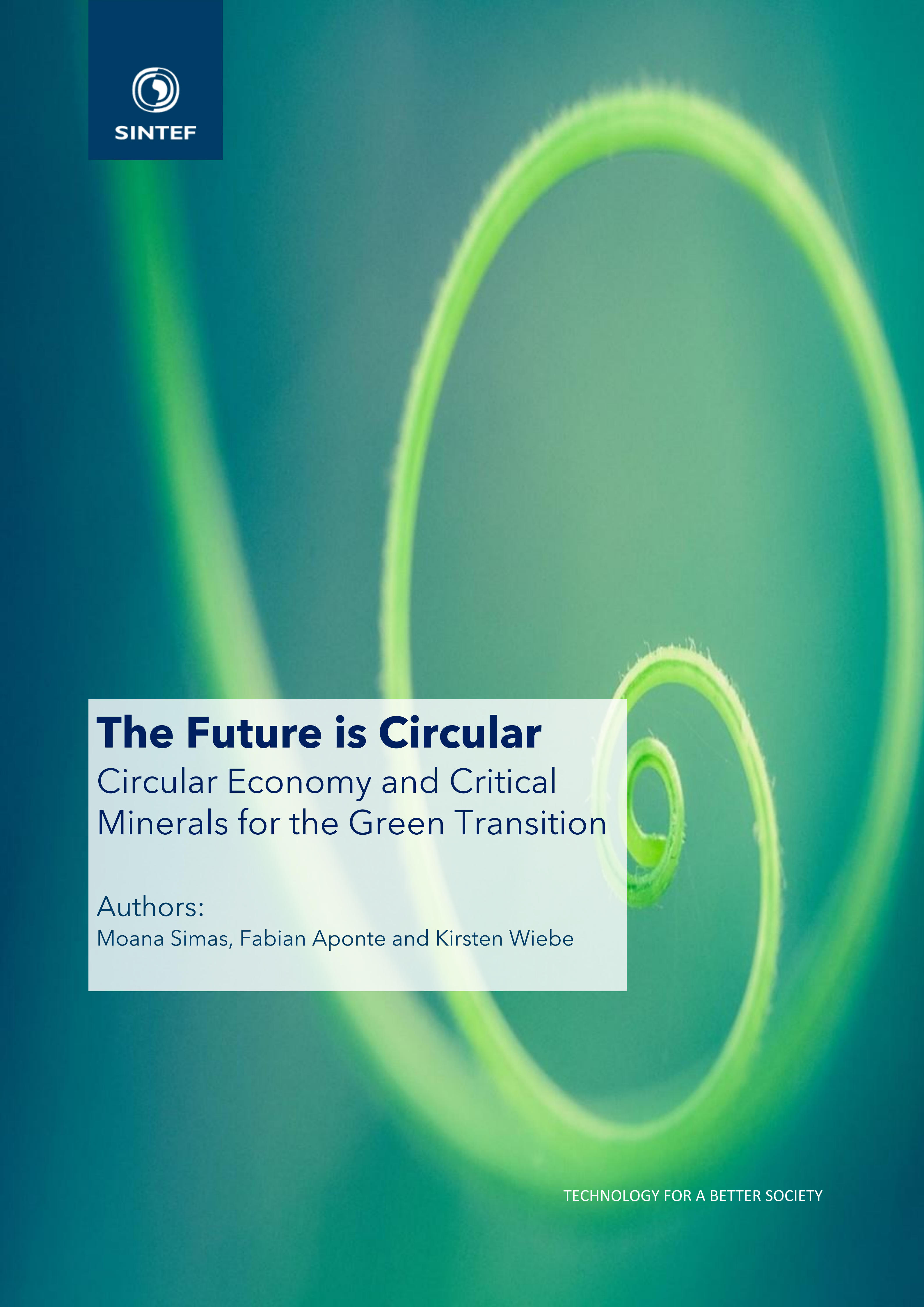

SINTEF

The Future is Circular

Circular Economy and Critical Minerals for the Green Transition

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Report

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KEYWORDS
Critical minerals
Circular economy
Green transition
Low-carbon technologies

VERSION
1

DATE
2022-11-15

AUTHORS
Moana Simas, Fabian Aponte and Kirsten Wiebe

CLIENT
WWF

PROJECT NO.
102027433

NO. OF PAGES/APPENDICES
67

SUMMARY
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REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
2022:01134	978-82-14-07926-5	Unrestricted	Unrestricted

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Acknowledgements
Eric Young
Ellen Johanne Beales
Jonas Brøske Danielsen

This report was prepared for WWF by SINTEF.

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November 2022

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Foreword

The task of transitioning our entire global economy to a sustainable, carbon-free model is among the most complex and challenging facing humanity today. Transitioning to a new model is always difficult and often meets resistance. In the marketplace of ideas, there are many competing arguments and proposals, and it can be difficult to assess the merits and genuine intent of one pathway over another.

WWF commissioned this report because some are arguing that the transition from fossil fuels to renewable energy sources and battery storage requires mining the ocean floor for critical minerals. That narrative leverages the acknowledged need to make this transition urgently, but it ignores the facts about the knowns and unknowns of the deep ocean and seabed – our planet's largest ecosystem by far.

Largely uncharted and little-studied, we are only beginning to catalog the species that dwell in the deep. We do know the seabed is an important carbon sink – making the idea of mining operations that would churn up sediment and release that carbon an unlikely "solution" to our climate crisis. The potential harms extend to fisheries and food security, as well.

But with potential profits "littering" the ocean floor, some are allowing these arguments in favor of deep seabed mining to gain traction. While WWF adheres to the science-supported precautionary principle to prevent environmental degradation, we also wanted to offer a data-based counterargument to the claim that deep-sea minerals are necessary for the green transition. The models presented here show the demand for critical minerals can be reduced by 58% from now to 2050 with new technology, circular economy models and recycling.

I agree with those who say we must take no options off the table in our quest to mitigate the climate crisis already unfolding. I share that grave sense of urgency. But we must not, once again, try to solve a problem while ignoring predicted consequences that could make the original problem even bigger. It is the very gravity of our current circumstances that requires us to act with utmost care for our planet's life-support system: nature. Opening a new reckless, speculative extractive industry in our ocean is not the path to a nature-positive future and could even exacerbate the climate crisis.

As this report outlines, the path forward includes a mix of technological innovation and changes to our current patterns of consumption and waste. With human ingenuity and an enlightened sense of self-preservation, this task is well within our collective capacity to achieve.

Marco Lambertini

WWF International Director General

Executive Summary

A net-zero energy system will require a significant amount of minerals, with concerns for mineral bottlenecks

The transition towards a net-zero economy will require a large-scale implementation of low-carbon technologies. Concerns have been raised whether the availability of minerals will be a bottleneck for the green transition, prompting discussion about the opening new mining frontiers for supplying these minerals. One of the most controversial options is the exploration of minerals in the deep sea.

Critical minerals are those that have a significant economic importance and that have risks to their supply. Many low-carbon technologies currently depend on these critical minerals. The total demand for minerals and whether critical minerals will become a challenge for the green transition depending on the path we take. The technological choices for decarbonisation in the coming decades are highly uncertain and depend on a wide range of factors such as prices, resource constraints, social and environmental standards, and innovation and technological development. How each of these factors will develop in the medium and long term and how they will interact with each other cannot be predicted.

This report looks at the mineral demand for a net-zero emissions energy system, based on the technological decarbonisation path of the *Net Zero by 2050* scenario developed by the International Energy Agency. It focuses on seven critical minerals for the green transition: lithium, cobalt, nickel, manganese, rare earth elements, platinum and copper. These are among the most discussed in studies on mineral bottleneck for new energy technologies and for which demand is expected to grow many-fold. The challenge of mineral availability is discussed from different perspectives.

Technological choices will shape the demand for critical minerals

How can different technological choices alleviate mineral demand? While the broad technological background (such as total installed capacity of wind power and number of electric vehicles on the road) follow that described in the *Net Zero by 2050* scenario, the technological choices refer to the specific technologies used, such as different chemistries for rechargeable batteries, or wind turbines with more or less critical minerals. In this report, we analyse four different technology scenarios:

(i) a current technology scenario, which describes what would be the mineral demand if we used the same technology as in 2021;
(ii) a business-as-usual scenario, which describes the evolution of different technologies based on patterns, learning curves, and industry signals;
(iii) a resource constraint for battery minerals scenario, where chemistries low in critical minerals correspond to the majority of the installed capacity; and
(iv) an advanced technology scenario, where new technologies low in critical minerals take off and become a larger share of the market share of annual installed capacity by 2050.

We show that technological choices make a significant difference for future mineral demand. Shifting to new technologies with less critical minerals can reduce total demand for the seven minerals considered in this report by 30%. The adoption of different chemistries for electric vehicle batteries and moving away from lithium-ion batteries for stationary applications could reduce the total demand for cobalt, nickel, and manganese by 40-50% of cumulative demand between 2022 and 2050 compared to current technologies and business-as-usual scenarios. Also, increasing the use of electric traction motors and wind turbine generators with low or no rare earth elements could cut the cumulative demand of these minerals demand by 20%.

There are high uncertainties in which technologies will be predominant in the coming decades. If state-of-the-art technology available 15 years ago was taken as the basis for estimating future technology mix and quantifying mineral demand, the picture would be very different from the one presented in this report. And there is no question that in 15 years the technology options available and the prospects of new technologies reaching commercialisation stage and entering the market will be different from what we observe today.

There are many technologies in early stages of development that could result in substantial reductions in the demand for critical minerals in the future. There are an increasing number of research grants for the development of low-carbon technologies with low or no critical minerals, as well as for upscaling the best recycling technologies available. In addition, many wind turbine and electric vehicle manufacturers have been successfully reducing the critical minerals content of their products during the past years. The success of these new technologies could mean a change in the mineral bottlenecks for decarbonisation.

Circular economy strategies are important for a responsible transition

A green transition must promote not only technological solutions, but also strategies to promote responsible use and sourcing of minerals. A circular economy model aims to move from a linear system of extraction, use, and disposal, to a system where services use is prioritised over products and materials. In a circular economy, extracted materials remain in society for longer and, when products and infrastructure reach the end-of-life, the materials are recovered and looped back into the production of new products and technologies. This report covered a range of circular economy strategies which can decrease total mineral demand by 18% between 2022 and 2030, in addition to the technological choices. The strategies can be grouped into three broad circular economy approaches: reduced demand, lifetime extension, and recycling.

Reduced demand decreases mineral demand by reducing the need for additional infrastructure. Different strategies will lead to a lower demand for minerals in society. In this report, we look at (i) reducing the purchase of new private vehicles by reducing car ownership while incentivising other transportation modes, and (ii) reducing the installation of electricity infrastructure as a result of decreased electricity demand from eliminating unnecessary material extraction and processing, increased material efficiency, and a shift on consumption patterns towards lower purchase of consumer products and higher re-use rates.

Lifetime extension decreases mineral demand by keeping extracted minerals in society for longer, increasing the time needed to replace aging infrastructure. Extending lifetime of low-carbon technologies has other benefits. By demanding lower replacement rates, it allows for more time for upscaling of new and more efficient technologies, for the development of more responsible mining sites and for improving recycling techniques and value chains. Therefore, replaced infrastructure has the potential to be more efficient, less intensive in critical minerals, and with a more responsible mineral sourcing. Lifetime extension corresponds to a range of different strategies that can influence how long materials stay in stock. For electric vehicles, the lifetime of batteries highly depends on the number of times a battery is used and recharged. Passenger vehicles can be used for longer by reducing the use of owned vehicles through the same urban planning strategies as for reducing vehicle ownership. Discarded electric vehicle batteries still contain around 80% of their capacity, and they can be extended for use in a second life in other stationary applications, such as households, commercial buildings or industries. For power plants, lifetime extension can be achieved through more maintenance and component replacement, mid-life investments, and repowering and retrofitting which re-uses part of the infrastructure in place. And finally, for all products and infrastructure, technology innovation and design for repair and replacement of key components contribute to lifetime extension.

Recycling does not decrease mineral demand, but it substitutes for mineral extraction. Increasing collection rates and upscaling best available techniques for mineral recovery from low-carbon technologies could supply 20% of the total mineral demand between 2022 and 2050. Due to the long lifespan of the low-carbon technologies considered in this report, recycled minerals would start playing a significant role in supplying critical minerals after 2040. This allows time for the development and upscaling of better techniques for recovery of critical minerals from, e.g., batteries and permanent magnets, for which recycling techniques are still overcoming technical and economic challenges for application in commercial scale. In addition, urban mining, that is the process of recovering materials from end-of-life products, buildings and waste, will also play an increasingly important role over time. Crucial for increased recycling rates is the design for disassembly and recyclability, which needs to be incorporated in early development phases of components and technologies.

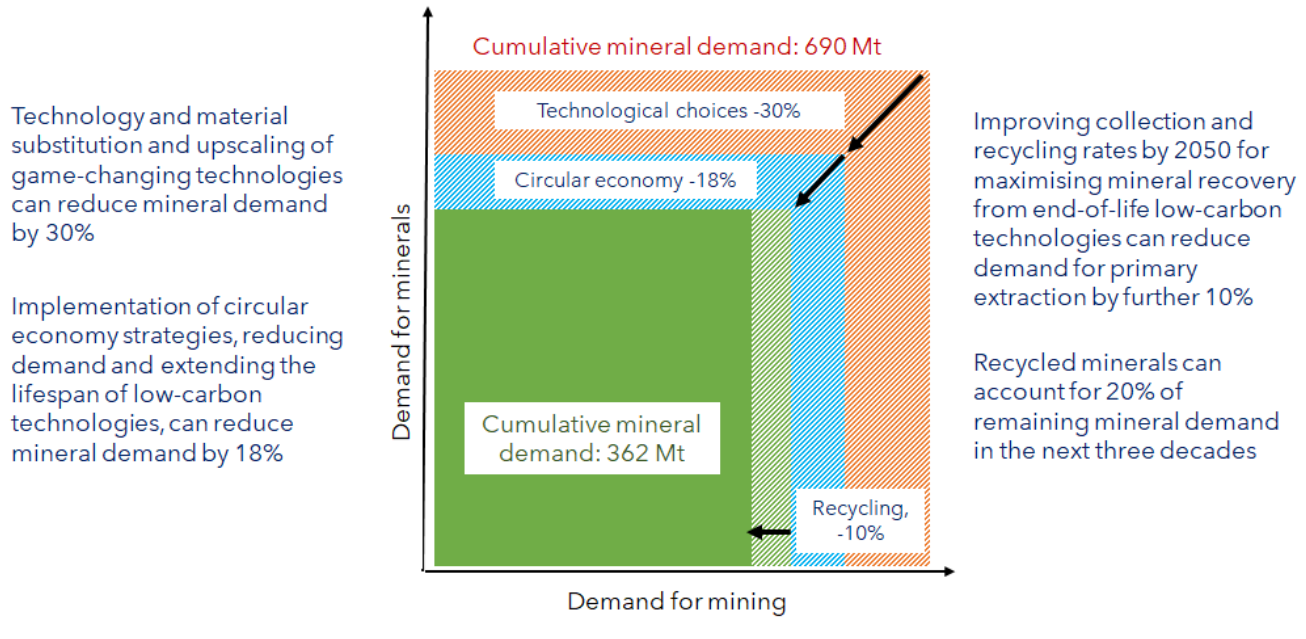

Figure: This figure summarises the reduction in mineral demand for low-carbon technologies installed between 2022 and 2050. The outer box (orange) represents a pathway of high critical minerals intensity in low-carbon technologies, characterised by a path of business-as-usual technological development. The middle box (blue) represents the mineral demand of the advanced technology scenario, where technologies with low critical minerals content are widely used, resulting in a reduction of 30% of mineral demand. The inner box (green) represents the scenario where, in addition to the advanced technologies, the circular economy strategies are also fully implemented, reducing mineral demand by further 18%. The difference between the shaded and the solid green boxes represents the reduction in demand for mining, by substituting primary extraction with recycled minerals, which can decrease the demand for mining in 10%, compared to the business-as-usual scenario (orange box). This substitution represents 20% of total remaining mineral demand, in a scenario with advanced technology coupled with circular economy.

Responsible mining will be required for the coming decades

By 2050, most of the minerals needed for the green transition will be able to be supplied by recycled minerals. Even though demand can be reduced by adopting technologies with lower minerals intensity and implementing circular economy strategies, there will be the need for increasing mineral extraction and refining, particularly in the coming decades.

The mining industry is important for many developing and developed economies, but current mining operations lead to major social and environmental impacts. Responsible mining involves using the best available practices and technologies and ensuring that mineral supply is conducted in a less harmful way.

This report shows that the higher demand for mineral extraction will be concentrated in the coming two decades. In this time frame, mining expansion can be covered by confirmed mineral reserves. This also includes investing in mineral supply from old mining sites, such as mining of tailings and other mines waste, which constitute a large potential source of minerals and revenue with possibly lower social and environmental costs.

Technological innovation and circular economy should form the backbone of the green transition

The coming decades are crucial for a shift towards a more sustainable society. The current paradigm of economic growth dependent on a linear and wasteful use of natural resources is causing two major crises related to climate and biodiversity. A green transition should encompass all dimensions of sustainability and avoid burden shifting between planetary boundaries. The transition towards a circular economy is vital for reducing environmental impacts. Eliminating unnecessary material use has direct impacts on mineral demand. Looping already extracted minerals back to production contributes to decoupling material use from social and environmental impacts.

The first step towards a responsible green transition is reducing the reliance on virgin minerals by lowering demand and increasing the availability of recycled materials. Creating a circular economy for critical minerals will demand a collaboration among multiple actors to develop circular business models that include circularity as an input to technology design and to create mature and commercially competitive recycling industries, markets and value chains at various levels (local, regional and global). At the same time, significant investments are required to develop and commercialise new low-carbon technologies with low or no critical minerals.

Advancements in mineral recovery can increase reliance and decrease the impacts of the supply of minerals for the green transition. Besides end-of-life energy technologies, these minerals are also present in other waste streams such as electric and electronic equipment, such as smartphones and laptops, and in tailings and other mining waste of old mines, which can provide a potentially significant amount of critical minerals required in the coming decades.

The direction we take in the next decades will determine whether minerals will pose a bottleneck for the green transition. The scale of mining expansion needed and associated impacts will depend on which technologies we choose to invest in, which policies we choose to support, and which environmental costs we choose to tolerate.

1. Introduction

The transition to a low emissions future will require the fast, large-scale implementation of low-carbon technologies across a wide variety of sectors, such as electricity generation and storage, industry, and mobility. The last decade has seen a surge of studies on whether mineral availability will hinder the transition to a low-carbon energy system. This is a discussion that has no clear answers, but the conclusion always points out that for deep decarbonisation scenarios, the production and refining of many of these critical minerals will need to grow several times during the coming decades.

The share of low-carbon technologies has increased many times in the past decade (IRENA, 2022) but energy-related CO_2 emissions have continued to increase at alarming rates (Ritchie et al., 2021), showing no likelihood of peaking or decreasing. The pattern in recent decades shows that global emissions only reduced during years of intense economic crises, such as the 2007–2008 financial crisis and more recently the COVID-19 pandemic, but quickly returned to the previous growth trends as economies recovered. New plans to ensure more sustainable economic recovery from economic crises have appeared with many government stimulus packages focused on more sustainable investments, such as renewable energy, energy efficiency, reforestation, as well as a transition to more sustainable agriculture (Carbon Brief, 2021; UN, 2020). In practice, however, the COVID-19 recovery has led to the highest level of greenhouse gas (GHG) emissions in history in 2021 (IEA, 2022a). It is clear that business-as-usual global economic growth is not compatible with the 1.5-degree target. Important restructuring of both the energy system and the global economy is needed to stay within the climate goals, to avoid the worst effects of climate change on people, health and biodiversity, and to reverse nature loss and avoid an even larger biodiversity crisis (WWF, 2022).

According to the International Energy Agency (IEA) (IEA, 2021a), a path towards an economically-feasible technological transformation of the energy system to achieve net-zero CO_2 emissions by 2050 is possible, fulfilling the sustainable development goals of affordable access to modern energy and reduction of energy inequality across countries. This transition, however, will require the practical implementation of policy commitments to transform the net-zero pledges into reality, particularly in low- and middle-income economies. Also, achieving net-zero emissions by 2050 will require a big leap in technological innovation.

This report focuses on the material challenges for this transition. Both solar and wind farms require materials upfront to produce solar panels and wind turbines and the construction of these power plants amounts to almost all materials used throughout the lifetime of the power plants. Coal and natural gas power plants require less materials during the construction phase for the same installed capacity, but need a constant flow of fuels to operate, resulting in impacts on material production (mining, transport and refining) spread throughout their entire lifetime. In addition, the materials required by low-carbon technologies, mostly minerals, have very different supply chains than the established supply chains of materials used in conventional energy infrastructure. The mineral intensity of many currently used low-carbon technology is much higher than conventional technologies (IEA, 2021b; UNEP, 2016). For example, current technologies for electric vehicles require, on average, six times more mineral inputs than conventional cars (IEA, 2021a). Many of the minerals required for low-carbon technologies are not yet widely used in the economy and their supply chains (mining, refining and eventual end-of-life and material recovery) have not matured. Many of these minerals, such as lithium, cobalt and rare earth elements (REE) are produced in low scale and are geographically concentrated in just a few countries. The accelerated growth in demand caused by the energy transition will put enormous pressure on ecosystems and communities due to an expansion in mining (Purdy & Castillo, 2022) and create supply bottlenecks due to resource prices and availability. This report specifically focuses on seven minerals (and mineral groups) required for the low-carbon transition: lithium, cobalt, nickel, manganese, rare earth elements (REE), platinum and copper. These minerals are among the recipients of the largest focus from bottleneck studies, and concerns about mineral availability has led to discussion of expanding towards new mining frontiers, in particular, the exploration of deep-sea mining.

We are at the beginning of an increasing and changing curve in the demand for minerals. While phasing out high-carbon technologies (coal and natural gas energy plants, internal combustion engine vehicles), new low-carbon technologies entering commercial operation during the next decades will change the material requirements for the future. However, there is uncertainty regarding how steep the increase in demand will be, and how much pressure it will exert on the need for new mining projects in the short, medium and long term. Which economic pathways and strategies will we take, and how can they impact the pace and volume of mineral demand in the coming decades? How will different technological options and new technological developments affect the demand for these minerals? And how will improvements and upscaling in recycling practices and new mining technologies change the need for the expansion of mining?

This report examines how new technologies and circular strategies can alleviate the mineral bottleneck of decarbonisation. The technology path in the IEA scenario *Net Zero by 2050* serves as the basis for the mineral demand assessment in this report. Yet, the solution to decarbonisation is not only technological. One of the focuses of this report is on the importance of circular economy strategies, not only on providing the minerals we need for this transition through recycling, but also on relieving many of the social and environmental pressures that will result from the expansion of mining activities due to decreasing the demand for minerals. Our main message in this report is that the energy transition must be a responsible transition that won't prioritise climate targets over important social, ecological, and environmental impacts. It should involve the efficient use and re-use of minerals and a shift on current paradigm of ever-expanding mineral extraction, especially on sensitive environments such as the deep ocean.

This report is divided into 7 chapters:

- Chapter 1 comprises this introduction, which presented a brief context and background for this report.
- Chapter 2 provides an overview of strategic and critical minerals for the low-carbon transition
- Chapter 3 presents the different technology scenarios and circular economy strategies used in the modelling of the demand for minerals and recycling potential
- Chapter 4 details the effects of different technology scenarios on the demand for minerals until 2050 and discusses new technology developments that can further affect future demand for minerals
- Chapter 5 describes how the circular economy strategies can further decrease the demand for minerals and the extent to which secondary minerals can be provided through improved collection and recycling
- Chapter 6 discusses the supply of critical minerals and responsible mining
- Chapter 7 presents a conclusion and policy recommendations for the responsible use and supply of critical minerals for the energy transition

2. Critical minerals for the low-carbon transition

The energy transition will require a lot of materials, not only the equipment itself, such as solar panels and wind turbines, but also for building and operating large infrastructure such as roads, foundations, mounting structures, as well as infrastructure for the transmission, distribution and storage of electricity. Renewable energy technologies are more material intensive, per capacity installed or energy generated, than fossil fuel power plants when accounting for materials such as copper, aluminium, steel and cement (UNEP, 2016). In addition, low-carbon technologies require a much higher amount of critical minerals than traditional energy and mobility technologies.

This section presents a brief review of the seven minerals important for the energy transition, that we cover in this report: lithium, cobalt, nickel, manganese, REE, platinum and copper. These are among the most discussed minerals that can represent a supply bottleneck for new energy technologies, and for which mining expansion is expected to grow many times to ensure we reach climate targets. These bottlenecks are often used as an argument for expanding mining into the deep-sea.

Critical minerals can be a challenge for the energy transition

Steel and aluminium correspond to around one third of all future material demand for the transition to a low-carbon energy system (IEA, 2019). However, it is mostly minerals used in smaller quantities, but many of them considered critical minerals, that dominate the discussion on the mineral bottleneck for the green transition.

Low-carbon technologies depend on minerals that are considered critical. Solar photovoltaic (PV) panels require silicon and thin-film solar panels require minor metals such as indium, cadmium, tellurium and gallium. New generations of wind turbines are more efficient than previous, but they rely on a technology which requires rare earth elements (REE) – in particular, neodymium, dysprosium and, in smaller scale, praseodymium and terbium. These REE are also used in electric traction motors, the dominant technology in current electric vehicles (EVs). State-of-the-art batteries for EVs and energy storage require lithium, cobalt, graphite, nickel and manganese. Technologies for the hydrogen economy – electrolysers and fuel cells – require platinum-group metals (PGMs) and, in smaller scale, REE.

All of these minerals have a limited and geographically concentrated supply, and most of them have low recycling rates. For many of these minerals, due to their limited use in the economy thus far, supply chains for mining, refining and recycling are decades behind those of major currently used metals such as steel, aluminium and copper. In addition, some of these minerals are also by-products of mining of other minerals, tying their supply to the demand for their parent metals.

What are critical minerals?

Critical minerals are minerals that have two characteristics:

1) They are essential for modern technologies and industries, and have high economic relevance

2) They have risks of their supply being disrupted

Critical minerals are used in the production of multiple technologies with growing applications, such as electronics, space technology, mobility, medical devices and low-carbon technologies. Some of these minerals are also widely used in the alloying of major metals such as steel for improving characteristics such as strength, resistance to corrosion, and conductivity.

Potential disruption of supply chains can happen due to factors such as constraints in production, concentration of production (extraction or refining) in a few countries, resource availability, as well as economic, political, social or environmental risks that can disrupt supply.

Lists of critical minerals are often regional as they consider the economic contribution to local industries, and the resilience of the supply chain of these minerals. Examples are the European Union List of Critical Raw Materials (30 minerals), the United States List of Critical Minerals (34 minerals), and the Australian Critical Minerals List (26 minerals).

Regardless of location, we can define critical minerals as being important for industries and technologies globally, with risks of global supply disruption or price volatility. Among these, some of the critical minerals that are important for the low-carbon transition are: chromium, cobalt, gallium, germanium, graphite, indium, lithium, manganese, nickel, platinum- group metals, rare earth elements, silicon, tantalum, titanium, and vanadium.

Copper is not found in regional lists of critical minerals, but it is also often discussed as a potential bottleneck for the energy transition. This is because copper is essential for all energy technologies and, in addition, to many other new and mature technologies. At the same time, copper mining is becoming increasingly more expensive in capital and energy consumption.

Allied to these factors, the expected growth over the coming decades for these minerals is resulting in high price increases, which some predict it could slow down the low-carbon transition, or make it more costly. Current and future price increases and risks of supply for these critical minerals justify the push towards technology innovation and a more circular economy. To ensure that we achieve the energy transition, stay within the climate goals and ensure functional ecosystems, there must be a move towards many concurrent strategies: material efficiency in all stages in the supply chain of infrastructure and final products that use these minerals, better product design that aims to improved collection and recycling rates, and when possible, the substitution of critical minerals for other materials with lower supply risks.

This report focuses on the following minerals: lithium, cobalt, nickel, manganese, rare earth elements, platinum and copper. Below is a brief review of the use of these minerals in low-carbon technologies relevant for the energy transition in the *Net Zero by 2050* scenario, why they are considered critical, and what role low-carbon technologies play in the estimated future growth in demand for these minerals.

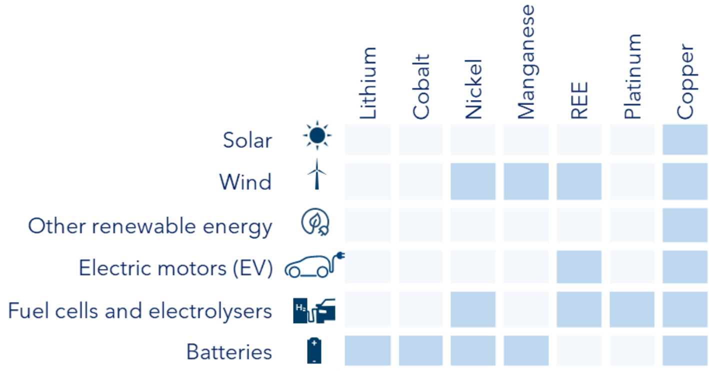

Figure 1 Use of critical minerals by low-carbon technologies covered in this report

Lithium use is highly concentrated on rechargeable lithium-ion batteries, accounting for three quarters of current lithium production. These batteries are increasingly used in electric vehicles and energy storage in grid applications, but also in portable electronic devices and electric tools (U.S. Geological Survey, 2022). The demand for lithium for the coming decades is predicted to put substantial pressure on lithium mining, even though production has expanded rapidly in recent years. Electric vehicles are expected to drive most of the lithium demand by 2050 (Watari et al., 2020) and there are few substitutes for lithium in EV batteries. There is virtually no recycling of end-of-life (EOL) lithium, with recycling rates lower than 1%. The role of recycling is critical, and it has often been concluded that increased recycling rates will be necessary to supply lithium for electric vehicles in the long term (Ambrose & Kendall, 2020b; Gruber et al., 2011; Kushnir & Sandén, 2012). Lithium mining is concentrated in Chile, Argentina and Australia, and refining is highly concentrated in China (U.S. Geological Survey, 2022).

Cobalt is a critical mineral that is mostly used in rechargeable batteries and in alloys for engines, as well as other minor uses across a variety of industries (U.S. Geological Survey, 2022). By 2050, future cobalt demand will be increasingly driven by EV batteries (Watari et al., 2020). It is estimated that the next generation of EV batteries will greatly reduce the demand for cobalt for EVs, and material substitution and increased recycling can also reduce cobalt demand in the long term. However, deep decarbonisation scenarios suggest supply constraints in the short and medium term, until the mid-2030s (Zeng et al., 2022). Cobalt mining is largely concentrated in the Democratic Republic of Congo (DRC) (U.S. Geological Survey, 2022), while cobalt refining is highly concentrated in China (Sun et al., 2019).

Nickel is a mineral that is mostly used to produce stainless steel and other ferrous and non-ferrous alloys. Stainless steel is widely used in infrastructure, including renewable energy generation. Another growing application for nickel is for rechargeable batteries, for both nickel-metal hydride (NiMH) batteries used in consumer electronics and in older-generation electric and hybrid vehicles, as well as lithium-ion batteries (LIBs), which have replaced NiMH as state-of-the-art EV batteries. The additional demand for nickel is not expected to become a bottleneck for low-carbon technologies, but high demand for EV batteries can result in higher prices for battery-grade nickel. Nickel has a relatively high EOL recycling rate of around 60% (Henckens & Worrell, 2020). Most nickel is mined in Asia, mainly in Indonesia, Philippines, Russia, and New Caledonia (U.S. Geological Survey, 2022), and refining is highly concentrated in China (Fraser et al., 2021).

Manganese is mostly used in iron and steel production. The demand for stainless steel is the main driver for the current and estimated future demand of manganese, and the contribution of low-carbon technologies for the expected manganese demand during coming decades is not significant as for other minerals such as lithium, cobalt, and nickel (Watari et al., 2020). Although the demand is rising, there are limited constraints on the expansion of manganese production (Sverdrup & Olafsdottir, 2019), although resources and reserves are concentrated in a few countries. Supply should not create any bottlenecks for low-carbon technologies (Schulz et al., 2017).

Rare earth elements are relatively common elements in the earth's crust, but their mining and refining is limited. REE are a group of 17 elements with some of them being relevant for the low-carbon transition, such as dysprosium and neodymium, the main use of which is in the production of permanent magnets used in wind turbines and EVs. They are considered critical due to their unique properties, the rapid growth in demand, and the geographic concentration of primary production and refining. Although mining of REE has been diversified in the last years, with production starting in mines in the United States, Australia, and Russia, China still concentrates most of the refining of these minerals. The future demand for these minerals is considered to be mainly driven by low-carbon technologies (Watari et al., 2020) and they are often considered to become a bottleneck to the energy transition (Lee et al., 2020). Substitutes for permanent magnets for wind turbine generators and EV engines with low REE or no REE exist, although to date they are not as widespread as those containing REE. Neodymium is the most abundant element in rare earth oxides and is the main rare earth component for permanent magnets. The high demand compared to rates of primary rare earth production, particularly dysprosium, highlights the urgent need to expand production, find adequate substitutes, implement material efficiency throughout all production chain, and increase recycling in order to increase the availability of primary and secondary REE for low-carbon technologies. Current recycling rates of REE from permanent magnets are lower than 1%.

Platinum-group metals are among the rarest minerals in the earth's crust and their primary production and reserves are highly concentrated in South Africa. Most PGMs are used in the chemical industry, metallurgy, jewellery, electronics, health, consumer goods and finance. Platinum and other PGMs are essential to the hydrogen economy. Supply constraints for low-carbon technologies not only relate to resource availability, but also to price and supply risks for political, economic and/or environmental reasons. Due to their economic importance, PGMs have high recycling rates. Around one third of the total platinum supply comes from secondary sources, mostly from EOL recycling (European Commission, 2020). In addition, retiring technologies such as catalysts for internal combustion vehicles and for the petrochemical industry will reduce the demand for PGMs from current uses.

Copper is essential for all energy technologies. This mineral is characterised by thermal and electrical conductivity and corrosion resistance, meaning it is used a lot all energy infrastructure, equipment and appliances. Regardless of the mix of technologies for the energy transition, copper will be essential because it is a key component of any energy system. It is used in cables, inverters, transformers and engines, all of which are essential for the production and consumption of electricity. Besides energy systems, copper is also the main mineral for various applications: digitalisation, communication, the electrification and mechanisation of tasks, the "Internet of Things", space and satellite technologies, medical devices, and many other emerging technologies. The global demand for copper more than doubled between 1990 and 2015, and this pattern of growth is expected to continue in the coming decades (Kuipers et al., 2018). Total future demand for copper is mostly driven by building and construction (excluding energy infrastructure) and consumer electronics (Watari et al., 2022). The share of copper demand for low-carbon technologies depends on the scenarios for the speed of decarbonisation and the technology mix. In a rapid decarbonisation scenario, the IEA estimates an increase of 270% of copper demand for low-carbon technologies by 2040 compared to 2020. The share of total copper demand that would be driven by new energy infrastructure would double when compared to 2020, reaching 40% of total copper demand in 2040. In this scenario, electricity networks would make the majority of expected growth, covering two-thirds of annual copper demand for low-carbon technologies by 2040 (IEA, 2021c). Although there is not necessarily a supply risk associated with copper, the high growth in demand and declining ore quality could result in challenges in mineral prices and supply in the future. It is one of the most relevant minerals for the energy transition, and the expansion of primary production, together with strategies of material efficiency, material substitution and higher recycling rates, will be fundamental to providing the volume of copper needed in the coming decades.

What are the bottlenecks in the minerals supply chain for the low-carbon transition?

The IEA has made mineral demand for the energy transition one of its strategic areas. The predicted mineral demand for the *Net Zero by 2050* scenario, which serves as the basis for this report, would result in a six-fold increase in the demand for critical minerals compared to today. The largest increases would be in battery minerals, particularly for lithium, for which annual demand could see a 100-fold increase (IEA, 2021d). Mineral availability in resources and reserves, however, is not always seen as a bottleneck in itself for this transition, but it is argued that it is the mining and refining capacity that is growing more slowly than the increasing demand, as a result of investment plans that are geared towards a world of gradual and insufficient actions on climate change (IEA, 2021c, 2022b).

The main concern regarding minerals as a bottleneck is how the demand for minerals in the coming decades will compare to current production volumes. These assessments mainly consider current technology and a business-as-usual technology development scenario, with some discussions on alternative technologies in a world with high innovation coupled with resource constraints. Also, there is significant focus on the need to expand new mining projects and limited discussion on how to reduce the demand for these minerals.

This report explores the different pathways that can influence the demand for critical minerals for a net-zero scenario. These different scenarios are influenced by different technological choices and the uptake of new technologies with lower demand for critical minerals, as well as by circular economy strategies which result in lifetime expansion and reduced demand. We also explore how higher collection and recycling rates can alleviate these mineral bottlenecks and discuss the potential of using different mineral sources such as reopening old mines, mining of tailings, and urban mining.

3. Modelling mineral demand for decarbonisation

To model the mineral demand for a low carbon future, two sources of information are used to provide data for the analysis of this report. First the IEA's *Net Zero by 2050* scenario, which shows in detail how much and where low-carbon technologies will be deployed. And second, information on the advancement of each of the technologies regarding the specific mineral requirement. The resulting total mineral demand is then discussed in the context of how circular economy strategies can help alleviate the pressure on primary resources.

This section is organised as follows: First, we describe the IEA *Net Zero by 2050* scenario. Here, we summarise the main assumptions of the scenario and present the technological path that forms the basis of the analysis in this report. Next, we describe different technology scenarios and how they can affect the future demand for critical minerals. Finally, we present the different circular economy strategies used in this report. A detailed description of the methodology, assumptions and data sources used in this report can be found in the Annex at the end of this report.

The *Net Zero by 2050* Scenario

The growth of what we call here "broad technologies" in the analysis in this report – total installed capacity of solar PV systems and wind power, number of electric vehicles and type of electric vehicles on the road, and the growth of battery storage and the hydrogen economy – is based on the *Net Zero by 2050* scenario from the IEA, described in this section.

The *Net Zero by 2050* is a scenario created by the IEA (IEA, 2021a) and involves a complete transformation of the energy system in just three decades, achieving nearly 100% renewable energy by 2050. It is not a prediction of how the energy system will develop in the coming decades. Rather, it represents one of the possible pathways to achieving a net-zero emissions energy system that will allow us to stay within the 1.5-degree target. According to the IEA, the pathway described is technically feasible, cost-effective and socially acceptable.

The *Net Zero by 2050* scenario is built on over 400 milestones ranging from electricity generation and storage, mobility, industry, to final energy use by residential and commercial buildings. This pathway requires significant investments, the right policy design and implementation, technology development and deployment, building of infrastructure, as well as international cooperation. It also heavily relies on innovation, particularly in technologies for batteries, hydrogen electrolysers, fuel cells and hydrogen fuels, allowing for the deeper decarbonisation of hard-to-decarbonise industrial and heavy-duty and long-distance transport.

Some of the main characteristics of this scenario are as follows:

- It takes into account the inequalities between world regions: developed economies will reach net-zero before developing countries, and this transition will include a reduction in energy inequality across countries, providing clean, affordable and modern energy to millions of people. It includes

access to electricity to 785 million people who currently have no or restricted access to electricity, and clean cooking solutions to 2.6 billion people who currently depend on traditional biomass.
- It reflects a significant decoupling of energy use and economic activity through energy efficiency. It considers a more than doubling of the world economy and a population increase of two billion more people by 2050, with a global energy demand around 8% less compared to 2020.
- The achievement of this net-zero pathway requires the immediate and massive deployment of existing technologies, allied to the rapid development and commercial use of low-carbon technologies that are in the pipeline. This translates into a rapid growth in technology use and thereby mineral demand, which is reflected in the steep mineral demand curves in this report.
- There are no new fossil fuel investments. This pathway has no oil and gas fields approved for development, apart from those already committed as of today (2021), and no new coal mines or coal mine extensions.
- There is significant focus on the electrification of both industry and mobility.
- It considers a range of behavioural changes and citizen participation regarding consumer choices.

In the following we describe four main aspects relevant to this report in more detail: renewable energy supply and storage, transport, the hydrogen economy, as well as the circular economy and behavioural changes.

Renewable energy supply and storage

The energy supply in 2050 would be largely based on renewable energy, compared to the current global energy supply, which is heavily based on fossil fuels. The total energy supply from fossil fuels is expected to drop from nearly 80% in 2020 to around half in 2035 and around 20% in 2050. The share of bioenergy on total energy supply will increase from around 10% in 2020 to around 20% by 2050.

Electricity generation is expected to increase over 250% between today and 2050. Electricity plays a major role in energy supply by 2050, mostly comprising solar PV and wind power. By 2050, almost 90% of electricity generation in this scenario will be from renewable sources, while most of the remainder will come from nuclear power and a small share from fossil-fuel electricity plants with carbon capture, use, and storage (CCUS).

This report only looks at renewable electricity generation infrastructure. The technologies relevant for the mineral demand are solar PV systems and wind power, which represent the highest growth in technology deployment and together account for around three-quarters of all installed capacity in 2050, as shown in Figure 2.

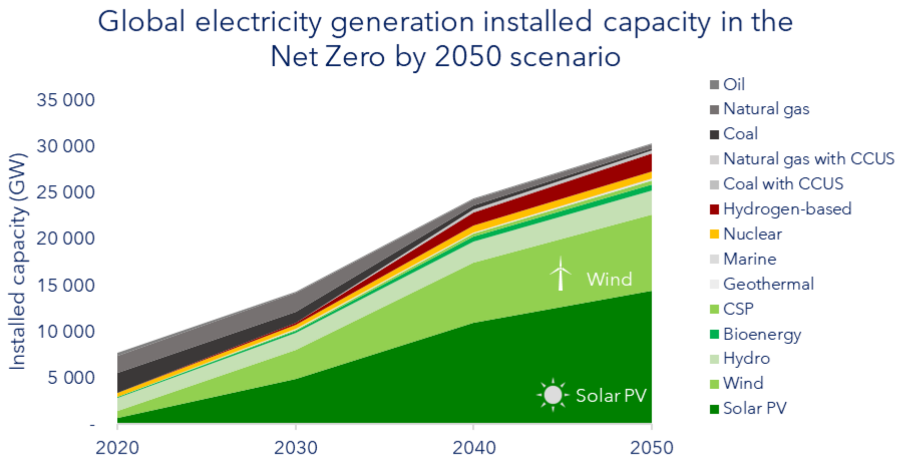

Figure 2 Installed capacity for electricity generation in the Net Zero by 2050 scenario. Data from the IEA (2021a)

Besides the actual power plants, two other important parts of the electricity system are the energy storage infrastructure and the transmission and distribution network. In the *Net Zero by 2050* scenario, battery storage infrastructure for grid application will experience a sharp increase from 18 GW in 2020 to almost 600 GW by 2030, and to over 3000 GW by 2050. In addition, there will be a large expansion in transmission and distribution networks, covering long-distance transmission from remote regions (wind power and solar PV), local distribution, EV charging points and grid substations. This report does not model the expansion and replacement of the transmission and distribution infrastructure, which is estimated to demand significant amount of copper.

Transport

There will be a rapid transition away from oil for transport, which currently represents 90% of transport energy use. In aviation and shipping, low-emission fuels from hydrogen and bioenergy would be a substitute for most fossil energy use. Relevant for the critical minerals in this report, road transport will experience rapid electrification. Electricity will become the main energy use in road transport, accounting for over 60% of energy use by 2050. For passenger cars, internal combustion engine vehicles will be phased out from new sales during the mid-2030s, and by 2050, most vehicles on the road will be running on electricity, either as hybrid or full battery EVs, and the remainder on fuel cells. For heavy-duty and long-distance trucks, hydrogen and hydrogen-based fuels will play a more significant role than for passenger vehicles.

The rapid electrification of transport can be seen in the scenario for the EV fleet. Annual sales of EVs will constitute 60% of total passenger cars by 2030, compared to 5% in 2020, and by 2050, all cars on the road will either be electric or hydrogen powered. Figure 3 shows the development in the number of vehicles on the road by fuel type on the left, and the growth of electric vehicles by type on the right.

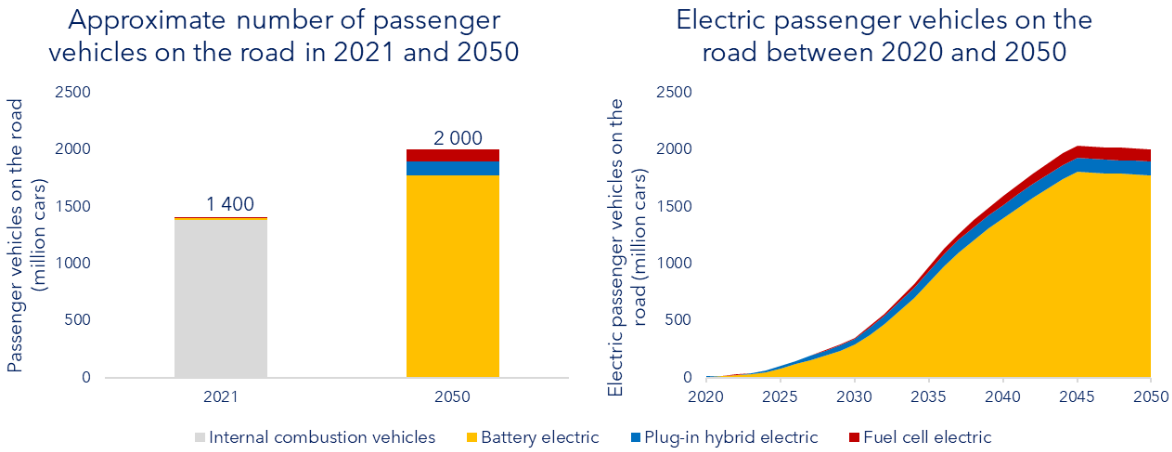

Figure 3 Total passenger vehicles on the road in 2020 and in 2050 by fuel (left) and growth of electric vehicles by type (right). Data from the IEA (2021a)

Electrification for trucks will be slower due to current state-of-the-art of battery density and charging infrastructure. By 2030, the *Net Zero by 2050* scenario considers that around 25% of heavy truck sales will be electric by 2030, and around two-thirds in 2050. It is considered that the electric bus fleet will grow from 500,000 to 8 million in 2030, and 50 million in 2050.

The analysis in this report only considers passenger vehicles, due to the fleet size, the importance of passenger vehicles on the EV market, as well as data availability.

The hydrogen economy

Hydrogen is expected to play a major role in a net-zero emissions energy system. Most hydrogen applications in the *Net Zero by 2050* scenario are concentrated in industry and transport. Hydrogen production is expected to increase from 87 Mt in 2020 to over 500 Mt per year in 2050. The biggest change is in the way that the hydrogen is produced: while almost all hydrogen produced today is considered grey hydrogen (production from fossil fuels without CCUS), by 2050 around 40% of hydrogen production is estimated to be blue (production from fossil fuels with CCUS), and the remainder will be derived from green hydrogen (production from electrolysis using water and renewable electricity as inputs). In this scenario, electrolyser capacity will grow from less than 1 GW in 2020 to 850 GW in 2030 and to 3585 GW by 2050. Hydrogen-based electricity production using fuel cells will reach over 1800 GW in 2050, from 0 in 2020. Most of this growth will happen between 2030 and 2040.

Fuel cells in vehicles will be used moderately in passenger vehicles, corresponding to around 9% of total passenger EV sales in 2050. Fuel cells will have a more important role in trucks, corresponding to around 30% of total electric heavy-duty truck sales in 2050. However, fuel cells in passenger EVs will still correspond to the majority of fuel cells use in transport.

Circular economy and behavioural changes

The *Net Zero by 2050* scenario does not specifically mention the circular economy, but introduces some behavioural changes in demand, and mentions recycling (particularly of plastics and steel) and material efficiency gains in industry. In the scenario, behavioural changes and consumer choices drive around half of emissions reduction. This is mostly due to technology changes, such as replacing internal combustion engines with EVs, installation of electric heat pumps, retrofitting and refurbishment of buildings to near-zero emission standards, installation of on-site renewable energy such as rooftop solar PV and solar water heaters, and the replacement of residential and commercial appliances with higher energy efficiency appliances.

A smaller part of behaviour change incorporated in the *Net Zero by 2050* scenario includes changes in the demand for energy by personal choices. The behavioural changes mentioned in the *Net Zero by 2050* report include:

- Reducing excessive or wasteful energy use, such as reducing indoor temperature settings to reduce energy consumption in buildings, adopting energy saving practices at home, and limiting driving speeds to achieve higher energy efficiency
- Transport mode switching, reduced car trips in cities in favour of public transport, walking and biking, fewer single-occupancy trips in favour of ridesharing, replacing air travel by train travel, and overall reduced flying. This scenario includes a reduction in car ownership, with 70% of all households in 2050 not owning a car and 22% of households with only one car. Nevertheless, the amount of passenger vehicles on the road will increase from 1.4 to 2 billion vehicles, an increase of around 40%.
- Reduced demand for materials, for example, reduction of single-use plastics, and higher recycling of household waste.

How do technology choices affect the demand for minerals?

The mix of *broad technologies*, i.e. the number of wind farms and EVs on the road, is based on the *Net Zero by 2050* scenario. For each of these broad technologies, however, the choice of different *sub-technologies*[1], such as types of wind turbines or battery chemistries, can significantly influence future mineral demand. There is considerable uncertainty regarding how different technologies will develop in the future, as it depends on different parameters such as production costs, technology innovation, mineral constraints, efficiency, location, energy prices or market preference. Here, based on the installed capacity of each of the broad technologies in the *Net Zero by 2050* scenario, we have applied four different technology scenarios to evaluate how the different *specific technology* mixes can influence mineral demand, summarised in Table 1. The next section details the technology mix in each scenario.

[1] From now on, "technologies" refer to different specific technologies, for example, types of wind turbines and different batteries chemistries

Scenario	Description
Current technology scenario (CT)	Describes what the mineral demand would be by 2050 if we used the same technology as those installed in 2021
Business-as-usual technology scenario (BAU)	Describes the evolution of the different technologies based on patterns, learning curves and industry signals
Business-as-usual battery constraints scenario (BC)	This scenario only changes battery chemistry for electric vehicles and stationary batteries, following a different path for battery development, partially influenced by constraints on availability or mineral prices
Advanced technology scenario (AT)	In this scenario, new technologies enjoy rapid advancement and take over a higher market share of annual additions by 2050. It also models the effect of the uptake of technologies that demand less critical minerals

Table 1 Technology scenarios

Wind turbines: demand for copper and rare earth elements

On a broad technology level, wind turbines can be classified as onshore and offshore. Onshore wind farms constitute around 95% of total wind power installed capacity, but offshore plants are becoming increasingly popular due to better wind conditions and rapid cost reductions and are expected to grow significantly over the coming decades. Offshore wind turbines are witnessing major technological innovations with growth in the size of turbines, floating foundations, and the development of drivetrain and control technologies (IRENA, 2019).

New generations of wind turbine generators use permanent magnets, resulting in more efficient and compact generators with fewer faults, less maintenance and lower costs. These permanent magnets require REE to be produced. Typical permanent magnets comprise a neodymium-iron-boron (NdFeB) alloy, combined with additives – usually dysprosium, but also praseodymium and terbium – to enhance their properties. On average, direct-drive generators contain around 600 kg of magnets per MW capacity, of which around one third of the weight is neodymium, and around 4% dysprosium. However, gearbox generators with permanent magnets can contain only around one third of the mass of these magnets, resulting in lower REE requirements (Carrara et al., 2020). Generators with no or a low amount of REE have a higher copper demand.

In 2018, wind turbine generators with permanent magnets accounted for 32% of all onshore and 76% of all offshore wind turbines installed (Carrara et al., 2020)[2]. It is expected that this technology will increase moderately for new onshore turbines but can account for most new offshore turbines installed in the coming decades due to its efficiency and low maintenance. In the business-as-usual (BAU) scenario, annual installation of turbines with permanent magnets will grow in both onshore and offshore wind. In the advanced technology scenario, in which turbines with low REE are preferred due to resource availability or prices, wind turbines with low or no permanent magnets will constitute most of the offshore wind turbines installed in 2050.

[2] Due to no detailed market share of different turbines in 2021, we estimated the market share for 2019 to 2022 based on technology diffusion curves using data on annual technology mix of technology installed from 2000 to 2018

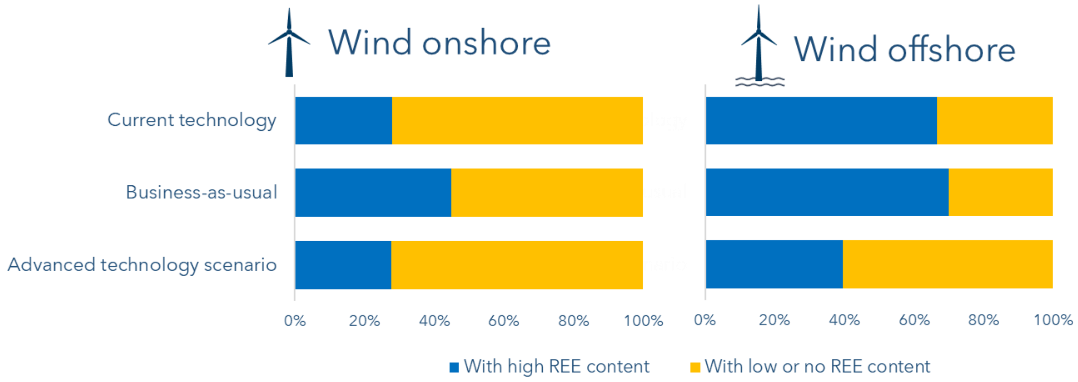

Figure 4 Technology scenarios for wind power onshore and offshore. Different technologies were aggregated into those with high rare earth elements (REE) content and those with low or no REE content

Solar photovoltaics: rooftop solar can reduce the demand for copper

Different solar PV technologies can result in many differences in critical or strategic minerals, mainly silicon and silver for crystalline silicon cells, and other critical minerals such as cadmium, tellurium, gallium and indium for thin-film PV cells. For this report, however, the main differences in technologies for solar PV are due to the balance of system, which includes cables, inverters and transformers. Rooftop-mounted PV systems require less copper than utility-scale PV systems (Frischknecht et al., 2020). In the BAU scenario, utility-scale power plants become more prevalent due to lower costs and a higher concentration of PV investments by energy companies. In the advanced technologies scenario, however, rooftop PV continue to constitute over 40% of the solar market share in 2050.

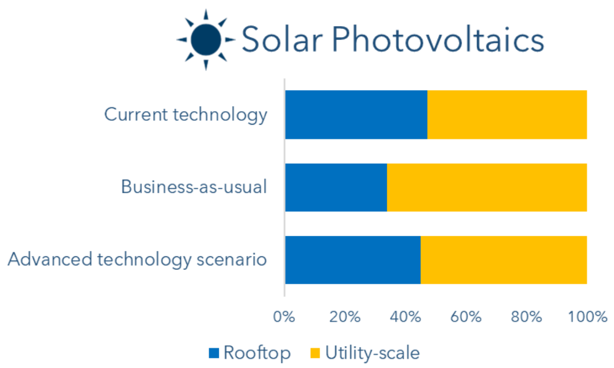

Figure 5 Technology scenarios for solar photovoltaics. The difference across scenarios was between rooftop and utility-scale installations

Electric vehicles: demand for battery minerals, rare earth elements and platinum

One of the technological pillars of decarbonisation is the electrification of transport. The main consumers of batteries for transport are passenger EVs (IEA, 2021a) which, in turn, are the main drivers for the demand for battery materials in the coming decades (IEA, 2021c). The coming decades will see a high growth of EVs on the road, not only in deep decarbonisation scenarios, but also following business-as-usual trends. EV sales have doubled in 2021 compared to 2020, reaching nearly 10% of new car sales globally, and new car sales in the first quarter of 2022 were 75% higher than in the same period in 2021

(IEA, 2022b). Many countries have pledged to ban the sale of new internal combustion engine cars in the next two decades, or at least have ambitious electrification targets.

Electric vehicles can be categorised according to different technologies. Plug-in hybrid electric vehicles (PHEVs) have rechargeable batteries that can be charged by an external power source and use an internal combustion engine to extend the vehicle's range. Battery electric vehicles (BEVs) run exclusively on one or more electric motors and are powered by rechargeable batteries, charged exclusively by external power sources. Fuel cell electric vehicles (FCEVs) use a fuel cell instead of rechargeable batteries to power the electric motor.

The demand for EVs will result in an increase in the demand for minerals, such as REE for electric traction motors; lithium, graphite, nickel and cobalt for batteries; and PGMs for fuel cell EVs. Rechargeable batteries are the main driver of critical mineral demand for EVs. The market for rechargeable batteries for EVs is dominated by different chemistries of lithium-ion batteries (LIBs), which require lithium, copper, nickel, graphite and, in most of the chemistries used today, cobalt. Different battery chemistries available on the market have different compositions, with different amounts of these minerals. The variety of technologies, rapid development, and price fluctuation of battery materials makes the future demand for minerals for rechargeable batteries one of the hardest to predict (Lee et al., 2020).

One of the most common technologies for LIBs are lithium-iron-phosphate (LFP) batteries, which are most commonly used in Chinese EVs. Nickel-cobalt-manganese (NCM) batteries have now become the most widely used battery chemistry in the Western EV industry due to their high energy density and steep cost decline over the last decade, and are expected to dominate the EV market until at least 2030. Different NCM chemistries exist. NCM111 has a similar amount of nickel, cobalt and manganese, while NCM811 has a high amount of nickel and low amount of cobalt. It is estimated that NCM622 and NCM811 will dominate NCM chemistries in the next years. Cobalt-free lithium-nickel-manganese oxide (LNMO) batteries are currently under development and it is estimated they will enter the market after 2030. Nickel-cobalt-aluminium (NCA) chemistries are similar to NCM chemistries, with a high nickel and a low cobalt content, and are currently only used by Tesla. Solid-state batteries (SSBs) are not yet commercially available and could enter the market after 2030. They would reduce the need for nickel and cobalt but increase the demand for lithium. If commercially competitive, these SSBs would gain an advantage over current nickel-rich chemistries due to their higher safety and energy density compared to current LIB technologies.

The different EV battery scenarios follow different pathways developed by Xu et al., (2020). In the BAU scenario, LIBs are largely dominated by NCM batteries, which has been the pattern in recent years and is expected to continue in the coming decades (IEA, 2022b). In a scenario with mineral constraints, LFP batteries take preference due to their low requirement for critical minerals and lower production costs. In the advanced technology scenario, SSBs will start to become commercialised from early 2030, and by 2050 they will dominate lithium-ion chemistries. In addition, the number of small and medium-sized vehicles sold, compared to SUVs, is higher in the advanced technology scenario than in the previous scenarios.

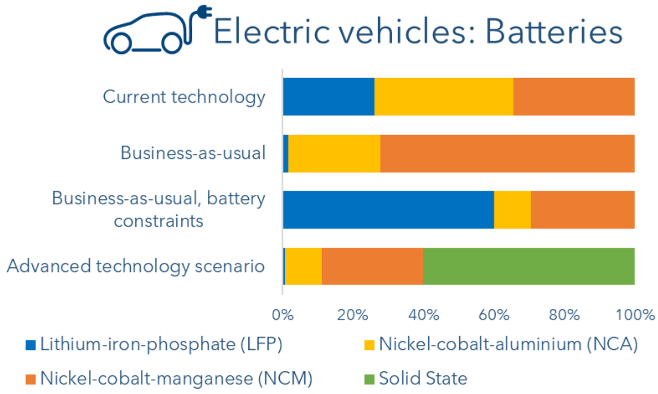

Figure 6 Technology scenarios for batteries for electric vehicles. Different chemistries for NCM are aggregated in this summary, but are differentiated in the model

Electric vehicles have been considered to drive most of the demand for REE for permanent magnets for the low-carbon transition (IEA, 2021a). Electric traction motors with NdFeB permanent magnets are the leading technology and accounted for 92% of all EVs sold in the first half of 2021 (Adamas Intelligence, 2021). In recent years, manufacturers outside of China, such as Nissan Motor, Tesla, and BMW, have been developing motors with low or no REE permanent magnets (Reuters, 2021). In the business-as-usual scenario, it is assumed that electric traction motors with permanent magnets will continue to dominate the market. In the advanced technology scenario, we modelled the uptake of electric motors with no permanent magnets and, by 2050, they will represent 40% of all vehicles sold annually.

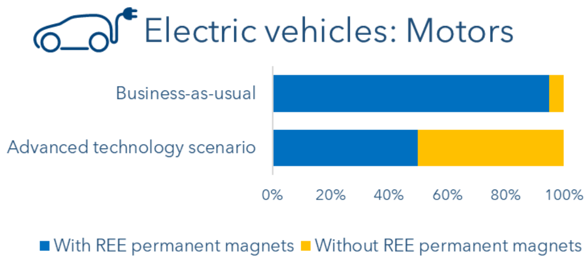

Figure 7 Technology scenarios for motors for electric vehicles. Different technologies were aggregated into with those using rare earth elements (REE) permanent magnets and those not using REE permanent magnets

Fuel cell EVs are powered by hydrogen in fuel cells, which provide the main source of electricity for the electric motor. These fuel cells drive the demand for platinum. Using the Toyota Mirai as a reference, current FCEVs require around 30g of platinum per vehicle, and this amount is expected to be further reduced to 5g per vehicle by 2040 (IEA, 2021c). In the technology scenarios, the difference in platinum demand comes from the downsizing of passenger car sizes in the advanced technology scenario.

Energy storage: Movement away from lithium-ion batteries can reduce resource constraints

A larger share of renewable energy technologies in the electricity mix poses a challenge. Wind and solar PV represent the largest additions of renewables in the coming decades. These sources are intermittent – depend on the wind blowing and the sun shining – and need to be balanced with larger grid systems, energy storage, flexible demand and/or flexible operation of other forms of power generation. Energy storage, particularly electrochemical storage such as batteries, will play a significant role in providing a smooth balance between the supply and demand for electricity in an electricity system with a significant share of variable renewable energy.

Although LIBs have accounted for the majority of stationary energy storage additions in the last decade, there are other technologies for stationary batteries for grid balancing that demand less critical minerals. For stationary applications, energy density (i.e. area needed to store the energy) is not as important as it is in vehicles. Flow batteries, also called redox flow batteries, are a promising technology for grid-scale energy storage, with no demand for lithium or cobalt, although the most current development in flow batteries relies on vanadium, another critical mineral. Other options for redox flow batteries under development, such as zinc-air flow batteries, demand no or few critical minerals. These batteries are an emerging technology that can displace LIBs as the main batteries for stationary storage.

In the BAU scenario, LIBs continue to dominate the stationary energy storage market, mostly LFP batteries due to their lower production costs and lower exposure to the highly volatile prices of critical minerals. The use of flow batteries will increase to 25% of all stationary batteries installed in 2050. In a scenario with mineral constraints, higher LIB prices will make flow batteries more competitive and result in more rapid commercialisation of flow batteries. In this scenario, flow batteries will achieve 40% of market share in 2050. In the advanced technology scenario, solid-state batteries will start to become commercialised from 2030 and take over most of the market for LIBs, including in stationary applications.

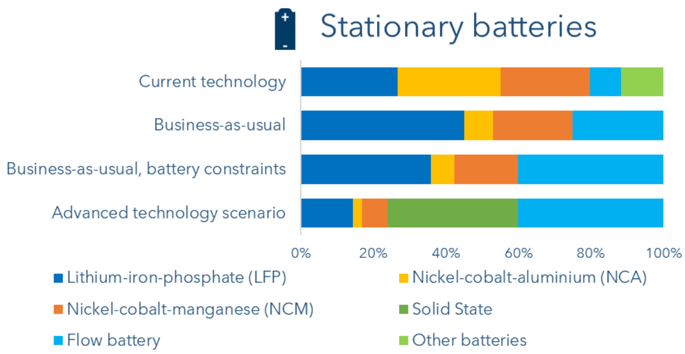

Figure 8 Technology scenarios for stationary batteries for stationary applications. Different chemistries for NCM are aggregated in this summary, but are differentiated in the model

The green hydrogen economy: concerns over the demand for platinum-group metals

Hydrogen is a versatile fuel and is expected to play an increasing role in the energy system in the coming decades. The production of hydrogen through water electrolysis can be used to balance variable renewable energy by using the surplus electricity from peaks of oversupply (for example, when more electricity is being generated from wind or solar power plants than is demanded by consumers) to produce a low-carbon fuel. This type of hydrogen is called *green hydrogen*. The main uses of hydrogen are industrial applications, as a substitution for natural gas, and in the production of electricity in fuel cells in both EVs and stationary applications. Hydrogen can also be used as a substitute for coal as a reduction agent in the iron and steel process industry or used as a feedstock for the chemical industry.

Electrolysers produce hydrogen and comprise three main technologies. Alkaline electrolysers are a mature technology that currently account for around three quarters of all installed capacity and current pilot projects in Europe (Patonia & Poudineh, 2022). These electrolysers require large amounts of nickel, but no PGMs. Proton-exchange membrane (PEM) electrolysers are smaller and more flexible to operate and correspond to most of the newly installed electrolysers. The major resource concerns for PEM electrolysers are their use of PGMs, in particular platinum, palladium and iridium. A new electrolyser technology called solid oxide electrolyser cells (SOEC) has a lower demand for minerals and requires no platinum or other PGMs. Major technology developments are currently underway in order to reduce the amount of critical minerals in electrolysers, with an estimated reduction of 70% iridium and 80% platinum in the coming decades (IRENA, 2020).

In the BAU scenario, PEM electrolysers will gradually gain a higher market share of installed capacity due to their improved abilities to balance intermittent renewable energy and industrial applications. The market share of SOEC will increase to 10% in 2050. In the advanced technology scenario, SOEC will grow to occupy 20% of all installed capacity in 2050, and PEM will become the predominant electrolyser technology in 2050.

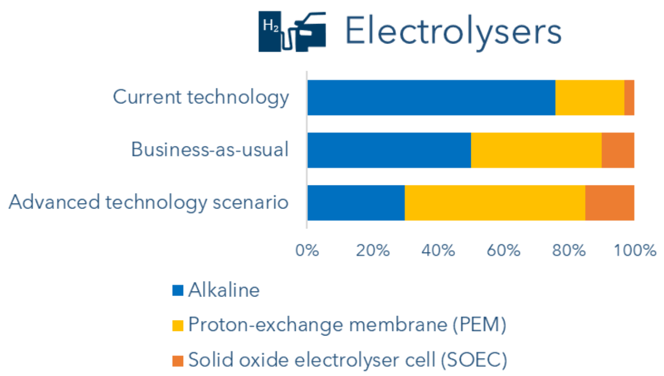

Figure 9 Technology scenarios for electrolysers

Fuel cells are used in FCEVs and in stationary applications in energy storage and in industries. Most fuel cells require platinum as catalysts. Similar to electrolysers, the main fuel cell technologies are alkaline, PEM and solid oxide fuel cells (SOFCs). Alkaline fuel cells are a mature technology and catalysts can be made from platinum or nickel. PEM fuel cells are mostly used in electric vehicles, while the development of SOFCs is mainly targeted at stationary applications. Ongoing developments of PGM-free catalysts for fuel cells are accelerating, and the average requirement for PGMs in fuel cells should decrease to close to the amounts used in internal combustion vehicles by 2030 (Hughes et al., 2021).

Modelling circular economy strategies

A key concept to achieve the goal of a sustainable society is the circular economy. Even though there are several definitions of the concept (Kirchherr et al., 2017), circular economy strategies generally aim to redefine the production-consumption system by creating changes in behaviour and production modes on both the producer and the consumer side. Regarding the low-carbon technologies in this report, we combined circular options into three different main strategies targeted to all or most of the technologies under study based on existing literature (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017; Watari et al., 2019). These strategies are **reduction** in demand, **lifetime extension** and **recycling**.

Reduction in demand

A more circular economy entails changes in the way materials are produced and consumed, resulting in more material efficiency, greater focus on the recycling of production scrap and end-of-life products, the reduction of unnecessary material flows such as single-use packaging, and repurposing of products and infrastructure. All of these changes will result in lower energy use that are beyond the technological solutions for energy efficiency assumed in the IEA scenario (Fragkos & Fragkos, 2022). This report assumes that this would result in a decline in electricity demand compared to the baseline scenario, from 0% in 2022 and gradually reaching a 3% lower electricity demand by 2050. This reduction in electricity demand will result in slight reductions in the demand for installed capacity of power plants.

We also modelled the reduction of car ownership on the demand for critical minerals. Urban planning, better public transport strategies and behavioural changes can reduce the future demand for private cars globally. There is a good margin for reducing the use of private cars and the distance people travel in the future with, for example, an increase in hybrid working modes, online work meetings and increased use of home office. Walking and cycling instead of driving can also improve quality of life and avoid private transportation modes (Barrett et al., 2021).

To calculate the potential in demand reduction in new private vehicles, we analysed the dynamics of advanced economies and continental trends. For advanced economies, we followed the scenarios designed by Barrett et al. (2021), which show an average annual reduction in new private car fleets of 0.8%. For Latin America and Africa, we assumed a steady state of no growth in private car ownership by remaining at around 100 cars per 1000 inhabitants, while for Asia, we assumed a slow increase in private car ownership per inhabitants as stated in several policy reports and international agencies' investment plans (Fan & Beukes, 2021; Takiguchi & Mizuno, 2013).

Lifetime extension

Lifetime extension of technologies already in use is a circular strategy as it reduces material demand by not replacing infrastructure before it is really necessary. If the use phase of a technology is doubled, material demand over time is halved, given that lifetime extension can be achieved without any major changes in the technology. Lifetime extension can be achieved through technological developments, maintenance, component replacement and, in the case of electric vehicles, changes in the use phase.

Assumptions on lifetime of wind and solar power plants are usually based on manufacturers' warranties, but the equipment and infrastructure can often be used for longer. For example, manufacturers such as

Siemens Gamesa are offering lifetime extension services for wind farms comprising midlife investment in upgrading components, as well as extensive monitoring, operations and maintenance, costs and output optimisation, which have proved to increase the lifetime of wind farms from 20 years up to 30 years[3] (Pakenham et al., 2021). In this context, this report assumes that these practices can be generalised across the major manufacturers of wind turbines with flexible financing options for energy operators.

For EVs, lifetime extension can be achieved through reduced use of private vehicles through changes in behaviour resulting from, for example, higher availability of alternative modes of transport (public transport, cycling, walking) and policies for reducing car use and car parks in densely populated areas. Besides extending the lifetime of batteries in EVs, it is assumed that used batteries reach the end of life when they achieve 80% of their original capacity. After their retirement from use in EVs, they can be repurposed for use in stationary applications such as home, commercial and grid storage. This repurposing is called *second life* of EV batteries.

Technology	Component	Lifetime (years)	Lifetime extension (years)
Solar PV power plants		**25**	**50**
	PV modules	25	50
	Cables	25	50
	Inverters	15	20
Wind power plants		**20**	**30**
	Wind turbines	20	30
	Cables	40	40
	Transformers and generators	20	35
Batteries (stationary)		**20**	**25**
Electric vehicles		**10**	**15**
	Electric motor	15	15
	Batteries and fuel cells	10	15
Electrolysers		**20**	**20**
	Electrolysis cell stack	10	20
	Balance-of-plant	20	20
Fuel cells		**20**	**20**
	Fuel cells stack	10	20
	Balance-of-plant	20	20

Table 2 Lifetime and lifetime extension assumptions for the different technologies in this report

It is assumed that the lifetime of technologies is dependent on the lifetime of the main components, and other components are replaced when necessary (Lopez et al., 2022). The assumptions on lifetime extension of low carbon technologies are based on literature reviews and discussions with experts in the field and are summarised in Table 2.

Recycling

Recycling has been highlighted as one of the most important strategies for the future supply of critical minerals, contributing to ensuring the supply of critical minerals and improved sustainability of material

[3] See, for example (Siemens Gamesa, 2022)

production (Vidal-Legaz et al., 2018). The rate at which recycled minerals can substitute primary extracted minerals depends on the minerals available from process scrap and EOL products, compared to annual demand.

The amount of minerals available for recycling depends on different factors. First, the amount of material in process scrap (pre-consumer production stages) and in products and infrastructure reaching its EOL from in-use stocks, such as the volume of copper in cables, equipment and transformers in retiring power plants. When reaching their end-of-life, these minerals are available for dismantling/disassembly, collection and treatment.

These materials can then be collected for treatment such as incineration, landfilling, refurbishment, repurposing or recycling. However, not all materials are collected. **Collection rates** indicate the share of materials that are sent for treatment. There is never a 100% collection rate due to a number of factors: dissipative losses, in which a material transforms into a form that cannot be recovered, for example, due to losses to the environment (Zimmermann, 2017); infrastructure, such as subsea cables being left after the decommissioning of offshore plants, often due to the high cost of dismantling and transportation (Al-Sallami, 2021), and hoarded and/or abandoned products and infrastructure that do not reach waste flows (Dewulf et al., 2021), such as vehicles (European Commission, 2017), infrastructure for the transmission and distribution of electricity (Krook et al., 2011) and household electronics (Thiébaud (-Müller) et al., 2018). This report has applied collection rates to EOL minerals based on technology and components when available. For example, in a decommissioned offshore wind farm, all wind turbines are collected, but not all subsea cables.

The materials that are sent for treatment and recycling to be used as inputs to production depend on the **recycling rate**. The recycling rate combines two activities: the volume of collected materials **sent for recycling** and the volume of materials **recovered in the recycling process**. The share of collected materials sent to recycling plants reflects the differences in recycling rates across the globe, as well as the fact that even in places with high recycling rates and policies, different components cannot be easily disassembled due to design choices or material characteristics (e.g. alloys), and are destined for different treatment options (landfilling, incineration, or are destroyed when recovering other materials). The recovery rate of minerals depends on available recycling technologies. For example, different recycling techniques allow for the recovery of from 48% to 99% of platinum from spent automotive catalysts (Yakoumis et al., 2021).

Current collection and recycling rates are estimated based on a literature review and experts opinions. In the circular economy scenario, we have assumed higher collection and recycling rates. High collection rates reflect an optimistic scenario, which is perhaps not unrealistic in large energy infrastructure projects but would require significant policy and regulatory efforts in the case of EV collection and recycling. Recycling rates in the circular economy scenario reflect a highly optimistic scenario where recovery efficiency globally would be close to the theoretical best based on available technology or under development, regardless of costs. The collection rates used in this report are summarised in Table 3.

Technology	Component	Collection rate (current)	Collection rate (circular economy)
Solar PV power plants		100%	100%
Wind power plants	Wind turbines	100%	100%
	Cables	75% (onshore) 50% (offshore)	100% (onshore) 75% (offshore)
	Transformers and generators	100%	100%
Batteries (stationary)		70%	90%
Electric vehicles		85%	95%
Electrolysers		100%	100%
Fuel cells		100%	100%

Table 3 Collection rates on current and circular economy scenarios

Of the collected materials, not all is sent for recycling. In all scenarios, the materials sent for recycling after collection increase over time, reaching 100% in 2050. Current rates of materials sent for recycling are 75% for solar and wind power plants (considering the minerals in this report only, not accounting for non-recycled components such as silicon PV cells or turbine blades), 5% for batteries (stationary and in EVs) and 5% for fuel cells in EVs. For solar and wind power plants, the rates for materials sent for recycling grow constantly over time, while for batteries and fuel cells, these rates will gradually increase until the mid-2030s, following the slow growth of the recycling infrastructure, and take off after 2035. The material that arrives at recycling plants is then recovered based on available material recovery techniques. The recovery rates for minerals are summarised in Table 4.

Mineral	Recovery rate (current)	Recovery rate (Best available technology)	Recovery rate (circular economy)
Lithium	> 1%	80%	80%
Cobalt	32–74%	96–99%	95%
Nickel	57%	90%	90%
Manganese	53%	95%	95%
REE – Dysprosium (from permanent magnets)	> 1%	60%	60%
REE – Neodymium (from permanent magnets)	> 1%	95–99%	95%
Platinum	60–70%	95–99%	95%
Copper	45–60%	100%	95%

Table 4 Mineral recovery rates for current, best available technology, and used in the circular economy scenario

4. Technology choices and their effects on mineral demand

There is a high level of uncertainty regarding which of the different technology options – with more or less critical minerals – will be predominant in the future. Technological advancements in the last decade have considerably changed the market share of different technologies, and it is expected that similar patterns will also occur in the coming decades. Onshore wind turbines with permanent magnets entered the market 15 years ago and quickly changed the wind power technology market, the same way that lithium-ion batteries radically changed the composition of battery systems in the past decade.

Technological advancements are dynamic. In recent decades, many technological advancements have changed economies, industrial production, energy consumption and generation, as well as livelihoods. If state-of-the-art technology available 10 or 15 years ago was taken as the basis for the quantification of future mineral demand, the picture could be very different from the one presented here. And there is no question that, in 15 years, the technology options available and the prospects of new technologies reaching the commercialisation stage and entering the market will be different from what we have today. There are many technologies in the early stages of development that could make substantial contributions to the demand for critical minerals in the future. Besides the cobalt-free lithium-ion batteries previously discussed, there has been research on the development of sodium-ion batteries that could be used in both stationary and EV applications and that do not require lithium, as well as research on different redox flow batteries for stationary applications that do not use any critical minerals, such as zinc-air flow batteries. There are an increasing number of research grants for the development of low-carbon technologies with low or no critical minerals, as well as for upscaling the best recycling technologies available. The success of these new technologies could mean a change in the mineral bottlenecks for decarbonisation.

Technology choices can make significant difference for mineral demand. Technology choices also have trade-offs: while the adoption of new low-cobalt batteries will reduce the expected demand for cobalt, it will increase the demand for nickel and lithium; and wind turbines with lower amounts of REE will increase the demand for copper. But how do these different technologies impact the future demand for each of the minerals?

Mineral demand is based on technology deployment in the *Net Zero by 2050* scenario. This means there is an accelerated technology growth. In addition to the growth in installed capacity is the replacement of components throughout the infrastructure's lifetime, and the replacement of retired technology.

This section looks at how different technology scenarios affect the demand for critical minerals. The figures in this section present the annual demand for each mineral, in tonnes, per broad technology (solar photovoltaics, wind, electric vehicles, stationary batteries and the hydrogen economy) in the different technology scenarios.

Lithium and cobalt

Technology choices for rechargeable batteries make significant difference for mineral demand. Battery demand for EVs will account for 80% to 90% of the demand for lithium and cobalt, 75% to 85% for nickel and 45% to 65% for manganese in 2050. Lithium and cobalt are used exclusively for rechargeable batteries. Battery technology scenarios for EVs can result in relatively minor differences in lithium demand. A battery constraint (BC) scenario with higher use of LFP batteries instead of NCM could result in a demand for around 6% of business-as-usual (BAU), while the advanced technology (AT) scenario, with solid-state batteries being commercialised after 2030, would result in an increased lithium demand of around 8% compared to the BAU scenario. A scenario with smaller cars and solid-state batteries would result in a lithium demand similar to the BAU scenario.

Different battery chemistries for EVs play a much bigger role for cobalt, nickel and manganese. For these minerals, the BAU scenario, with a higher share of NCM batteries and reduction in LFP batteries, will result in a higher mineral demand than the current technology (CT) market share. A scenario with higher LFP due to resource prices or constraints, or due to choices to reduce cobalt use due to environmental or social standards, would result in a major reduction in mineral demand: the demand for cobalt, nickel and manganese would fall below 50% of the BAU scenario by 2030. In the advanced technology scenario, mineral reduction would happen after 2030, but would quickly fall to close to 40% by 2040.

For stationary batteries, the transition from lithium-ion to redox flow batteries and towards less costly LFP batteries will significantly reduce mineral demand compared to the current technology mix.

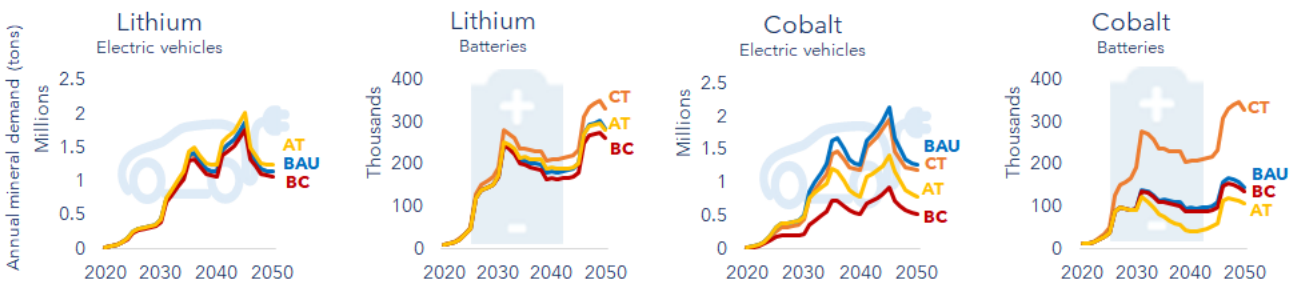

Figure 10 Annual demand for lithium and cobalt by electric vehicles and stationary batteries between 2020 and 2050 for the different technology scenarios

Nickel and manganese

Wind power technologies also result in differences in the demand for nickel and manganese, albeit on a lower scale than for batteries. Wind turbines would be responsible for around 2% to 4% of the total nickel demand and 25% to 45% of the manganese demand in 2050, due to the use of stainless steel and other steel alloys in the production of generators, nacelles and towers. Annual nickel and manganese demand for wind turbines could be 5% to 10% lower in the advanced technology scenario compared to BAU scenario.

The hydrogen economy would be responsible for 1% to 3% of nickel demand for low-carbon technologies in 2050. The current technology mix, which relies on more alkaline electrolysers, uses a higher volume of nickel. The transition to more PEM and SOEC could reduce the annual nickel demand by 10% to 20% between 2030 and 2050 in the BAU scenario and by 15% to 40% in the advanced technology scenario, compared to the current technology mix.

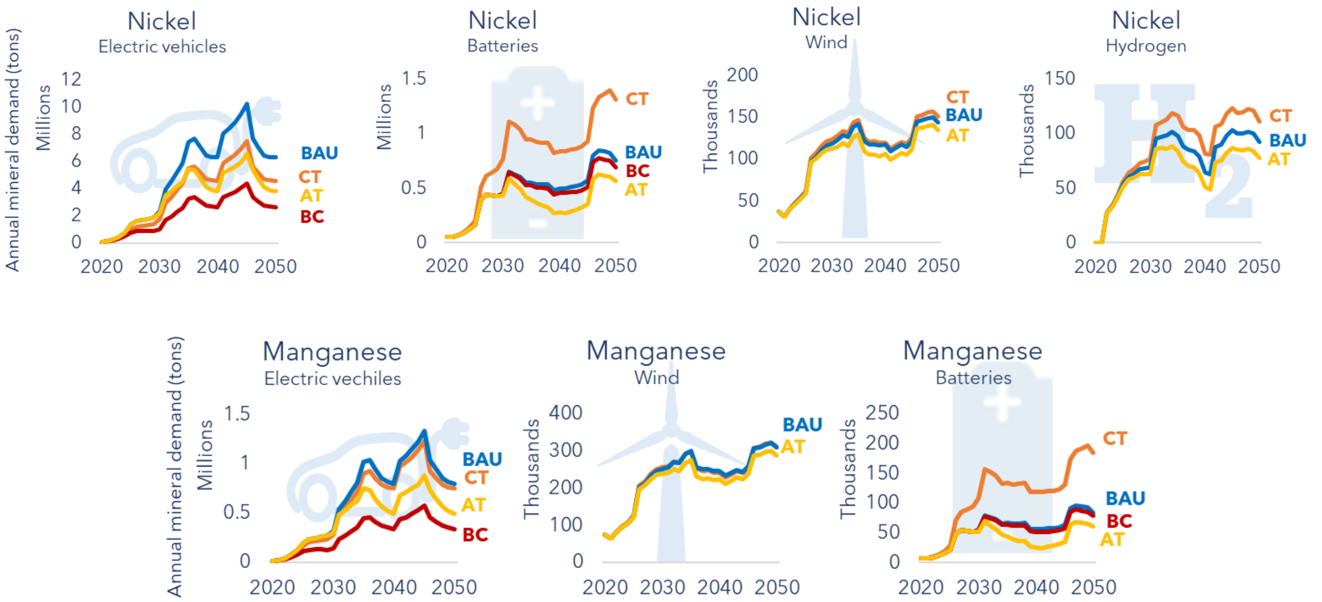

Figure 11 Annual demand for nickel and manganese by electric vehicles, stationary batteries, wind power and hydrogen electrolysers between 2020 and 2050 for the different technology scenarios

Rare earth elements

About three quarters of the demand for REE (in this report, only neodymium and dysprosium) for low-carbon technologies are due to the growth of EVs. For EVs, the reduction in the use of REE comes from increasing the market share of non-REE electric traction engines, a direction that some car manufacturers outside of China have been taking due to supply risks. For wind turbines, the BAU scenario involves a move towards a higher share of low or no REE generators. After the Chinese quota reduction on exports of REE in 2010, resulting in substantial price increases (Shen et al., 2020), some manufacturers decided to move towards the production of wind turbines with less or no REE (Reuters, 2011). Since then, reducing or eliminating the use of heavy REE, especially dysprosium, in permanent magnets has become a strategy for wind turbine manufacturers such as Siemens Gamesa, Goldwind and GreenSpur Renewables, and of automotive manufacturers such as Toyota, Nissan Motor, Tesla and BMW (Alves Dias et al., 2020). Thus, future supply constraints or price hikes could have the same effect on reducing the dominance of direct-drive wind turbines with permanent magnets in both the onshore and offshore wind industry, of electric traction motors with permanent magnets for EV, and pushing towards the design and use of permanent magnets with reduced REE content.

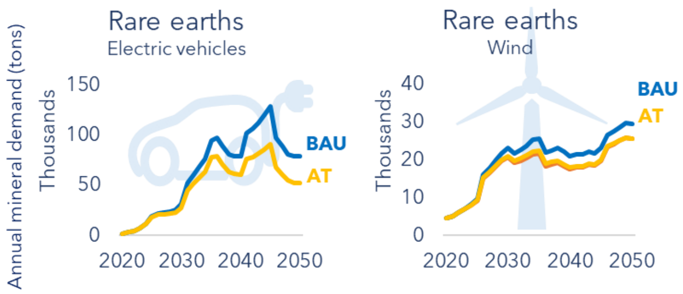

Figure 12 Annual demand for rare earth elements by electric vehicles and wind power between 2020 and 2050 for the different technology scenarios

Platinum

Platinum demand is driven by the growing hydrogen economy, including fuel cells for vehicles. The high driver of platinum demand in this scenario is the growth of FCEVs. Fuel cells in FCEVs constitute a significant share of platinum demand for the low-carbon technologies. The values in this analysis do not account for the predicted reduction in the use of platinum and other PGMs in fuel cells, which could cut the annual demand for platinum and PGMs by over half (IRENA, 2020). For electrolysers and fuel cells, both the BAU and the advanced technology scenarios will result in higher demand for platinum, as new technologies replace alkaline electrolysers and fuel cells. For FCEVs, the reduction in the advanced scenario is due to the reduction in car size.

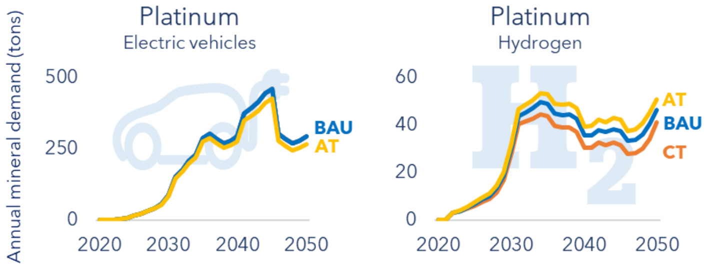

Figure 13 Annual demand for platinum by fuel cell electric vehicles and fuel cells for electricity generation between 2020 and 2050 for the different technology scenarios

Copper

Finally, copper is demanded by all low-carbon technologies in this report. The highest demand for copper for the *Net Zero by 2050* scenario is the growth of EVs, which accounts for 40% to 50% of future copper demand for low-carbon technologies. The copper demand in this report, however, does not take into account the transmission infrastructure for connecting new power plants to the grid and to consumers, which is estimated to account for the majority of copper demand for the energy transition (IEA, 2021c). For all technologies, the advanced technology scenario will result in a reduction in copper demand compared to business-as-usual, as well as to the current technology mix.

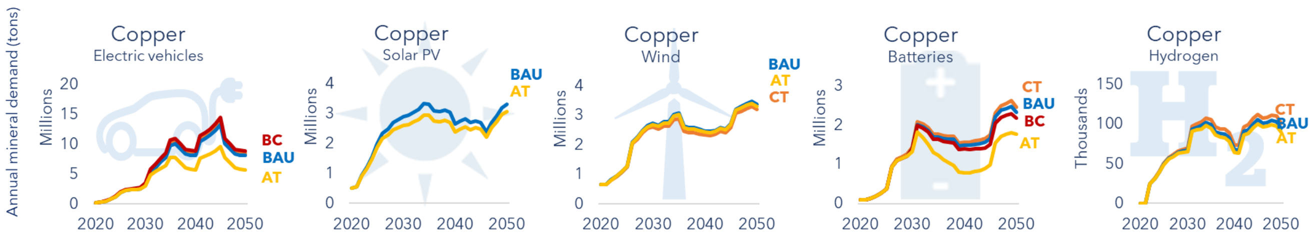

Figure 14 Annual demand for copper by electric vehicles, solar photovoltaics, wind power, stationary batteries and the hydrogen economy between 2020 and 2050 for the different technology scenarios

Resource constraints can make the energy transition more expensive, but technology substitution is possible

Raw material scarcity can be alleviated by using different technologies that can provide the same services. While it is natural to be concerned about not being able to meet the anticipated demand for a certain product, it is easy to forget that it is not the product itself that is demanded but the service which the product provides. A variety of technological options for providing the service creates flexibility, which makes a system resilient to supply shortages. Technological substitution can be viewed at varying degrees of resolution. For example, technology substitution in the case of transportation can be viewed on a vehicle-specific level; perhaps a low-cobalt or cobalt-free battery EV, or fuel cell EVs instead of battery EVs; or the mode of transportation; perhaps electric bikes or public transport can replace for EVs; or the end goal of transportation; perhaps a virtual meeting can replace the need to travel.

New and transformative technologies which are under development can change the scale of demand for these minerals in the medium and long term. There is a push for designing critical minerals out of many low-carbon technologies, which should be intensified in the next decades. This is a common subject for industries, policymakers and the research community. New technologies for fuel cells and electrolysers are being developed with no platinum or other PGM. Wind turbines and EV manufacturers have invested in decreasing the use of REE in permanent magnets. Research in stationary battery is moving away from the use of LIBs, and instead developing flow batteries based on vanadium or other non-critical minerals such as zinc for large-scale storage. For EVs, a wide range of battery technologies have been developed or are currently under development, each of which uses various component minerals in different ratios and quantities. Cobalt content in battery chemistry mixes has been reduced by the development of high-nickel cathodes that have comparable energy densities, and the next generations of batteries to be commercialised in the coming decade should be fully cobalt-free. Meanwhile, LFP chemistries can be used to avoid the use of nickel, cobalt and manganese altogether, and car manufacturers outside China have announced a move towards the use of LFP in new models (IEA, 2022b).

Material substitution in technologies occurs also on other products and technologies that use the same minerals that are needed for low-carbon technologies. For example, nickel-containing stainless steel is the main consumer of nickel, using more than 10 times as much as battery production in 2019. Substituting non-nickel-containing stainless steel in some stainless steel applications and sorting stainless steel scrap for recycling to minimise the addition of alloying metals to recycled steel can free up large amounts of nickel to be used for energy transition technologies. Carbon nanomaterials, an abundant material, can substitute a wide range of critical minerals, including cobalt and nickel in hard materials such as cemented carbides and alloys, and platinum in catalytic converters (Arvidsson & Sandén, 2017). Platinum demand for catalytic converters for reducing air pollution from vehicles with internal combustion engines will decline in a scenario of deep decarbonisation and high electrification of transport, as well with decreased passenger vehicle ownership and use. Some uses of copper can be substituted by aluminium, such as in overhead transmission lines in electricity networks – one of the main drivers for the expected copper demand in the energy transition. In addition, copper has been substituted in other products, such as plumbing, tubes, telecommunications, and air conditioning, and increases in mineral prices due to resource constraints should increase this substitution in the future.

However, no mineral can be fully substituted in all applications, and this is increasingly relevant as products and technologies become more complex. But even in uses where no or little opportunities for material substitution are possible, products and processes can be designed for material efficiency and lower mineral content due to possible price volatility, resource constraints, or due to environmental or social impacts of mineral production.

5. How can a circular economy alleviate mineral bottlenecks?

Circular economy strategies can have three concurring effects on the demand and supply of minerals. First, they reduce annual mineral demand. Second, they increase the lifetime of infrastructure and services, making extracted minerals stay in society for longer. And third, they determine when and how much material can be recovered and re-enter the manufacturing process, as a substitute for primary raw materials.

An increase in the time that materials provide services before they need to be replaced is highly desirable, as it will result in lower demand for materials and, therefore, lower social and environmental impacts associated with material production. It also means that these materials will take longer to be recycled and used as secondary material sources. The steep mineral demand curve for a net-zero energy system will result in a high demand for the supply of minerals, either from primary (mined) or secondary (recycled) sources. The longer these minerals remain in stock, the longer it will take to replace mining with recycling. This can also be beneficial for the recycling industry. The recycling of many of these critical minerals is still in its infancy. The additional time required for these minerals to reach their EOL and enter waste streams can also mean that there is more time for recycling techniques, markets, supply chains, infrastructure, and policies and regulations to mature, resulting in higher recycling rates when these minerals are ready to be collected and recycled. In the same way that it takes years for new mines to be opened, it will take years for the best available techniques for recycling of permanent magnets and batteries to achieve large-scale commercial capacity that is capable of absorbing a significant share of EOL wind turbines and EV batteries.

High recycling rates do not automatically translate into a high share of replacement of primary (mined) for secondary (recycled) materials. Recycling rates and the use of secondary materials are two indicators that complement each other, but that represent different outcomes. Even with a high rate of mineral recovery, the composition and lifetime of in-use stocks and the growth in demand for critical minerals can result in low rates for the use of secondary materials in terms of total material demand. The long lifetime of power plants and vehicles means that these minerals will not be available for recovery before decades after being installed. Thus, a significant share of the material demand for low-carbon technology will come from primary extraction, but increased end-of-life collection and recycling rates can result in a substantial reduction in the demand for mined materials in the next two to three decades.

This section quantifies the effect of circular economy strategies on the annual demand and availability of recycled minerals. The figures in this section present a comparison of the annual demand per minerals in tonnes, as the sum of all technologies, for the scenarios with and without circular economy measures. Each figure shows the development of the three indicators:

- Annual demand for minerals, in orange, where the range represents the different technology scenarios,
- Minerals currently in the stock of all low-carbon technologies that will reach their end-of-life, in grey, and
- Minerals that are recycled, in yellow. The gap between yellow and grey are minerals which are lost to landfill or incineration.

The annual mineral demand is based on the technology deployment in the *Net Zero by 2050* scenario, considering the growth of different technologies between 2020 and 2050, and in all the years in between. It includes the replacement of components and end-of-life technology. The large growth in mineral demand between 2030 and 2040 represents large growth in low-carbon technology in the *Net Zero by 2050* scenario, particularly for electric vehicles.

Battery minerals: lithium, cobalt, nickel and manganese

A reduction of car ownership and lifetime extensions of battery life by five years could reduce annual battery mineral demand by 10% to 20% between 2030 and 2040 and reach up to half of the annual demand by 2050 compared to the baseline. In a scenario with no circular economy measures, EOL minerals leaving the stock and being available for collection and treatment will reach 15% of the annual demand by 2035 and represent around 90% of the annual demand after 2045. A lifetime extension of batteries by five years will reduce mineral demand by delaying the need to replace spent batteries, and will also delay minerals from leaving the stock and, only by 2040, will the amount of EOL minerals reach a more significant share of the annual demand by around 20%. The number of spent batteries between 2040 and 2050 will increase substantially and minerals available for collection and recycling will correspond to up to 80% of mineral demand for new batteries. The steep growth of end-of-life batteries after 2040 will be a result of the large increase in battery use after 2030 in the *Net Zero by 2050* scenario.

For **lithium**, considering current recycling rates of around 1%, this mineral stream will be lost to landfills and incineration. However, higher collection and recycling rates mean that a more significant share of this mineral will become available as a substitute for primary mined lithium: by 2045, half of the annual lithium demand could be derived from recycled batteries.

The annual demand for **cobalt**, **nickel** and **manganese** and the availability of EOL minerals are highly dependent on future technology choices. The large difference in these choices is visible in the figure from the large bandwidths for mineral demand, recycling and mineral content in EOL batteries. These minerals have relatively high recovery rates, between 50% and 75%, and lower end-of-life recycling rates are highly influenced by collection rates and whether the materials are sent for recycling. Considering current collection and recovery rates, recycled cobalt, nickel and manganese could provide up to 62%, 47% and 44%, respectively, of the annual demand in 2050. In a circular economy scenario, with lower annual mineral demand and higher collection and recycling rates, recycled cobalt, nickel and manganese could cover up to 80–90% of the demand for these minerals in 2050.

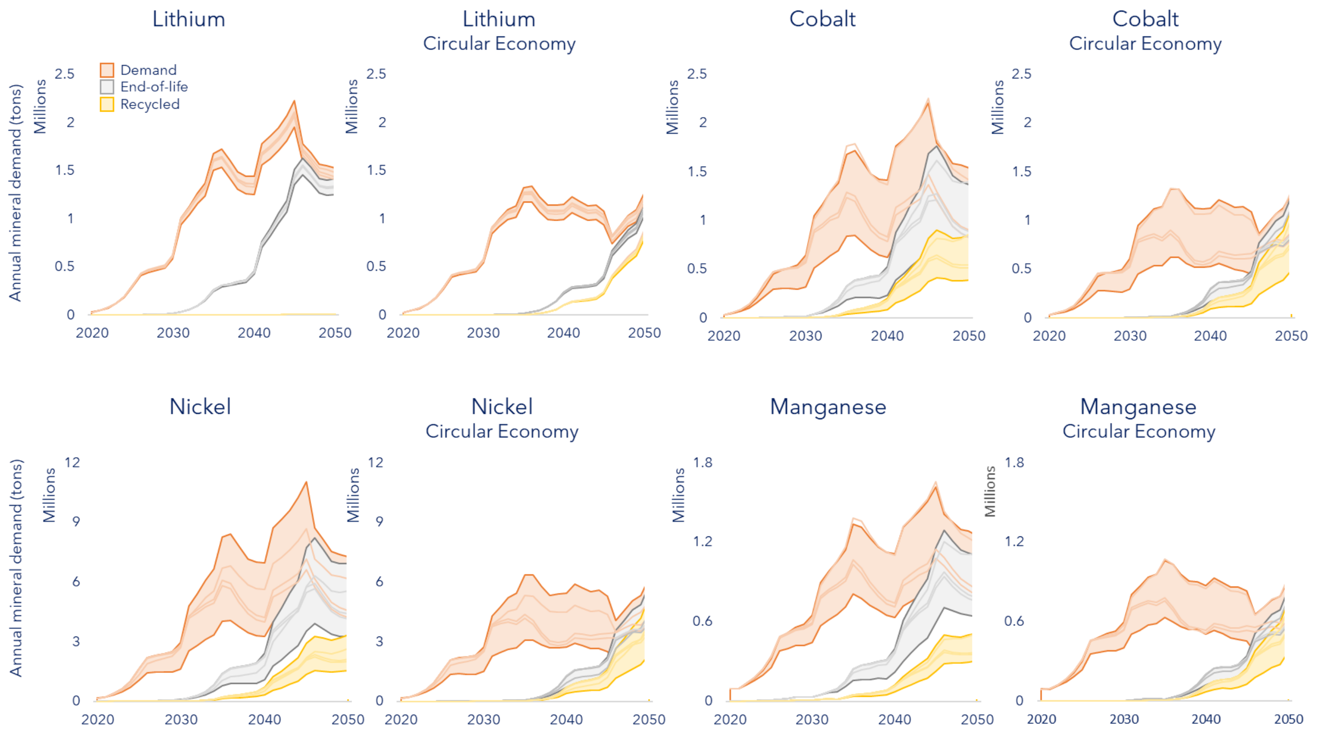

Figure 15 Annual demand for lithium, cobalt, nickel and manganese (orange), end-of-life (grey) and recycled (yellow), in metric tons, between 2020 and 2050. For each mineral, the figures on the right called "Circular Economy", include circular economy strategies for reduction, lifetime extension and recycling

Rare earth elements

Circular economy measures influence the demand for rare earth elements in different ways. A reduction in electricity demand leads to a small decrease in the demand for installed capacity of wind turbines, and lower car ownership leads to lower demand for electric motors for new vehicles. The main contribution, however, is from lifetime extension of 10 years for wind turbines and 5 years for EVs, which leads to lower annual demand for minerals for the replacement of wind farms and vehicles. These circular economy measures could reduce the demand by 20% by the mid-2030s and halve the demand for rare earth minerals by 2045. Permanent magnets reaching their end-of-life could represent a significant share of the annual demand. If no lifetime extension is assumed, rare earth minerals in EOL magnets would account for around 50% of the annual demand by around 2040, and by 2050 they would account for 90–100% of the annual demand. Lifetime extension of wind turbines and electric vehicles would reduce the availability of minerals from EOL, but not by a significant amount. By around 2040, rare earths in EOL magnets will constitute around one third of the annual demand, and by 2050 they will account for 80%–97% of the annual demand. In the advanced technology scenario, where the proportion of wind turbines and electric traction motors without REE gain a much larger market share, EOL minerals will account for over 100% of the annual demand in 2050.

Current recycling rates of rare earth minerals from permanent magnets are around 1%. If this recycling rate were to continue, the mineral stream from EOL technology would be lost. Higher collection and recycling rates could cover over half of the demand for dysprosium and over 80% (up to 100% in a scenario with circular economy and low REE technologies) of neodymium in 2050.

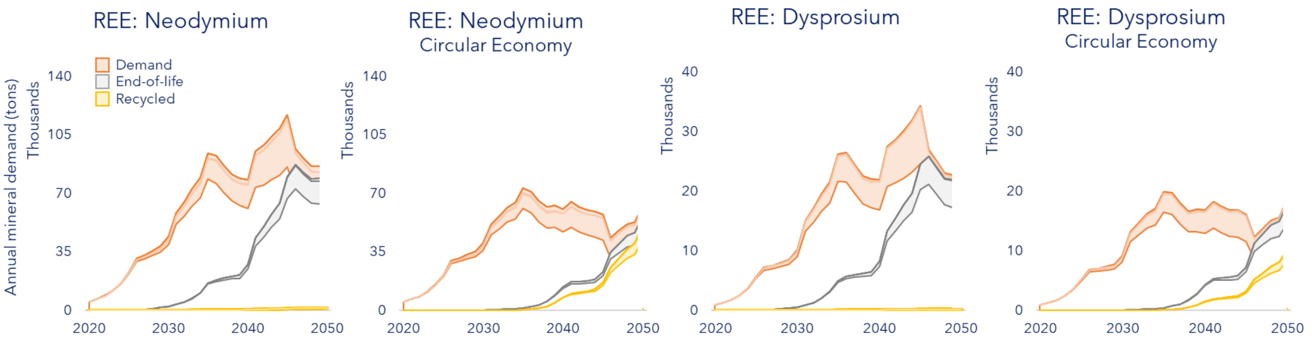

Figure 16 Annual demand for neodymium and dysprosium (orange), end-of-life (grey) and recycled (yellow), in metric tons, between 2020 and 2050. For each mineral, the figures on the right, called "Circular Economy", include circular economy strategies for reduction, lifetime extension and recycling

Platinum

Circular economy strategies for fuel cells in electric vehicles will result in a reduction in the demand for platinum by a quarter. The reduction in private vehicle ownership and the lifetime extension of fuel cells will result in a reduction in the annual demand of platinum of around 50% in 2045. Platinum from fuel cells reaching end-of-life will increase from the mid-2040s in a circular economy scenario, reaching up to 90% in 2050. This figure considers current platinum loading of fuel cells and does not take into account for reduced future demand due to technological innovation and material efficiency. As PGM loading of fuel cells is expected to reduce significantly in the coming decades, this figure could become even higher. Platinum is a mineral with high recyclability and recovery rates, and a significant share of current platinum use is already derived from secondary sources. Extended collection and recovery rates could result in recycled platinum from fuel cells and electrolysers meeting over 80% of total platinum demand for the hydrogen economy.

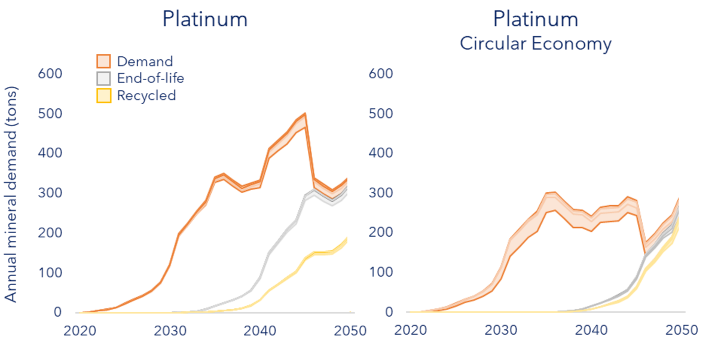

Figure 17 Annual platinum demand (orange), end-of-life (grey) and recycled (yellow), in metric tons, between 2020 and 2050. The figure on the right, called "Circular Economy", includes circular economy strategies for reduction, lifetime extension and recycling

Copper

Copper is needed in all the technologies reviewed in this report, and all circular economy strategies affect copper demand. A reduction in electricity demand leads to lower demand for all power generation technologies, and a reduction in car ownership also reduces the demand for copper in electric vehicles. Lifetime extension of power generation technologies, EVs and batteries makes the highest contribution to reduced copper demand.

Circular economy strategies can cut the expected demand for copper by half by 2045, and by 2050, copper from low carbon technology reaching end-of-life could constitute up to 85% of copper demand for the replacement and installation of new low-carbon infrastructure. Increasing recycling rates from 60% to 95% of recovery of copper from end-of-life scrap could generate enough recycled copper to cover over almost 75% of the annual demand by 2050.

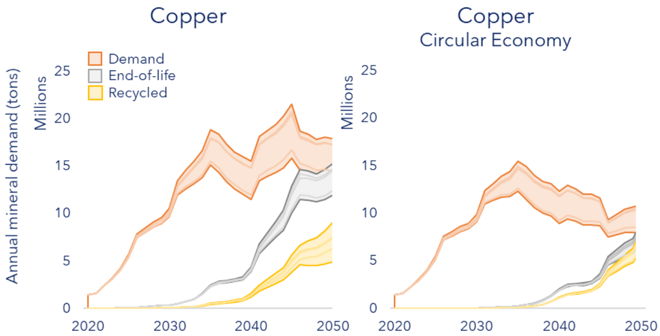

Figure 18 Annual copper demand (orange), end-of-life (grey) and recycled (yellow), in metric tons, between 2020 and 2050. The figure on the right, called "Circular Economy", includes circular economy strategies for reduction, lifetime extension and recycling

Circular economy strategies as enablers for a low-carbon future

Besides technology, product and material substitutions, a range of non-technological solutions are needed for achieving climate targets while ensuring we do not further contribute to the ecological decline. Circular economy strategies are necessary to ensure both the decrease in the demand for minerals and, later, the recovery and re-use of the minerals that have already been extracted. The strategies modelled here acted, concurrently, in different ways.

First, by decreasing the **total volume of material needed** from reduced demand. Different strategies will lead to a lower demand for minerals in society, for example, reducing the purchase of private vehicles by reducing car ownership while incentivising other transportation modes will lead to an overall decrease of the total demand for battery minerals. Another important strategy is reducing the electricity demand not by just installing efficient technologies, but by getting rid of inefficient processes such as unnecessary mineral extraction and processing, increased material efficiency, and a shift on consumption patterns towards services and higher re-use rates, including on consumer products.

Second, by **spreading the mineral demand over a longer timeframe** through strategies of lifetime extension. The longer these minerals stay in stocks, the longer time we will need to replace the aging infrastructure, giving more time for the upscaling of new and more efficient technologies, for the development of more responsible mining sites and for increasing the contribution of recycled minerals to replacing primary extraction in the medium and long term. Lifetime extension correspond to a range of different strategies that can influence how long materials stay in stock. For EVs, the lifetime of batteries highly depends on the amount of cycles, i.e. the amount of times a battery is used and recharged. Passenger vehicles can be used for longer by reducing the use of owned vehicles e.g. by reducing daily commute to work in favour of public transport, biking or walking, or incentivising more ridesharing to reduce the number of trips per person per year. Further extending lifetime of batteries can be achieved through using spent batteries from EVs into a second life as home storage or grid applications, delaying the need for the production of new stationary batteries. Once an EV battery reaches 80% of its capacity, it is deemed as its first life as an EV battery is over, but it can still be incorporated to other uses where energy density (i.e. the amount of energy stored and supplied per area) is not the priority. For power plants, lifetime extension can be achieved through more maintenance and component replacement, mid-life investments, and repowering and retrofitting, re-using part of the infrastructure in place. And finally, for all products and infrastructure, technology innovation and design for repair and replacement of key components contribute to lifetime extension.

In this section we described the effects that different circular economy strategies could have in lowering the demand for mining. When comparing the figures for each mineral without circular economy measures with the figures representing the scenario with circular economy measures, it becomes clear that annual mineral demand (orange) is significantly lower, while the amount of recycled materials (yellow) increases, and the curves representing the minerals that will be freed up when technologies reach end-of-life shift to the right, i.e. minerals become available for recycling somewhat later due to various circular economy measures resulting in life-time extensions.

End-of-life minerals leaving the stock follow the demand for minerals, with a time lag reflecting the lifetime of technologies. For minerals used in electric vehicles, the curve for end-of-life minerals corresponds to the same line for mineral demand, but 15 years later. This means that the large growth in demand between 2030 and 2035 leads to a significant amount of minerals reaching the end of life between 2045 and 2050. Until 2030, these are still insignificant compared to total mineral demand but after the mid-2040s they start to reach a significant share of the total supply that is necessary to fulfil mineral demand. However, minerals reaching the end-of-life that are not recovered are lost minerals that end up in landfills or incinerators, and extending the recycling rates of these minerals is crucial for reducing the need for (and impacts from) mining in the long term.

Beyond mining: Recycling is vital for the responsible supply of minerals

The supply of raw materials needed should not only focus on the expansion of new or old mining frontiers. The current resource extraction, use and discard economy is not sustainable. Resources locked in stocks have seen a 23-fold increase during the 20th century (Krausmann et al., 2017), with recycling rates far from ideal, and low inputs of secondary (recycled) materials to total material demand. The transition towards a more circular economy is instrumental for the mitigation of environmental impacts associated with mining and GHG emissions, and it should be key to the discussion of mineral needs for the energy transition. On the demand side, circular economy strategies will reduce the demand for minerals. On the supply side, reuse and recycling are key circular economy strategies to provide at least part of the demand for critical minerals. Recycling is considered essential for the responsible supply of minerals, as it makes no logical sense, at least from an environmental perspective, to dispose of large amounts of used and recyclable minerals into landfills and incineration plants while causing large environmental and social impacts in the extraction of a similar amount of virgin minerals.

Some recycling techniques can have high energy requirements and result in lower quality of secondary material not able to substitute primary materials in the low-carbon applications. While metals can theoretically be recycled indefinitely, current use of metals is increasingly complex, used in small quantities and in complex alloys or composite materials, making separation of such metals more demanding and costly (Haas et al., 2015). Policies and regulation must be implemented to ensure these critical minerals are recycled using advanced and high-value techniques, keeping these minerals in the loop for advanced applications, instead of downcycling them into bulk recycling for lower-value applications.

Design is often overlooked in circular economy discussions, as recycling is seen as an end-of-pipe activity. However, technology design, with early thoughts about dismantling, access and recycling protocols, is a main factor regarding the technical and economic feasibility of the recycling process (Thompson et al., 2020). There are a few main issues with recycling concerning product design. The first issue is that products that are reaching their end-of-life in the next years – not only wind turbines, solar PV panels or batteries, but also other traditional products such as portable electronics – have rarely been designed for durability, reuse, remanufacturing, repairability and recyclability (Babbitt et al., 2021). Disassembling and separating the desired materials in a way that allows them to be technically and economically recyclable is not always possible.

Despite the concerns regarding the sustainability and resilience of the supply of critical minerals for clean technologies, the use of recycled minerals in the manufacturing of new technologies is not taking place on a large commercial scale. Some of the reasons for this low input of recycled minerals relate to quality concerns of current recycling techniques for the purity and performance requirements for these critical minerals for low-carbon technologies, with virgin raw materials meeting quality requirements at a lower price. It will take considerable effort to improve the sorting and identification of material grades, develop and implement better dismantling techniques, and more suitable pre-treatment of recycled materials. There is an urgent need for increasing the demand for these recycled minerals using advanced and more expensive recycling technologies in order to drive investments and large-scale innovations in the recycling industry (Velenturf et al., 2021).

Another issue is the design of recycling value chains. This includes logistics for the collection and transport of products to be recycled, as well as markets for recycled products and circular business models. For the energy industry, for example, short-term thinking and continued pressure on companies to reduce costs make it difficult to create circular business models and the uptake of circular economy solutions that focus on long-term benefits. This is particularly important for new technologies, such as offshore wind, which are focused on moving from technology innovation into commercial exploitation, fighting to provide cost-competitive energy to compete against mature technologies (Velenturf et al., 2021). Collaboration among actors in technology value chains to create circular business models – from design to manufacture to recycling – is essential in order to move towards a circular economy for new low-carbon technologies (Jensen et al., 2020).

A more circular economy, with higher collection and recycling rates, is possible (and necessary) for all minerals.

Recycling rates for minerals are highly dependent on the source of material and location.

According to latest economy-wide studies, average recycling rates for **cobalt** are around 32% (UNEP, 2011), mainly due to the low collection and recycling of process scrap and end-of-life products, meaning that two thirds of cobalt leaving the stock every year are sent to landfills (E. M. Harper et al., 2012). Recovery of **nickel** from production scrap accounts for around 82% of total pre-consumer waste, but nickel recycling from end-of-life products constitutes only 57%. The main sources of nickel recycling are melting of stainless-steel alloys, spent catalysts and nickel-containing batteries. In addition, 14% of nickel from end-of-life products is downcycled and diluted in metal alloys (Henckens & Worrell, 2020). Average recycling rates for **manganese** are relatively low, and latest estimates point to end-of-life recycling rates around 37% (UNEP, 2011), as ferrous and non-ferrous scrap, and scrap recovery specifically for manganese is negligible (U.S. Geological Survey, 2022). **Platinum** recovery is high, between 60 and 70%. The main sources of recycled platinum are spent automotive exhaust catalysts, spent chemical catalysts and electronic and electrical component scrap. Global end-of-life recycling rates for **copper** are estimated to be 45%, and over half of all copper leaving stocks is disposed of in landfills or waste incinerators (Henckens & Worrell, 2020).

Urban mining is the process of recovering materials from end-of-life products, buildings and waste. Many products that form part of in-use stocks, such as batteries, electric and electronic equipment and components, and vehicles, contain critical minerals needed for building a low-carbon society. The world produces over 50 million tonnes of electronic waste, comprising electrical and electronic equipment (EEE), batteries, solar PV cells, medical devices, among other electronic products, all of which contain some amount of critical minerals. This volume is expected to increase substantially, reaching up to 120 million tonnes by 2050 (World Economic Forum, 2019).

Electrical and electronic equipment (EEE) constitute important uses of critical minerals, and can, for example, be found in circuit boards, smartphone components and rechargeable batteries. The lifetime of critical materials in EEE largely depends on the products and can last from a few months or years in lamps and smartphones, up to decades in high efficiency motors, buildings and energy infrastructure. There are many challenges to improving the recovery of critical minerals from EEE. The mineral content of consumer products reaching the end-of-life can be very different from the products demanded by new technologies. For example, current smartphones, laptops and televisions require different materials than those that were produced 10 years ago. Besides the design issues and complex alloys discussed in this report, there are many hibernating electronics, which are products not in use that are stored in households and not yet discarded, and small electric and electronic devices that are thrown away in unsorted household waste, reducing the potential for the recovery of secondary materials. In addition, the recycling of EEE is not focused on the recovery of all minerals. The value of the minerals contained in these products is often low, and present in low quantities. It is estimated that all the mineral content in smartphones corresponds to USD 1–1.3 per phone, almost three quarters of it due to the small gold content. Approximately 82% of the total mineral value in smartphones – corresponding to only around 6% of the weight of the minerals – can be recycled using currently available commercial methods (Bookhagen et al., 2020). This is because the main driver of recycling is the price of minerals. The high price fluctuation of other critical minerals contained in EEE can improve the recovery rates of other minerals such as rare earths.

Urban mining is a crucial aspect of the recovery and recycling of copper. Copper is available in virtually every type of in-use stock: buildings, energy infrastructure, industrial uses, transport and consumer products. It is estimated that in the European Union alone, the amount of copper in end-of-life scrap amounts to over three million tonnes (Ciacci et al., 2017). However, environmental impacts and costs of recycling are not always low. Not only do they depend on the mineral that is being recycled, but also on what products are being recycled and the mineral content and the form it is contained in products. Energy consumption in copper recycling can range from very low from the recycling of copper from cable and wire scrap, to close to the energy requirements of ore mining and refining when recycling copper from construction and demolition debris (Espinoza et al., 2020).

Due to the way that products are manufactured and built, urban mining poses some complex challenges and therefore requires the cooperation of several actors. On the one side, authorities and governments should provide the legal framework and adequate infrastructure to enable the effective recovery of materials. On the other side, industry has an important role to play in urban mining, not only in the collection and recycling stages, but also by designing products in a way that allows material separability. Finally, better informed consumers can ease the current separation and collecting of products for their further treatment and processing. The mineral content in products is often higher than in original ores in existing or new mines. However, the cost of recovery and refining these minerals from end-of-life products can be several times higher than virgin minerals, even though energy requirements and environmental footprints are usually lower for recycled products than for mining products (Espinoza et al., 2020).

Complex and diluted waste streams call for elaborated processes, for which techniques and energy use can be more similar to the mining of tailings. Landfills concentrate a wide range of waste. Non-active landfills can represent a source of critical minerals, although there is very little data specific to the composition and amount of different materials in landfills, particularly in countries in which landfilling constitutes the primary method of waste disposal and treatment. Due to a range of products, such as electronic waste, being disposed of in landfills instead of being properly sent for recycling, the concentration of critical materials in landfills can be higher than in some mined ores (Mathieux et al., 2017). However, there are major challenges to providing a substantial amount of critical materials from landfills at a profitable cost (Särkkä et al., 2013).

Expanding urban mining and recycling and refining value chains is an important factor to reduce the vulnerability of the highly geographically concentrated critical mineral supply. By building infrastructure to collect, recover and refine critical minerals in end-of-life products, the supply of minerals for the low-carbon transition and other technologies will become more resilient.

The challenge of mineral recovery from steel alloys

Alloying metals provide different properties depending on the demands of the final product, such as resistance to corrosion, conductivity or lightweight. The recovery of these alloys in the recycling of steel scrap is not straightforward. The most common recovery of these metals depends on a proper sorting and recycling of steel aiming to generate steel with as close composition as needed. Improving sorting can lead to lower losses of alloying metals, reduce the need to dilute the recycled steel from undesired elements, and to reduce the pressure on primary production of alloying elements (Nakamura et al., 2017). The most common alloying metals for steel for wind turbines are chromium, nickel, molybdenum and manganese (Carrara et al., 2020). Nickel and manganese use for other applications is expected to grow significantly doe to the foreseen growth of EVs. Although recovering nickel and manganese from alloyed steel for battery applications might not be optimal, increasing recovery of these metals in steel recycling can reduce the demand for primary nickel and manganese for steel production.

The importance of the battery recycling industry

The growth of the global recycling industry for batteries is fundamental in the sustainable and resilient supply of minerals for the electrification of transport. The potential for supplying secondary materials in the short term is limited, but an efficient recycling system could greatly reduce the reliance on raw mineral extraction and decrease supply vulnerabilities in the medium and long term (Baars et al., 2021; Zeng et al., 2022). As shown in this report, the expected volume of minerals in end-of-life batteries will increase exponentially in the coming decades.

Thus far, the battery recycling industry has been driven by the recovery of highest valuable minerals. The main focus on recycling of LIBs has been on the recovery of cobalt, due to the amount of cobalt in today's battery cathodes, as well as the high value of recycled cobalt. With larger battery packs, recycling has also aimed to recover other high-value minerals such as nickel, copper and aluminium (Ambrose & Kendall, 2020a). Without further incentives, the growth of chemistries that are low in cobalt and cobalt-free, and of LFP batteries in the market can pose a challenge for the economic profitability of recycling of batteries with materials of lower economic value (IEA, 2022b).

Current lithium recycling rates are lower than 1%. The largest opportunity for recovering lithium is from spent lithium-ion batteries (Swain, 2017). The recovery of lithium from spent LIBs can be an energy-intensive and costly process, compared to the impacts of extraction and refining of primary minerals. However, even if preliminary studies find no significant reduction in the carbon footprint of recovered lithium compared to primary extraction (Ambrose & Kendall, 2020a), recycling can minimise a myriad of other environmental impacts associated with mining expansion. The main challenge for lithium recovery from spent batteries remains the high cost of recycling, compared to primary lithium. In a resource-constrained future, increasing recycling rates for lithium are essential to ensure a responsible sourcing of minerals.

Current recycling rates for end-of-life LIBs are less than 5%, mainly due to the complex and costly processes of recycling, safety concerns, and to the abundance and costs of primary materials (Pinegar & Smith, 2019). Another barrier for the growth of the LIB recycling industry is a lack of viable collection mechanisms for spent batteries, lack of environmental regulations for recycling, and uncertainties regarding potential cost reductions relating to the scaling-up of recycling techniques (Mayyas et al., 2019).

There is a need for policy and regulatory directions to push for the growth of battery recycling. An example is the proposed European Commission Battery Directive, which includes targets for recycled content on EV battery production, incentivising industries to close their material loop, by both recycling production scrap and end-of-life batteries. Besides advances in recycling techniques and reducing recycling costs, major requirements are the implementation of an extended producer responsibility and improved collection, sorting and separation infrastructure for spent LIBs, and that batteries are designed to be easily disassembled and recycled (Bridge & Faigen, 2022).

Advancements in recycling of permanent magnets

There is currently no large-scale commercially available recycling of end-of-life permanent magnets, although there are many ongoing technological developments (Fujita et al., 2022; Schulze & Buchert, 2016). As permanent magnets in wind turbines and EVs reach the end of their operational life, the availability of secondary REE will increase. Currently, there is no secondary dysprosium production, very low recycling rates for neodymium, and around 6% recycling of praseodymium from other products.

Current recycling of neodymium and dysprosium is concentrated on magnet-containing electronic products, such as hard disk drives, speakers and smartphones. Recovering REE from these small devices poses both an economic and technical challenge due to factors such as low concentrations and the presence of complex alloys, as well as difficulty in disassembly and processing, making it a labour-intensive process. This results in extremely low recycling rates of REE from post-consumer waste, mostly concentrated in China and Southeast Asia (Espinoza et al., 2020). The large-scale supply of rare earths from large permanent magnets in wind turbines and EVs can provide a basis for a higher flow of REE into the recycling industry and allow for the development and scaling up of new techniques with higher efficiency. Promising techniques are being developed that have low environmental impacts and can provide an efficient flow of REE that is compatible with the quality requirements for the production of new permanent magnets to be used for new low-carbon technologies (Prodius et al., 2020).

6. Responsible and resilient supply of minerals for the energy transition

The most prominently discussed bottlenecks related to minerals for the green transition are mine production capacity and reserves of critical minerals. In this section, we discuss the supply side of critical minerals. First, we discuss the availability of minerals, considering current production, reserves and resources. We also discuss the vulnerability of mineral supply due to the geographical concentration of production and reserves. We then discuss the role of responsible mining in the supply of critical minerals.

Production, resources and reserves

Different indicators are available for analysing primary production:

- First, the actual **mining** operations of ore extraction.
- **Resources** represent deposits of minerals that are currently or potentially feasible, and deposits predicted based on preliminary geological surveys. Some of the resources are not considered economically competitive for extraction in current conditions due to factors such as grade, quality or extraction methods, but technological advancements and resource prices can transform a potentially profitable resource into a reserve status.
- **Reserves** are those resources that have been assessed to be economically profitable to mine.
- Finally, the **refining** stage converts ore into metal products and into the purity grade and active materials to be used in low-carbon technologies (for example, battery-grade minerals, permanent magnets and stainless steel).

The mining of the minerals covered in this report is concentrated in a few countries, and reserves are also concentrated. Figure 19 shows the main producers and reserves of primary minerals in 2021 (U.S. Geological Survey, 2022). The geographical concentration of mining is unlikely to change in the near future, as the current planning of new mines indicates little scope for diversification. The development of new mines, from exploration, planning, licensing, construction until production, takes many years. New lithium mines can take between four and seven years to become operational, and over 15 years for copper, between 13 and 19 years for nickel (IEA, 2021c), and between 10 to 20 years for REE (Jowitt, 2022). Known reserves and resources have grown in recent decades, as growth in demand and technological advancements drive more exploration, and higher mineral prices makes it feasible to explore areas that were previously not considered to be commercially viable.

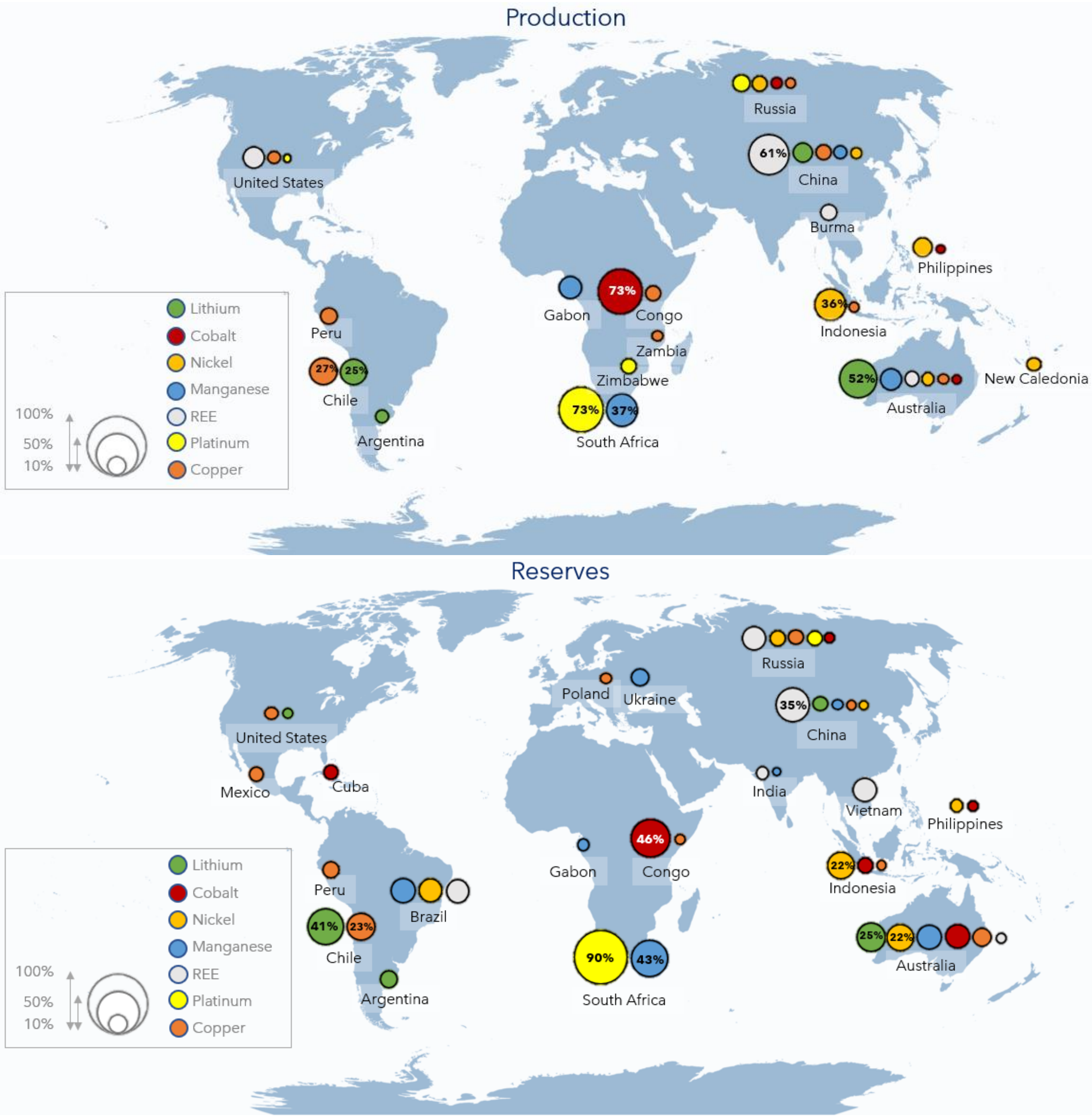

Figure 19 Main primary producers (mining, at the top) and reserves (at the bottom) of lithium, cobalt, nickel, manganese, rare earth elements, platinum and copper in 2021. Producers and reserves above 20% of total supply/reserves are marked. The total covered by these countries: lithium 97% (production) and 87% (reserves), cobalt 84% (p) and 85% (r), nickel 76% (p) and 77% (r), manganese 78% (p) and 99% (r), REE 93% (p) and 95% (r), platinum 94% (p) and 97% (r) and copper 76% (p) and 74% (r). Data from the U.S. Geological Survey (2022)

In 2021, around 100,000 tonnes of **lithium** ore were mined, a 20% increase from 2020, mostly concentrated in Australia, Chile and, on a lower scale, in China and Argentina. Lithium is produced from two different sources: brine salt lakes and spodumene ores. Extracting lithium from brines is achieved by pumping up lithium-rich water from underwater reservoirs into large open pools in which the water evaporates, leaving lithium carbonate and other by-products for further processing. Most of the global lithium reserves are located in brine lakes in the lithium triangle, an area in the Andes bordering Argentina, Bolivia and Chile, with Chile being the single largest producer of lithium from brines. The growing lithium demand in recent years has led to growth in the production of lithium from spodumene, with Australia emerging as the largest producer of lithium (IEA, 2021c; Kelly et al., 2021). Reserves of lithium amount to around 22 million tonnes, with resources reaching around 89 million tonnes. Due to the growing market, exploration for new resources and reserves has increased considerably in recent years and is expected to continue increasing. Estimated reserves and resources have grown by 57% and 44%, respectively, between 2019 and 2022.

Cobalt mining reached 170,000 tonnes of ore in 2021, an increase of 20% compared to 2020. Nearly two-thirds of cobalt mining is concentrated in the Democratic Republic of Congo (DRC), bringing high vulnerability for the primary supply and prices of cobalt. With the exception of production in Morocco (around 1.5% of the supply), and artisanal mines in the DRC, most cobalt is mined as a by-product of copper or nickel. In addition to the impacts on the environment and on nearby communities common to mining industries, cobalt mining has received much publicity due to the poor working conditions and reports of child labour in the cobalt mines in the DRC, making issues such as transparency in supply chains and material substitution highly relevant. These issues are more prevalent in artisanal mines, which account for 10–30% of total cobalt mining in the DRC (World Economic Forum, 2020). Reserves of cobalt amount to around 7.6 million tonnes and are more geographically dispersed than current production. Cobalt resources stand at around 25 million tonnes, the vast majority of which are located in copper or nickel deposits.

Most **nickel** mining occurs in Southeast Asia and the Pacific, with Indonesia, the Philippines and New Caledonia accounting for over 55% of nickel ore supply, and Russia for a further 10%. Mine production in 2021 amounted to 2.7 million tonnes of ore. Nickel is a carrier mineral, meaning it is mainly mined for its own purpose, and its mining typically generates other mineral products from the same deposits, such as PGMs, cobalt, copper and iron (Mistry et al., 2016). There are two types of primary nickel products: class-1 high-purity nickel (>99.8%) and class-2 low-purity nickel (<99.8%). Nickel used in batteries is class-1 high-purity nickel. The total demand for nickel is likely to be covered by current production and mining expansion trends. Nickel reserves amount to over 95 million tonnes and identified resources contain at least 300 million tonnes. Reports about current reserves and resources grew steadily in the 20th century, indicating that nickel availability is unlikely to pose any challenge for the low-carbon transition. However, class-1 nickel products could have a risk of shortages or price volatility.

Manganese mine production in 2021 amounted to 20 million tonnes, with South Africa, Gabon and Australia accounting for more than 70% of total manganese primary production. The reserves are vast, in the order of 1500 million tonnes, over 40% of which is concentrated in South Africa. Most of the manganese is used in the metallurgical industry, in connection with steel production. Non-metallurgical demand for manganese is increasing, but even with high electrification scenarios, it is not expected to significantly impact the overall manganese demand or become a mineral bottleneck for the energy transition (Olivetti et al., 2017).

Rare earth elements are relatively abundant, but their occurrence in concentrations that are feasible for mining are scarce. REE comprise 17 elements, of which the most relevant for the energy transition are dysprosium and neodymium, and in lower demand, praseodymium and terbium. Until recently, China accounted for virtually all rare earth mining: in 2010, China supplied 95% of all mined REE. The geographical diversification of mining increased after the Chinese reduction of export quotas in 2010 that resulted in shortages and price hikes for REE in the international market (Shen et al., 2020). Although still responsible for most global production, only 60% of rare earths were mined in China in

2021. Total primary production of rare earths was 280,000 tonnes in 2021, with the United States, Myanmar and Australia providing around one third of total primary production. Reserves for REE are estimated to be 120 million tonnes. Different REE are contained in the same ore deposit, with varying composition, and often found together with radioactive elements such as thorium and uranium. Since multiple REE occur in the same deposit, the high increase in the supply of neodymium and dysprosium to meet the demand for low-carbon technologies can result in the oversupply of other REE, and challenges in planning for the long-term expansion of new mines (Jowitt, 2022).

Platinum mining is highly concentrated in South Africa, which amounts to 73% of global production. Mine production in 2021 amounted to 180 tonnes. Reserves of PGMs are estimated to be 70,000 tonnes, and resources amount to over 100,000 tonnes. Most reserves and resources are also concentrated in South Africa. In addition to the high geographical concentration of mines, global mine production is also dominated by only a few companies (European Commission, 2020), making the supply of primary platinum and other PGMs vulnerable to disruptions. The primary use of platinum is in catalysts for diesel vehicles, and the decrease in the production of new diesel vehicles in a low-carbon transition will result in a reduction in the annual demand for platinum for current uses.

Copper is one of the most mined minerals in the world. Primary copper production reached 21 million tonnes in 2021, with Chile and Peru accounting for over one third of the global supply of mined copper ore. Reserves are estimated to amount to 880 million tonnes, and resources are estimated to amount to over 2 billion tonnes. The challenge in copper refining is in the declining ore grade, which increases the energy demand and cost of extraction. Copper mined in the late 19th century had around a 10–20% metal content, decreasing to 2–3% in the first half of the 20th century. Today, copper ore grades have declined to below 1%, and as low as 0.4% (Henckens & Worrell, 2020). The challenge for future copper ore mining is more about energy and water demand and related CO_2 emissions than about mineral availability (Kerr, 2014), and emissions associated with the primary production of copper could see a three-fold increase by 2050 (Kuipers et al., 2018).

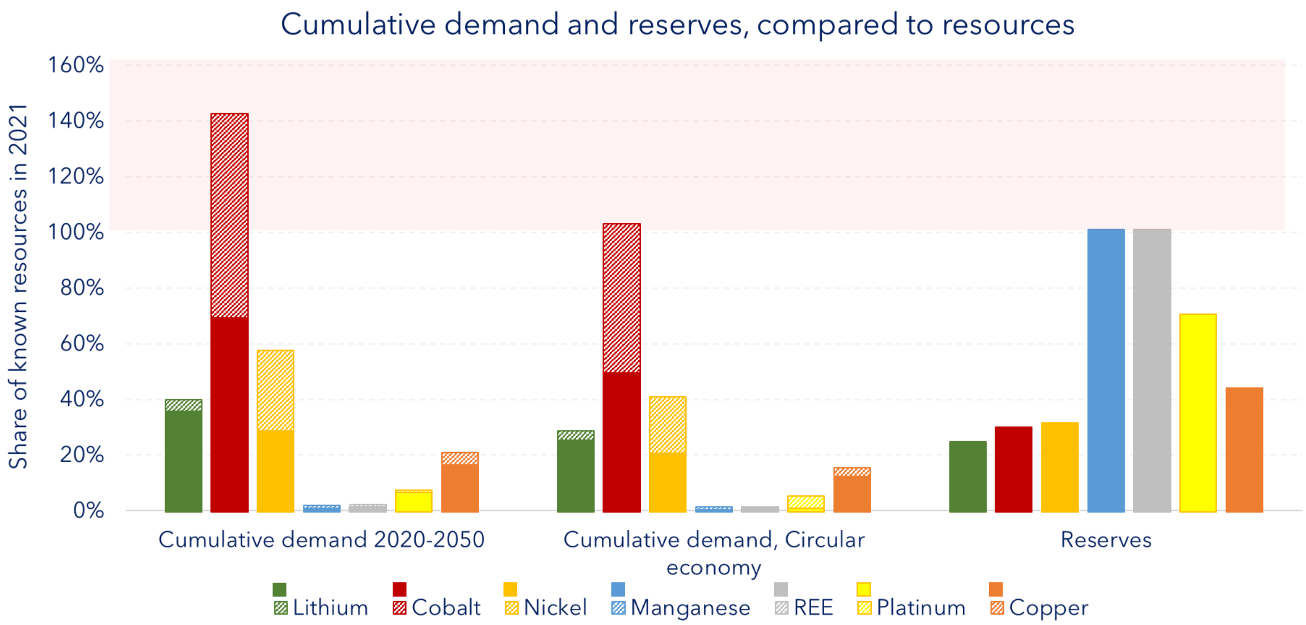

Figure 20 Cumulative demand between 2020 and 2050 with and without circular economy strategies, and reserves of lithium, cobalt, nickel, manganese, rare earth elements, platinum and copper, as a proportion of total known resources. 100% constitutes all known resources in 2021. For manganese and REE, the US Geological Survey does not report known resources, only reserves. The solid bars represent minimum demand and the shaded bars represent maximum demand. Cumulative demand varies with technology scenarios

It is not the availability of resources that is the main challenge regarding mineral availability for the green transition, but rather the steep increase in demand allied to the limited production and refining capacity. Figure 20 compares cumulative demand between 2020 and 2050 in the technology scenarios with and without circular economy strategies, with the known reserves and resources. When comparing demand with the known reserves, at first glance, demand for lithium, nickel and particularly cobalt becomes an issue. For cobalt, the upper ranges of mineral demand correspond to the use of current technology – but low-cobalt and cobalt-free batteries are in rapid development and will likely enjoy a more significant share of battery market in the coming decades. However, a comparison of cumulative demand with known reserves and resources does not provide a complete picture of the future availability of minerals:

- Known reserves and resources have grown in recent decades and are likely to grow in the next three decades as the demand for these minerals increases, new technologies for exploration develop, and mineral prices increase, opening new economically feasible reserves for exploration. The last 25 years have seen a ten-fold increase in lithium reserves and a seven-fold increase in resources, while cobalt, nickel and copper resources and reserves have more than doubled.
- The comparison of demand and reserves ignores the role of recycling to reduce the demand for mining. As shown in the previous section, the availability of end-of-life minerals to be recycled can reduce the demand for mining, particularly by the second half of the period covered in the scenario and beyond. Also, many of these minerals are contained in stocks of other products not covered in this report, such as retired electricity networks, electric and electronic products, traditional fossil fuel technologies, among others and, with the exception of lithium and REE, a recycling infrastructure is already in place, with recycling rates above 50% for end-of-life products. Thus, improving the collection and recycling rates of different products in the coming years is essential for achieving a responsible mineral supply.

Responsible mining is needed for the green transition

As shown in the previous sections, the coming decades will rely on the primary extraction of minerals for the transition to a net-zero energy system. Although we do not deny the need to expand mineral extraction for achieving the climate goals, this will result in many negative social and environmental impacts, often far removed from the final users of these minerals. Mineral supply for a green transition must be responsible: we cannot ensure one sustainability goal – reduce climate impacts – at the cost of other planetary boundaries and decreasing quality of life and livelihood options for local communities.

The impacts of mining are significant. Using current technology, the area needed to provide all the future demand for minerals for the energy transition will be substantial. For example, it takes 250 tonnes of lithium ore from mined spodumene or 750 tonnes of mined ore from brines to produce one tonne of battery-grade lithium (G. Harper et al., 2019). Declining ore quality means that more land and more energy will be needed to extract the required minerals. Responsible mining is a concept that aims to provide an equitable distribution of the benefits of mineral extraction, while minimising the negative impacts on communities and the environment, and respecting and protecting the interests of all stakeholders (Arvanitidis et al., 2017). This includes responsibly dealing with the landscape and the environment, with local communities, and with local and national governments.

Responsible mining also involves using the best available practices and technologies and ensuring that mineral supply is conducted in a less harmful way. The current pathway for mineral extraction is not responsible, and we must act to change course towards a less harmful mineral supply (Bilham, 2021), which mainly involves increasing material efficiency and decreasing the impacts of mining. Material efficiency not only applies to product manufacturing, but also to mineral supply in the extraction and processing of ores and in the recovery of resources from mine waste streams, including tailings.

The Initiative for Responsible Mining Assurance

The Initiative for Responsible Mining Assurance (IRMA) is an organisation that provides verification and certification for a more socially and environmentally responsible mining.

The IRMA Standard for Responsible Mining is a standard developed through a multi-stakeholder process that covers 26 chapters on business integrity, social responsibility, environmental responsibility, and planning for positive legacies. The standard reflects the best practices on the mining industry, including human rights due diligence, mining in conflict-affected areas, resettlement and cultural heritage, revenue and payments transparency, security, labour rights and worker health and safety, tailings management, and biodiversity management.

Many large vehicle manufacturers have committed to this initiative to ensure that the minerals in their value chains are sourced responsibly, such as BMW, Ford, General Motors, Mercedes-Benz, Volkswagen and Tesla.

Increasing mineral supply without opening new mines

Metal ore mining amounts to approximately 4.5 million tonnes per year. However, the actual metal content of these ores is only around 18% of the total material mined, and the remaining 3.7 million tonnes are tailings and process slag that are usually discarded (Haas et al., 2015). Other estimates put globally generated mining and metallurgical waste above 15 gigatons per year (Lèbre et al., 2017).

Extractive wastes are generated during the prospecting, extraction, treatment and storage of mineral resources from quarries. It includes wastes from mineral excavation, such as overburden and waste rocks; waste from mineral processing and treatment, such as tailings and waste gravel, sand and clays; and drilling wastes. These waste streams still contain some of the minerals extracted, besides other minerals which are present in the same ore but not targeted for extraction. Different critical minerals such as cobalt and PGMs can be recovered as by-products from the processing of minerals such as copper and nickel, and mining waste can provide a source of critical mineral supply. Reprocessing of mine waste, although classified as a primary extraction activity, also contributes to a more circular economy by looping large waste streams back to the production process.

In Australia, the government organisation Geoscience Australia, together with the University of Queensland, RMIT University, and the Geological Survey of Queensland, have started a contribution to launch the "Atlas of Australian Mine Waste", which aims to map mine waste sites across the country and identify the potential for mineral extraction (Geoscience Australia, 2022). Ongoing research is being conducted on the technical and economic feasibility of cobalt mining in copper tailings in the country (Queensland Government, 2021) that could provide better management of mining waste, a new source of revenue, and a more responsible supply of critical minerals without the need to open new mines. In Ireland, the BRAVO (Bauxite Residue and Aluminium Valorisation Operations) project was set up to recover critical minerals such as REE from bauxite residues (red mud) (Mathieux et al., 2017).

The feasibility of the recovery of critical minerals from mine waste is dependent on the minerals extracted, waste volume accumulated, market demand and material prices. Moreover, using tailings for the active recovery of minerals can alleviate environmental and cost pressure on the treatment and storage of mining waste. Mine tailings from old mines have a higher potential as mining technologies in the past were not as efficient as today. Thus, material concentration on such tailings can be higher, even surpassing concentrations on some primary sources (Edraki et al., 2014). However, the recovery of minerals in mining waste still faces many technical challenges, as energy consumption for material separation increases exponentially as the concentration of the target mineral declines. Minerals that are present in significantly low concentrations or in complex form are difficult and expensive to recover (Blengini et al., 2019). Ongoing research is developing new technologies for increasing the viability of such operations, such as bioleaching – the process of extracting minerals by using living organisms – which is a promising technique due to its relatively low cost and low environmental impact (Sarker et al., 2022). More public and private investments in the next decade could make the recovery of minerals from tailings a potential new source of critical minerals for the green transition.

In addition, the changes in prices and the development of mining technologies can result in closed mines being re-opened. Rising copper demand and new technologies have led to projects for re-opening old copper mines, such as the copper mine that is planned to be re-opened in the coming years in Kiruna (Northern Sweden)[4].

The importance of the refining and downstream supply chain of minerals for the energy transition

An additional issue beyond the total availability of mineral reserves and the location of production is the capacity and location of refining industries. This is true for the refining of ore into metal, but particularly for the refining and production of the high-purity minerals that are needed for low-carbon technologies. For example, minerals such as nickel, cobalt and manganese are produced and recycled globally. However, to be used in the production of battery cathodes, the minerals must be refined to a high-purity chemical form, and this stage of production in the battery value chain is currently concentrated in a limited number of locations. For lithium, cobalt, nickel and REE, China is the main producer of high-purity minerals. This particularly applies to battery-grade materials, for which China is responsible for 60–80% of production (Bridge & Faigen, 2022), and to permanent magnets, for which China is responsible for over 90% of the NdFeB magnet production chain (European Commission, 2020). Investments and diversification in the downstream supply chain of mined materials – from refining until their application to low-carbon technologies and further to the recycling industries – will be fundamental for reducing supply risks and increasing resilience in the supply of minerals for the energy transition.

[4] See for example (Copperstone Resources, 2021)

The deep-sea mining frontier is highly uncertain

Scientific research estimates that there are considerable amounts of critical minerals on the seabed, spread around the globe, and mainly concentrated in three differentiated sediment structures: polymetallic nodules, massive sulphides and cobalt-rich crusts. The concentrations of the minerals under study vary in quantity, purity and concentrations on each of the three main natural structures in or on the seabed, and the estimates on mineral availability are highly uncertain and the potential exploitable recovered resources from the seabed face extreme uncertainty when compared to land-based mining reserves.

Polymetallic nodules contain manganese, nickel, copper, cobalt, molybdenum and REE. A particular characteristic of these nodules is that mineral formation occurs at a very low rate of a few centimetres per million years (Miller et al., 2018). Massive sulphides, located in hydrothermal vents along oceanic ridges are rich in copper, zinc, lead, barium and silver. Finally, cobalt-rich crusts contain a mixture of manganese, iron, cobalt, copper, nickel and platinum. These seabed formations are host to large variations of microbial organisms that constitute the base of the food web.

The feasibility of deep-sea mining requires the evaluation of several dimensions, each associated with high risk: environmental impacts (emissions, pollution, threat to species and marine ecosystems), economic impacts from negatively affected ocean users such as fisheries, tourism and other sectors, economic viability (costs, income structure, tax system, property rights in the sea), legal and governance structures, (national and international), technical challenges relating to the exploitation (remotely operated vehicles, extreme conditions such as pressure, extraction process), and climate impact due to carbon release from the sediment and the reduction of CO_2 absorption, to name a few.

The deep sea is the largest habitat on the planet, it stores the most carbon, and is the least studied so far. It is estimated that over 90% of the existing species in the bottom of the ocean have not been identified or described, and it is uncertain how deep sea mining will affect those species and their role in the ecosystem (Paulus, 2021). The role of the deep sea on ecosystem services such as carbon sequestration and fisheries production on pelagic species that live further up the water column, and the role of the cycle of elements such as carbon and nitrogen in the ocean, are also uncertain (Amon et al., 2022; Miller et al., 2018). Polymetallic nodules have been shown to be key structures in the support of a high diversity of species and play a critical role in the food-web integrity in the deep-sea (Stratmann et al., 2021), and the high impacts and slow recovery of simulated mining activities in 1989 in the Peru basin seabed shows that ecosystem functions can suffer irreversible losses from mining activities (Simon-Lledó et al., 2019).

The large knowledge gaps of many different aspects of the deep sea and any potential impacts of deep-sea mining upon its functions and species will take many years to fill, making deep-sea mining an undesirable alternative to alleviate minerals bottleneck for the green transition (European Investment Bank, 2022; The Ocean Panel, 2020; UNEP, 2022). Investing in responsible use and supply of minerals is needed, but it should focus on reducing the environmental footprints of terrestrial mining, increasing recycling rates, and supporting the transition towards a circular economy.

7. Conclusion

Concerns have been raised over whether we will be able to provide the minerals required for the low-carbon technologies needed for the green shift. By examining how different technology pathways could change critical minerals requirements, and how different strategies for circular economy can further reduce the minerals demand, this report shows that there is *not one solution* to the question of mineral availability. Instead, a successful transition will maximise emission reductions while simultaneously minimising the impacts of mining expansion on communities and the environment.

The current resource extraction and consumption system relies on the paradigm of a linear economy, a structure of "take, make and waste" which is reflected on the extraction of high-quality resources from the natural environment, converted into products with limited lifetime, and then disposed back to the environment as waste, with minimal recovery. In the current system, the option between extraction of virgin resources from nature and the recirculation of materials already in society is viewed as a purely economic decision, with little concerns regarding externalities and how these decisions affect people and ecosystems on the other side of the planet.

This report approached the issue of availability of seven critical minerals for the green transition: lithium, cobalt, nickel, manganese, rare earth elements, platinum and copper. These are among the most discussed in studies on mineral bottleneck for new energy technologies and for which demand is expected to grow many-fold. New mining sources, including from deep-sea mining, are being discussed by industries and policy-makers as a solution to the mineral bottleneck for the green transition. However, a green transition must promote not just the technological solutions, but strategies to promote responsible use and sourcing of minerals.

Whether critical minerals will pose a challenge to a low-carbon future depends on which path is taken. This report approached this issue from three fronts. First, how technological development and different technological choices can alleviate material demand. Second, how different circular economy strategies can contribute to reduce mineral demand. And third, how improving collection and recycling can replace a significant volume of mineral extraction in the medium and long term.

The role of technological innovation in reducing mineral demand

Technological choices will have a major influence on the demand for minerals. In this report, a scenario with high technological innovation and substitution will reduce the total demand for these minerals by 30% between 2022 and 2050. This includes the early adoption and upscaling of new technologies with lower demand for critical minerals that are either available or under development. The use of different chemistries for electric vehicle batteries and moving away from lithium-ion batteries for grid applications could greatly reduce the total demand for cobalt, nickel, and manganese by half. Similarly, increasing the use of electric traction motors and wind turbine generators with low or no content of permanent magnets with rare earth minerals could cut the total demand of rare earth elements by one third. These technologies are not a futuristic dream. Manufacturers of wind turbines and electric vehicles are investing in reducing the critical mineral content of their products, and an increasing number of research and innovation grants are being distributed for developing and upscaling prototypes of low-carbon technologies with lower reliance on these minerals.

There are many uncertainties on the technology trajectory in the next decades. Technological advances can happen rapidly and bring significant changes for the use of resources. If state-of-the-art technology available 10 or 15 years ago was taken as the basis for the quantification of future material demand, the picture could be very different from the one presented here. The previous decades have seen major game-changing developments on low-carbon technologies brought by advances not only in energy technologies, but in a range of fields such as computation, information technology, digitalisation, and space technology, making it possible to envision a technically possible pathway towards a net-zero emissions energy system. And there is no question that technology will continue advancing towards higher energy and material efficiency.

Innovation, resource constraints, social and environmental standards, price fluctuation for critical minerals, and policies and regulations will determine whether we take a path with high or lower demand for critical minerals. However, a future with technology choices that will reduce the demand for these minerals is possible.

Circular economy strategies will contribute to a more responsible use of minerals

The solutions which can enable a green transition are not only technological. The transition to a circular economy involves a broad toolbox of strategies to decrease material demand and increase recycling rates. This will not only secure a more resilient supply of critical minerals, but a circular economy of minerals is also needed for making supply and use of resources more sustainable.

This report covered a range of circular economy strategies which can decrease total mineral demand by further 18% between 2022 and 2030. The strategies included here can be grouped into three broad circular economy approaches: reduced demand, lifetime extension, and recycling.

Reduction in demand for new infrastructure will decrease the minerals needed for new additions such as power plants and vehicles. By investing in urban planning, public transport, ridesharing, safety considerations for pedestrians and cyclists, and by reducing the need for commuting long distances to work, there will be a reduction in private vehicles ownership, reducing the demand for minerals for electric vehicles. In addition, a higher material efficiency in industry and society can be achieved through a shift in consumption patterns of industries and households towards re-use, repurposing of waste streams as raw material, and the elimination of unnecessary production processes such as single-use products with short lifespan. In the context of a low-carbon energy system, by removing these inefficient processes, there will be a reduction in the demand for energy, including electricity, leading to a decrease in the amount of wind turbines and solar panels needed in the coming decades.

Lifetime extension will keep the extracted minerals in society for longer, reducing the time needed for replacement of infrastructure and components. It comprises a range of different strategies. The urban planning strategies that reduce car ownership will also increase the lifespan of vehicles in use, taking longer for these vehicles to be scrapped and replaced by new ones. Extending the lifetime of electric vehicles batteries by giving them a second life as applications in residential, commercial, or industrial storage will reduce the need to produce new stationary batteries. And investing in lifetime extension for power plants through maintenance, mid-life investments, refurbishing and repowering, and replacing components will delay the need for their replacement.

Recycling can replace extracted minerals in the long term

Increasing recycling rates is a key aspect of a circular economy. When reaching the end-of-life, the minerals contained in products and infrastructure can be recovered and cycled back into production, decreasing the need for expansion of mineral extraction from nature. However, collection and recycling rates are far from high, and need to be improved. All minerals which are not recovered are lost to landfills or incineration, and unable to be retrieved at a later time. Improving collection and recycling rates for minerals in end-of-life low-carbon technologies can decrease the need for mineral extraction from mines by 20% between 2022 and 2050, and increase the resilience in the supply of critical minerals.

However, there are significant challenges to overcome for increasing a more circular loop for critical minerals. First and more important is the implementation of design for dismantling and recycling in technologies and products, making it feasible to disassemble and separate the desired materials in a technically and economically feasible way. A second challenge is the investment into the upscaling of recycling techniques that provide minerals at a high level of purity compatible to uses in high-performance applications at lower costs and energy requirements compared to the extraction and processing of primary minerals. Investments in research and development and in pushing towards large-scale applications and commercialisation must be set as a priority for increasing the use of recycled critical minerals. Finally, circular business models and value chains must cover all stages of production, use, and recycling of minerals. There must be collaboration among actors in the entire technology value chains: from design and manufacturing, including logistics of collection and transport, the recycling industries, and finally, a market for the recycled minerals.

A responsible supply of minerals is needed

Technological innovation and circular economy measures from both demand and supply side are vital for reducing the need for mineral extraction and associated impacts. Total mineral demand can be halved by 2050, and recycling can supply about 20% of this remaining demand. By mid-century, most of the annual mineral needs for the green transition will be able to be supplied by recycled minerals. However, as much as demand can be reduced by adopting technologies with lower minerals intensity and implementing circular economy strategies, there will be the need for increasing mineral extraction and refining, particularly in the coming decades.

Investing in responsible use and supply of minerals is crucial. The supply of minerals for the green transition must be achieved not by expanding the mining frontier to new landscapes and ecosystems. Priority must be reducing the demand for minerals through circular economy strategies, increasing the recycling of minerals from urban mining and end-of-life products and infrastructure, and reducing harmful impacts of terrestrial mining.

An effective transition to a circular paradigm will enable a society which is characterised by use of few resources without being characterized by scarcity. Humanity's need for energy and transport will be satisfied without the environmental costs that we have currently learned to live with, and without the worry that the resources we rely on will someday run out. We will need primary extraction in the next decades, but how much depends on which technologies we choose to invest in, which policies we choose to support, and which environmental costs we choose to tolerate.

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Annex

List of acronyms

AT	Advanced technology (scenario)
BAU	Business-as-usual (scenario)
BC	Battery constraints (scenario)
BEVs	Battery electric vehicles
CCUS	Carbon capture, use, and storage
CT	Current technology (scenario)
EEE	Electric and electronic equipment
EOL	End-of-life
EVs	Electric vehicles
FCEVs	Fuel cell electric vehicles
GHG	Greenhouse gas
IEA	International Energy Agency
LIB	Lithium-ion battery
LFP	Lithium-iron-phosphate
LNMO	Lithium-nickel-manganese oxide
MW	Megawatt
NiMH	Nickel-metal hydride
NCA	Nickel-cobalt-aluminium
NCM	Nickel-cobalt-manganese
NdFeB	Neodymium-iron-boron
GW	Gigawatt
PEM	Proton exchange membrane
PHEVs	Plug-in hybrid electric vehicles
PGMs	Platinum-group metals
PV	Photovoltaic
REE	Rare earth elements
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxide fuel cell
SSBs	Solid-state batteries

Detailed methods

The results on the report "The Future is Circular: Circular Economy and Critical Minerals for the Green Transition" were calculated through a simplified dynamic stock modelling (Wiedenhofer et al., 2019) of the demand of minerals for renewable energy systems.

Dynamic stock models are models that account for both stocks and flows of materials in the economy. Stocks quantify those materials that are locked in, for example, infrastructure, that will be used to provide services over an amount of time, usually years to decades. The materials locked in stocks are not available for use or recycling until they reach the end-of-life. When referring to infrastructure, such as power plants and roads, these stocks also provide a lock-in into inefficient or carbon-intensive systems, which delay the transition to a low-carbon society (Bertram et al., 2015). Flows of materials are those materials entering the stock (for example, new power plants being installed in a certain year) or reaching the end-of-life and leaving the stock, after which they can be dismantled, collected and, if possible, recycled to be used in new products and infrastructure. Dynamic stock models are a type of stock-flows model that allow the study of the long-term development of material demand and stocks linked to specific technologies. These models are based on annual modelling of stocks and flows, and take into account drivers of material demand, lifetime of infrastructure, and replacement of stocks over time.

The model

This model combines a technology scenario, using the International Energy Agency's report *Net Zero by 2050* (IEA, 2021a) as a base, to assess the demand of key minerals for the low-carbon energy transition: lithium, cobalt, nickel, manganese, platinum, copper, and two rare earth metals (dysprosium and neodymium). Using assumptions on current lifetime of technologies, data on existing stocks, and year these stocks entered the market, we built a model to assess stocks and flows of technologies and materials projected year-by-year until 2050. The model gives information on the demand of materials every year to increase the installed capacity of low-carbon technologies, as well as the demand for materials to replace the retiring components and infrastructure, and the volume of materials available to be used as secondary materials after end-of-life recycling of these energy infrastructure. Different scenarios were developed to estimate the effect on material demand of the upscaling of different new technologies in the next decades, as well as the effects of the intensification of different circular economy strategies.

The starting point for the model is the input of installed capacity of energy technologies for each year in the time series. The time series, in this report, corresponds to 2020-2050 following the scenario built in the *Net Zero by 2050* scenario. This scenario accounts for low-carbon technologies growth required to meet the annual demand for energy based on different parameters such as: population and economic growth in different countries, improved energy efficiency, transition towards a highly reduced fossil fuel consumption energy system, new technologies such as hydrogen and new batteries entering the market in commercial scale, as well as accounts for some policies for reduced vehicle and airplane trips and some circular economy measures. The installed capacity in the *Net Zero by 2050* scenario corresponds to total capacity installed in each year. The additional capacity which serves as inputs for the model corresponds to the difference of installed capacity between years, plus the replacement of retiring capacity each year.

The inputs from the *Net Zero by 2050* scenario comes in installed capacity for each broad technology group: wind onshore, wind offshore, solar photovoltaics (PV), concentrated solar power (CSP), hydropower, electrolysers and fuel cells, among others. The *Net Zero by 2050* scenario also provides an estimate of electric vehicles (EVs) on the road by 2050, with a split between plug-in hybrid (PHEVs), battery (BEVs) and fuel cell (FCEVs) vehicles; installed capacity of stationary batteries; and other infrastructure such as transmission and distribution lines and EV charging stations, which we do not model here. For measuring the impact that different technology advancements have on overall stocks, flows, and associated material demand, we apply assumptions for the distribution of sub-technologies in the market share of all new installed capacity. Example of sub-technologies are different generators for wind turbines, rooftop or large-scale solar farms for PV, and different chemistries for stationary and EV batteries. These market shares are defined for each year, as factors such as technology development, costs, and trends determine changes in annual market share. For historical data (2000-2021), these annual market shares have been estimated based on statistics and literature. For the period between 2022-2050, these annual market shares represent different scenarios, which have been estimated based on literature review, expert opinions[5], and economic theory of technology diffusion. Diffusion curves are extensively used in technology development (Rogers, 2003), and dependent on the technology readiness level (TRL) of each technology.

Each sub-technology installed has a specific material composition for each of the relevant minerals. These material compositions are fixed over time. The source for material intensity (e.g. kg of lithium per vehicle, or tons of copper per MW of installed power capacity) and lifetimes of sub-technologies are summarized in the next section.

The summary of sources for the sub-technology scenarios are summarized in table A.1. It is important to note here that the amount of materials calculated correspond to the technology-grade material in the technology itself. For example, this step calculates the demand for battery-grade cobalt for cathode production for EV.

Table A.1. Summary of sub-technologies and sources used to estimate annual market shares

Technology	**Sub-technologies**	**Sources used to estimate annual market shares in sub-technology scenarios**
Solar PV	Rooftop, silicon Rooftop, thin-film Utility-scale	Historical market share based on: Martinez-Duart, J., Hernandez-Moro, J., & Antonio, R.-F. (2013). Energy and Sustainability highlights, 2013. *Current Trends in Energy and Sustainability.*, 43–53. IRENA. (2022). *Renewable Energy Statistics 2022: Renewable Capacity*. The International Renewable Energy Agency. Future market share scenarios based on technology diffusion curves and expert opinions.
Wind onshore and offshore	Doubly-Fed Induction (DFIG), gearbox Permanent Magnet Synchronous (PMSG), gearbox Permanent Magnet Synchronous (PMSG), direct drive	Historical market share based on: Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.*

[5] Expert opinions based on conversations with professionals and researchers on technology development of different energy technologies.

	Electrically Excited Synchronous (EESG), direct drive (Onshore only) Squirrel Cage Induction Generator (SCIG), gearbox (Offshore only) High-Temperatre Superconductor (HTS), direct drive (Offshore only) Others	Future market share scenarios based on technology diffusion curves, expert opinions, and global technology scenarios in Carrara et al (2020).
Electric vehicles batteries	Lithium-iron-phosphate (LFP) Nickel-cobalt-aluminium (NCA) Nickel-cobalt-manganese (NCM) in the following chemistries: 111, 523, 622, 622-Graphite(Si), 811-Graphite(Si), 955-Graphite(Si) Solid-state batteries on the following chemistries: Lithium-sulphur and Lithium-air	Historical and future market share scenarios based on: Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., & Steubing, B. (2020). Future material demand for automotive lithium-based batteries. *Communications Materials*, *1*(1). https://doi.org/10.1038/s43246-020-00095-x
Stationary batteries	Lead-acid Sodium-based Nickel-cadmium Zinc-air Flow Lithium-ion batteries in the same chemistries as EV	Current market shares based on: U.S. Department of Energy. (2022). *DOE Global Energy Storage Database*. https://sandia.gov/ess-ssl/gesdb/public/statistics.html Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., & Steubing, B. (2020). Future material demand for automotive lithium-based batteries. *Communications Materials*, *1*(1). https://doi.org/10.1038/s43246-020-00095-x (for lithium-ion batteries) Future market share scenarios based on expert opinions and a mix of literature review, including the *Net Zero by 2050* scenario and Xu et al (2020).
Electrolysers and Fuel cells	Alkaline Proton-exchange membrane cells (PEM) Solid-Oxide cells (SOEC, SOFC)	Current and future market shares based on expert opinions and a mix of literature review.

The lifetimes, in years, of all technologies and sub-technologies are recorded on the year they are installed. These lifetimes are different for different components which are relevant for the materials in this report. For example, cables, inverters, foundations, and wind turbines have different lifetimes, and some of these components must be replaced before the power plant reaches the end of time. Likewise, some of these components can be re-used in the case of lifetime extensions, repowering, or refurbishing of existing power plants.

The retiring capacity for each year corresponds to the amount of the sub-technologies and components in the stock reaching the end of life. These retiring technologies do not have the same composition as the market share of installed capacity in each year, but they come with a lag of years to decades after being installed. This means that we can compare the material composition being installed each year, and the materials reaching the end-of-life and being able to be collected and recycled in the same year.

The material leaving stocks can then be collected for treatment such as incineration, landfilling, refurbishment, repurposing, or recycling. However, not all material gets collected. Here, collection rates indicate the share of materials that get sent to treatment. This collection rate is never 100% due to a diversity of factors: dissipative losses, where the material transforms into a form that is not available to be recovered, for example due to losses to the environment, infrastructure such as subsea cables being left after decommissioning of power plants, and hoarded and abandoned products and infrastructure that do not reach waste flows such as vehicles, infrastructure for transmission and distribution of electricity, and household electronics. Here, we apply collection rates to the end-of-life materials based on technology and components (for example, in a decommissioned offshore wind farm. the totality of wind turbines are collected, but not all the subsea cables) when available.

The amount of materials that go to treatment and become recycled material to be used as inputs to production depend on the recycling rate. This recycling rate combines two activities: share of collected materials that go to recycling and share of materials recovered in recycling. Regarding the first, the amount of materials that go to recycling plants, reflects differences in recycling rates across the globe, as well as the fact that even in places with high recycling rates and policies, different components cannot be easily disassembled due to design choices or due to material characteristics (e.g. alloys), and are destined to different treatment options (landfilling, incineration, or get destroyed in the recovery of other materials). Second, the recovery rate of the material depends on different recycling technologies. For example, different recycling techniques allow for the recovery of 48% up to 99% of platinum from spent automotive catalysts (Yakoumis et al., 2021).

The materials leaving the stock which cannot be turned into secondary materials are assumed to be material losses and are not able to be recovered for a circular economy. There are material losses from end-of-life products and infrastructure due to materials not being collected, not being sent to recycling, and the losses from the recycling techniques. The material losses occurring in the production of the primary material (mining, refining, and manufacturing) are outside the model boundaries.

Data sources

The data for material intensity of different specific technologies, and the lifetime of infrastructure and main components[6] are taken from the following sources:

[6] We only considered components relevant for the minerals in this report

Solar PV:

Frischknecht, R., Stolz, P., Krebs, L., de Wilde-Scholten, M., & Sinha, P. (2020). *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*. https://iea-pvps.org/wp-content/uploads/2020/12/IEA-PVPS-LCI-report-2020.pdf

Concentrated solar power:

Gasa, G., Lopez-Roman, A., Prieto, C., & Cabeza, L. F. (2021). Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with and without Thermal Energy Storage (TES). *Sustainability*, *13*(7), 1–20. https://doi.org/10.3390/su13073672

Wind onshore and offshore:

Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020). Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. In Jrc:119941. https://doi.org/10.2760/160859

Gielen, D., & Lyons, M. (2022). Critical materials for the energy transition: Rare earth elements. In *IRENA - International Renewable Energy Agency, Abu Dhabi*.

Lloberas-Valls, J., Benveniste Perez, G., & Gomis-Bellmunt, O. (2015). Life-Cycle Assessment Comparison between 15-MW Second-Generation High temperature Superconductor and Permanent-Magnet Direct-Drive Synchronous Generators for Offshore Wind Energy Applications. *IEEE Transactions on Applied Superconductivity*, *25*(6). https://doi.org/10.1109/TASC.2015.2493121

Electric vehicles:

Blagoeva, D. T., Alves Dias, P., Marmier, A., & Pavel, C. C. (2016). Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030. https://doi.org/10.2790/08169

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Stationary batteries:

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