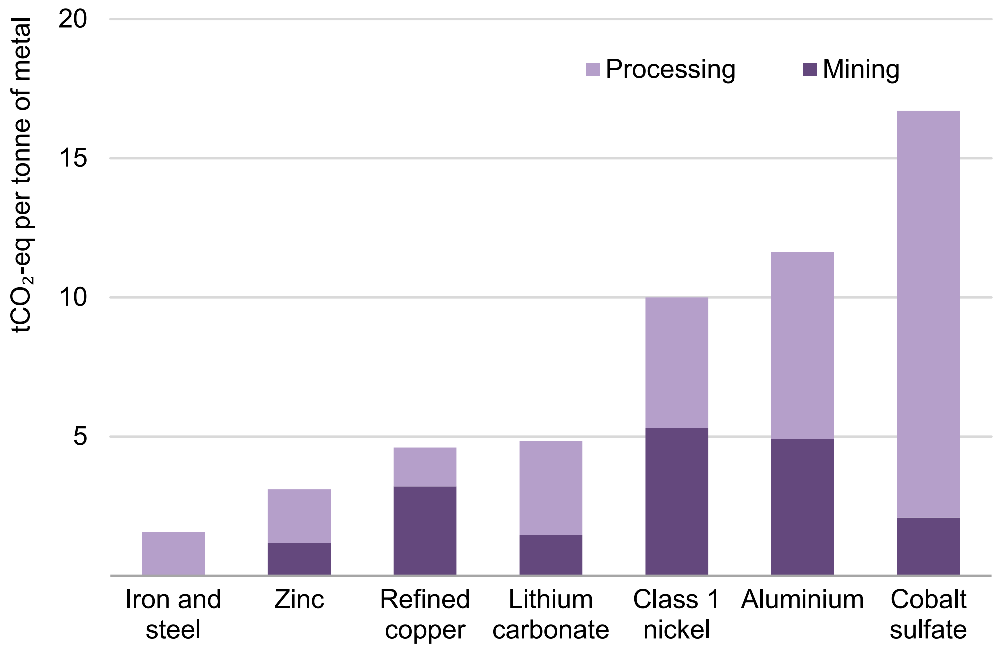
Amount of spent lithium-ion batteries from EVs and storage and recycled and reused minerals from batteries in the SDS



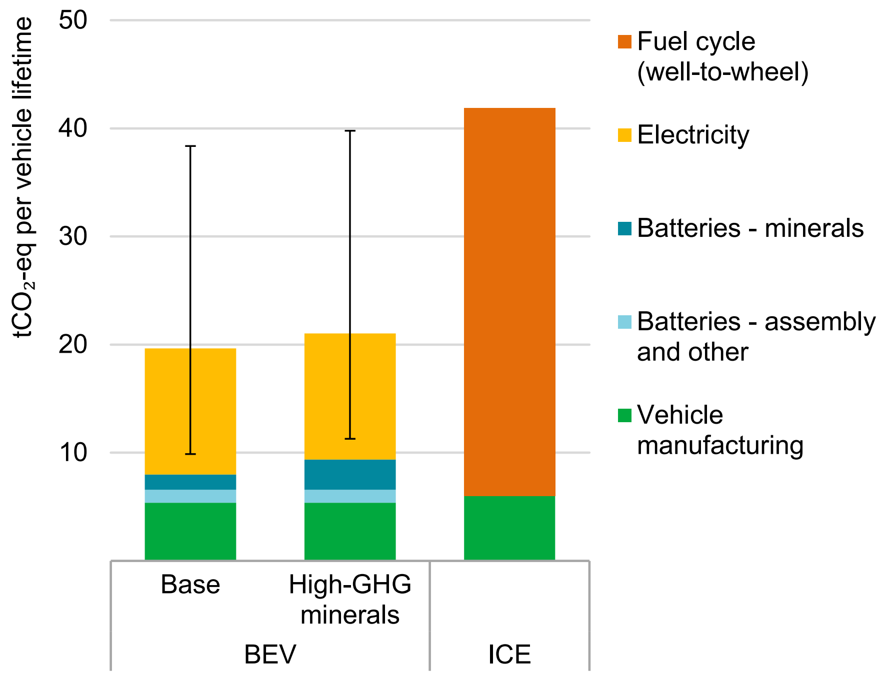
Note: GWh = gigawatt hour.

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

Average GHG emissions intensity for production of selected commodities



Life-cycle GHG emissions of a BEV and ICE vehicle



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 Laboratory (2020); Argonne National Laboratory (2019); Rio Tinto (2020); S&P Global (2021); Skarn Associates (2021); Marx et al. (2018).

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 diversified 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.

Introduction

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.

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.

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.

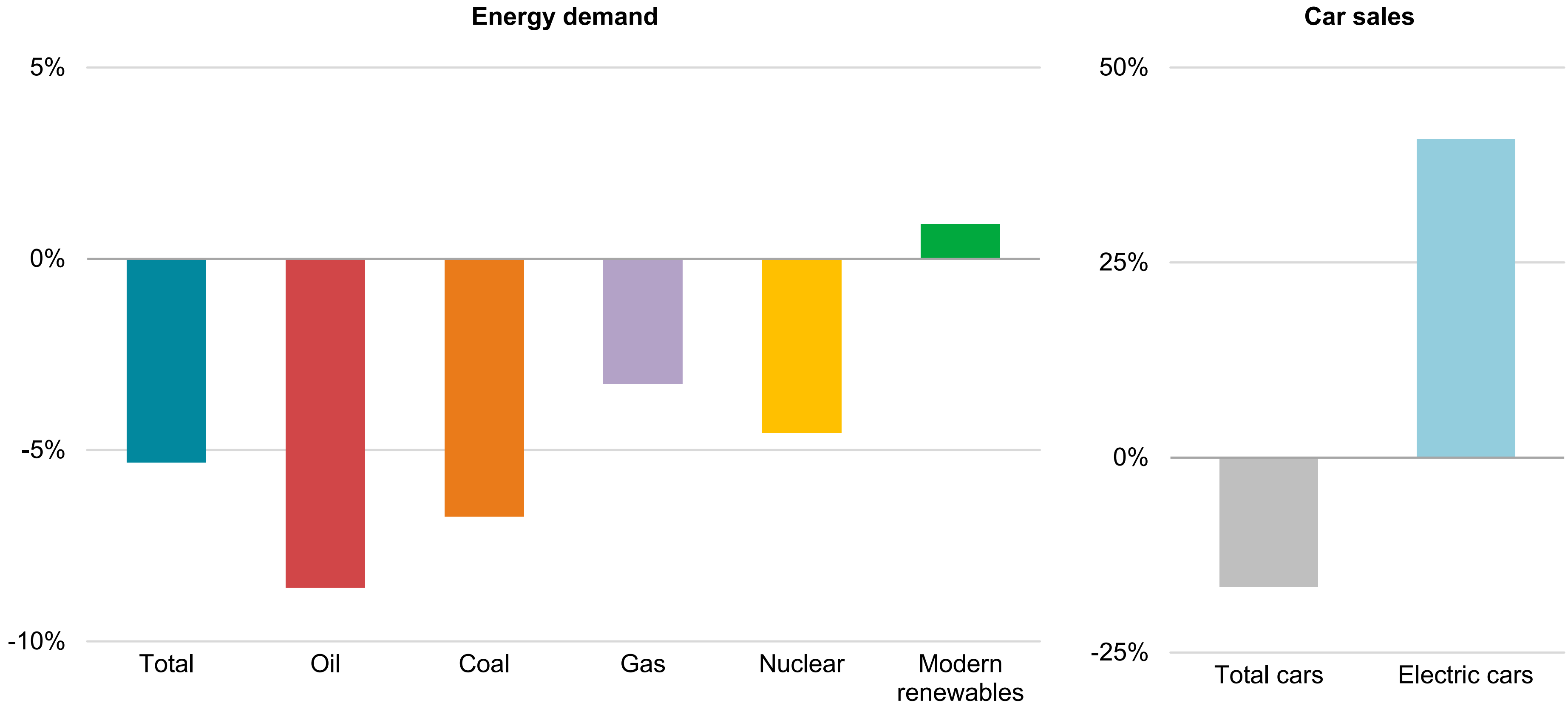
Using our analysis and lessons from historical episodes of disruption, we identify policy approaches to ensure reliable supply of minerals in an evolving market environment.

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.

The state of play

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

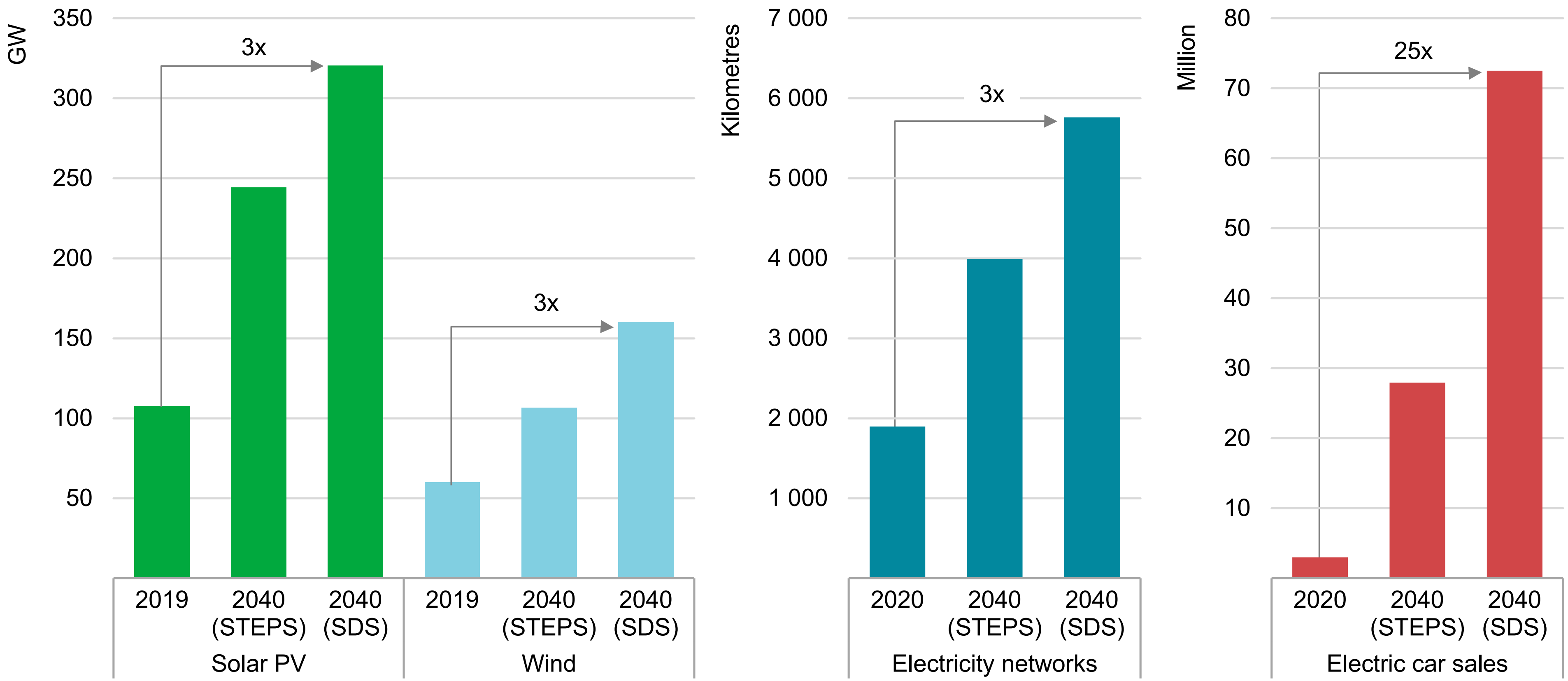
Change in energy demand and car sales by type in 2020 relative to 2019



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

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

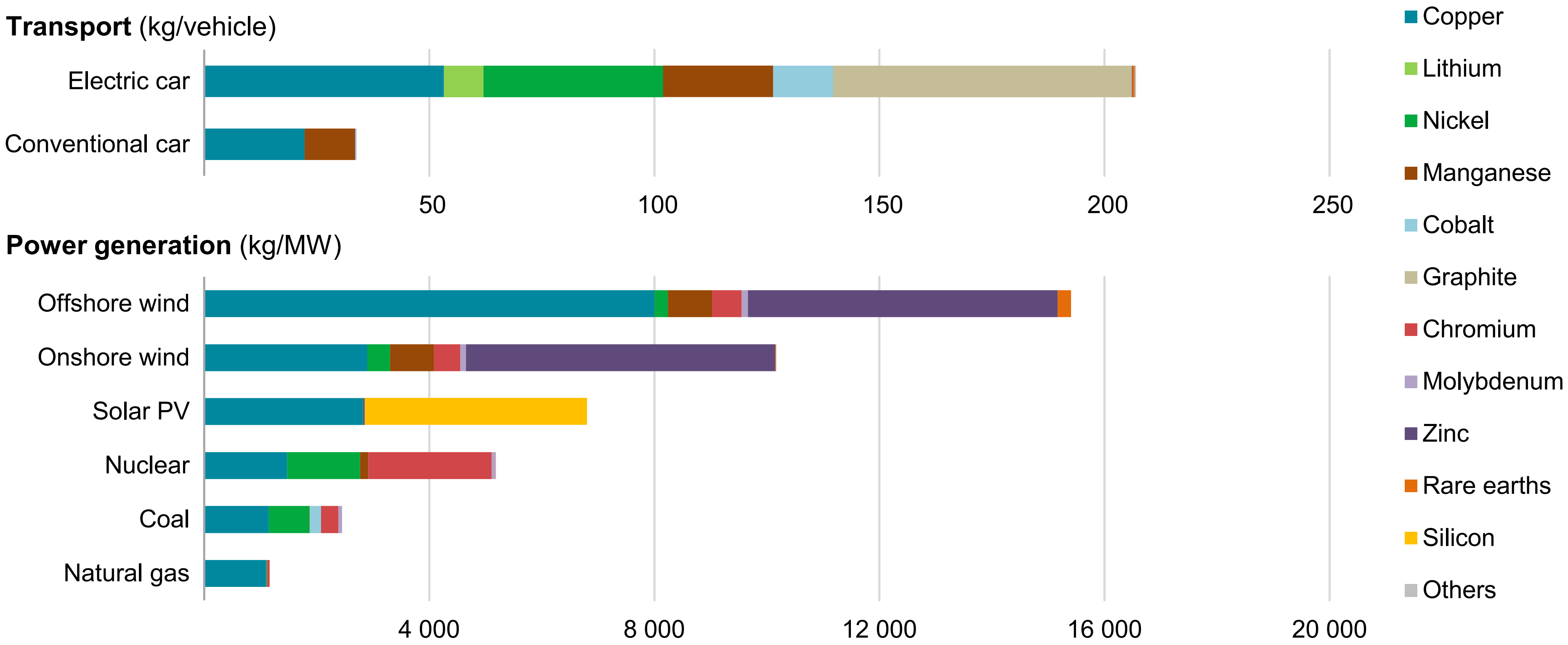
Annual deployment of clean energy technologies by scenario



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

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

Minerals used in selected clean energy technologies



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.