IRENA
International Renewable Energy Agency

# CRITICAL MATERIALS FOR THE ENERGY TRANSITION

---

TECHNICAL PAPER 5/2021
BY DOLF GIELEN

**© IRENA 2021**

Unless otherwise stated, material in this publication may be freely used, shared, copied, reproduced, printed and/or stored, provided that appropriate acknowledgement is given of the author(s) as the source and IRENA as the copyright holder. Material in this publication attributed to third parties may be subject to separate terms of use and restrictions, and appropriate permissions from these third parties may need to be secured before any use of such material.

ISBN 978-92-9260-366-3

**Citation:** Gielen, D. (2021), *Critical minerals for the energy transition*, International Renewable Energy Agency, Abu Dhabi.

## About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

## Acknowledgements

I would like to thank Carlo Papa (Enel Foundation), Hans De Keulenaer (International Copper Association), and Efstathios Peteves, Evangelos Tzimas and Samuel Carrara (European Commission Joint Research Centre) for their valuable expert input and information leads. All conclusions, errors and shortcomings in this technical brief are the sole responsibility of the author.

For further information or to provide feedback: **publications@irena.org**

## Disclaimer

The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of IRENA. This publication does not represent IRENA's official position or views on any topic.

The Technical Papers series are produced as a contribution to technical discussions and to disseminate new findings on relevant topics. Such publications may be subject to comparatively limited peer review. They are written by individual authors and should be cited and described accordingly.

The findings, interpretations and conclusions expressed herein are those of the author(s) and do not necessarily reflect the opinions of IRENA or all its Members. IRENA does not assume responsibility for the content of this work or guarantee the accuracy of the data included herein.

Neither IRENA nor any of its officials, agents, data or other third-party content providers provides a warranty of any kind, either expressed or implied, and they accept no responsibility or liability for any consequence of use of the publication or material herein. The mention of specific companies, projects or products does not imply that they are endorsed or recommended, either by IRENA or the author(s). The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA or the author(s) concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

# TABLE OF CONTENTS

# FIGURES

# TABLES

# BOXES

# ABBREVIATIONS

| | |
|---|---|
| **Al** | aluminium |
| **Ag** | silver |
| **Cd** | cadmium |
| **Cu** | copper |
| **DD** | direct drive |
| **DFIG** | double fed induction generator |
| **EESG** | electrically excited synchronous generator |
| **EVs** | electric vehicles |
| **Ge** | germanium |
| **GB** | gearbox |
| **Gt** | gigatonne |
| **GW** | gigawatt |
| **HDS** | high-demand scenario |
| **In** | indium |
| **ISA** | International Seabed Authority |
| **kg** | kilogram |
| **kt** | kilotonne |
| **kWh** | kilowatt-hour |
| **LCE** | lithium carbonate equivalent |
| **LDS** | low-demand scenario |
| **LFP** | lithium iron phosphate |
| **LMO** | lithium manganese oxide |
| **LNO** | lithium nickel oxide |
| **MDS** | mid-demand scenario |
| **Mono-Si** | monocrystalline silicon |
| **Mt** | megatonne |
| **Multi-Si** | multicrystalline silicon |
| **NCA** | lithium nickel cobalt aluminium oxide |
| **NCM** | lithium nickel cobalt manganese oxide |
| **NCMA** | lithium nickel cobalt manganese aluminium oxide |
| **NdFeB** | Neodymium-iron-boron |
| **NiMH** | nickel metal hybride |
| **PM** | permanente magnet |
| **PMSG** | permanent magnet synchronous generator |
| **PV** | solar photovoltaic |
| **rpm** | revolutions per minute |
| **Te** | tellurium |
| **TWh** | terawatt-hour |
| **US** | United States of America |
| **USGS** | United States Geological Survey |
| **yr** | year |

# EXECUTIVE SUMMARY

## ENERGY TRANSITION SHOULD BE PLANNED WITH CRITICAL MATERIALS IN MIND

- Energy transition in line with the IRENA 1.5°C pathway can raise demand for certain minerals and metals substantially.
- The energy transition should be planned with critical materials in mind to avoid unforeseen delays. This planning relates to both supply and demand aspects. Better public data are needed regarding the capacity to ramp up mining of primary materials in the coming years. Also, the potential of innovation to avoid or minimise use of critical materials needs to be better understood, as do the geopolitical implications and the possible strategies to deal with potential risks.
- Today, global fossil fuel supply and demand is a topic of geopolitical concern. In the future, the attention may shift to the geopolitics of critical materials. The interdependencies will change from the existing ones. Supply risks must be managed properly, and governments will need to keep the long-term geopolitical issues in mind while the private sector deals with the market fluctuations. There is a role for both government and the private sector in finding strategies to reduce risk and minimise emerging critical materials dependencies through innovation.

## CRITICAL MATERIALS SUPPLY WILL NEED TO INCREASE

- Whereas reserves and resources are generally known, it is the "soft" factors – such as acceptance and access for new mining projects or the geopolitical implications of certain supply routes – that need to be better understood for a proper judgement of criticality.
- The necessary resources exist. Therefore, long-term availability is a matter of expanding production volume and ensuring diversity of supply. However, for the period to 2030, supply issues exist for a number of critical materials. One indicator is the rising material prices in recent months. It remains to be seen if these are short-term supply chain issues that will be resolved in the coming years or structural long-term bottlenecks that will impact the direction of the energy transition.
- The supply problem has several distinct aspects: the rate at which mining and processing can expand, the absolute availability of reserves and resources, and the geographical and geopolitical risks related to supply.
- Renewable power generation and electrification of end uses can have a profound impact on the demand for critical materials. The implications of energy efficiency and carbon capture and storage on demand for materials have not been studied in detail.
- Solar photovoltaic (PV) and wind power generation, grid expansion and electromobility (motors and batteries) will be the main drivers of critical materials demand in the energy transition in the coming years.
- The issues and the potential solutions vary by material; generic statements should therefore be treated with caution.

- Whereas demand for critical materials for energy transition applications may grow exponentially, this does not mean that total demand for these materials (for all uses) will also rise exponentially. The share of energy applications in total consumption today varies widely. For many materials, the additional quantities are not that significant compared with total consumption; energy applications constitute, in many cases, only a fraction of total use. Copper and nickel are examples where this is the case.
- Some materials – such as rare earth metals and lithium – have traditionally had no significant uses; therefore, the effect of growth in demand can, in relative terms, be very significant. However, that is by itself not an indicator of potential supply problems in the future.
- Prices of some critical materials have increased substantially in recent months. This is an indication of supply shortfalls and may reflect rising scarcity. However, hoarding and other forms of market behaviour may also play a role.
- Not all changes in demand related to the energy transition are detrimental: for example, demand for platinum will plummet as demand for internal-combustion-powered car exhaust catalysts will fall.

## THERE IS A ROLE FOR GOVERNMENTS, THE PRIVATE SECTOR AND THE RESEARCH COMMUNITY IN DEALING WITH CRITICAL MATERIALS ISSUES

- Although shortfalls can be expected in the coming years, several strategies can be deployed to avoid major supply challenges in the period to 2050. These strategies include increased extraction, product design to avoid or minimise use of critical materials, and recycling of products to recover scarce materials.
- Significant substitution potential exists in new applications but also in some existing applications, and this may help increase materials availability for the energy transition. For example, battery cathode materials can be adjusted to avoid or minimise cobalt use, copper use cabling can be replaced with aluminium, and copper water pipes can be replaced with other materials.
- In all cases, a technical solution exists to avoid critical materials bottlenecks, but this may result in technically reduced performance or in higher cost. This trade-off needs to be understood. New supply sources (*e.g.* subsea metal resources) should be explored further, and the sustainability of such supply routes needs to be better understood.
- Product redesign can, in many cases, reduce the need for strategic materials. For example, wind turbines and electric vehicles can be designed without permanent magnets.
- Recycling can only help to some extent in the short and medium term, as a materials stock build-up is needed in the economy.

## THE CHARACTERISTICS OF SPECIFIC CRITICAL MATERIALS SHOULD BE CONSIDERED

- Copper for electric wiring plays a key role throughout power production, transportation and use. Electricity demand will increase substantially, and this will raise copper demand. Although the copper resource is adequate, the quality of copper ore resources is decreasing.
- Neodymium and dysprosium play a key role in permanent magnets, which are widely used in high-performance electric motors (including electric vehicles) and in generators (wind turbines). The key challenge is that mining and processing of these materials is dominated by one country, whereas supply of other critical materials is more diversified.

- Lithium is a critical component for light-weight batteries for vehicles. As battery use dominates total lithium use, the foreseen rapid growth of battery manufacturing will require a rapid upscaling of lithium production. Electric cars accounted for around 4% of global car sales in 2020; this share may grow five- to tenfold in this decade, and lithium production needs to grow accordingly.

- Cobalt supply is critical for batteries. Demand may double between 2020 and 2030, and vehicle batteries may account for 60% of total cobalt demand in 2030. However battery design innovations can reduce this dependency substantially.

- Nickel demand may increase substantially due to its widespread use in battery cathodes. Already, producers are considering alternative battery chemistries (notably Lithium Iron Phosphate cathodes), but the product performance is inferior. However, such alternatives can reduce the growth in nickel demand substantially.

- Today, around a tenth of all silver is used for solar PV modules. This share may rise further as demand for solar PV grows. To some extent, this can be balanced by more material-efficient cell design.

- Demand for other minerals and metals will grow but seems less critical. Such minerals and metals include aluminium, chromium, graphite, indium, iron, lead, manganese, molybdenum, titanium, vanadium and zinc. For some of these, the resource is abundant; for others, alternatives exist, such as substitution of materials and changes in product design that provide similar technical performance.

- Increased production of minerals and metals will increase the energy and carbon footprint. However, this effect is dwarfed by the emissions reduction that can be achieved when those minerals and metals are deployed in renewable energy technologies. The deployment of renewable energy in mining and processing operations should be considered.

## THE ENERGY TRANSITION SHOULD BE SUSTAINABLE, JUST AND FAIR, INCLUDING IN MINING

Increased mining activities should be sustainable: good working conditions, local economic development, respect for cultural and natural heritage, and net-zero carbon energy use. Mining activities are increasingly subject to lengthy approval processes, and local acceptance is critical for a timely and adequate growth of primary materials supply. If done properly, new materials supply chains can create socio-economic benefits that will increase support for the global energy transition.

An inherent tension exists between markets and government intervention. There is a need to find a balance, with appropriate roles for both. Governments see energy transition as a source of jobs and economic growth, and governments also actively engage in supply of critical materials. A number of initiatives have been set up to deal with the security of critical materials supply at a national scale, yet truly international approaches are lacking. Global markets will always be the sum of the actions of different public and private actors. However, well-functioning markets need transparency.

To enhance understanding of the critical materials challenge, there is a need to properly measure reserves, resources and demand impacts, accounting for innovation and circular economy concepts while continuing to refine understanding of the direction of energy transition. IRENA will continue to deepen its work in this area to support its members with their accelerated energy transformation.

# INTRODUCTION

The world needs an energy transition. This transition will be based on three main pillars: renewable energy supply, electrification of end use and efficient use of energy. It will entail a fundamental shift in power generation, where the share of solar and wind power needs to increase substantially. The IRENA *World Energy Transitions Outlook: 1.5°C Pathway* proposes, globally, a 63% share for solar and wind power by 2050, up from around 10% today. At the same time, the end use sectors (buildings, industry and transport) will need to be electrified. As a result, electricity demand will nearly triple, to more than 70 000 terawatt hours (TWh) in 2050. Electromobility will become the dominant form of road transportation, with around 1.8 billion electric cars needed on the road by 2050, a nearly 200-fold increase from the approximately 10 million electric vehicles (EVs) on the road today (IRENA, 2021a).

Such a transition is daunting. One strand of critique regarding the feasibility of such a transition relates to the availability of the necessary minerals and metals: the future access to those critical materials, the ability to ramp up the materials supply and production fast enough, the rising cost of such materials, and the geopolitical and strategic implications of new resource dependencies (Global Commission, 2019). Some even talk of a possible “cold war” over critical materials (Lee and Bazilian, 2021). Also, some concerns have been raised that the energy return on investment (*i.e.* the energy needed per unit of energy provision) may be on the rise and could become an issue in the energy transition, as it could result in additional carbon dioxide emissions (Fabre, 2019).

Building on the recently released "Materials for the Energy Transition" (Gielen and Papa, 2021), the focus of this paper is on the rapid growth in demand for critical materials not widely used today induced by the energy transition in renewable power generation, electricity grids and electromobility. New clean technologies in these segments are dependent on a number of critical materials, and a rapid transition is foreseen.

Demand for materials may also grow due to other aspects of energy transition. For example, demand for stainless steel may grow for subsea pipelines and other marine applications. Demand for other types of infrastructure and for the built environment may also increase. For example, global demand for steel, cement and copper for the building sector is estimated to reach 769 megatonnes per year (Mt/yr), 11.9 gigatonnes per year (Gt/yr) and 17 Mt/yr, respectively, by 2050. For steel and cement, this represents a respective growth of 31% and 14% compared with present levels (Deetman *et al.*, 2019). Energy transition may augment such growth further, for example if the building renovation rates are tripled as foreseen in the 1.5°C pathway. However, in this paper, such applications have not been considered in further detail.

This paper will assess how the growth of renewables will put critical materials at the centre of the energy transformation, with the objective of highlighting the criticalities related to the sector and of identifying how technological developments and innovation can positively reduce geopolitical risks.

# WHAT ARE CRITICAL MATERIALS?

For a start, there is the question of what determines criticality. Generally, attention has focused on minerals and metals that require a significant extraction effort, where the production is concentrated in a few countries, where the quality of natural resources is declining, where a massive ramp-up of supply will be needed and where prices have shown large fluctuations that reflect supply-demand imbalances.

Certain materials have been used in growing quantities for decades or centuries, and their growing supply does not face constraints. For example, steel and concrete are generally not considered to be critical materials, despite recent concerns regarding sand and gravel availability for concrete in parts of the world. Also, aluminium is not considered to be critical, despite a need for a massive ramp-up of supply: the resource is in place and widely distributed.

A review of recent literature suggests there is little consensus on what materials are critical (DERA, 2021a; European Commission, 2021; Hund *et al.*, 2020; IEA, 2021). But some materials are included in most assessment studies, and those are the focus of this paper:

- cobalt
- copper
- nickel
- lithium
- rare earth metals, notably neodymium and dysprosium.

A much longer list of critical materials is given in one or more of these studies: aluminium, chromium, gallium, germanium, graphite, indium, iron, lanthanum, lead, manganese, molybdenum, platinum, rhenium, ruthenium, scandium, silver, vanadium, tantalum, titanium, yttrium and zinc. For the sake of this paper, they will not be discussed in more detail. But their listing points to the fact that the definition of "critical material" is somewhat fluid and that new developments can change the critical materials list.[1]

Metals dominate the list. This is not surprising, as metals dominate the periodic table of elements. But not all critical materials are metals (*e.g.* graphite). The term "critical materials" refers to the processed output; sometimes the term "minerals" is also used, which refers to the mined commodities. For the sake of this paper, we will use the term "critical materials".

For some of the critical materials, the field of applications is limited. In other cases, the application is rather pervasive. For example, demand for lithium, cobalt and nickel is closely related to demand for lithium-ion batteries. Demand for neodymium and dysprosium is closely related to the use of permanent magnets in electric motors and generators. However, copper is used in all three fields of application: in renewable power generation, in power grids and in electric end use applications such as EVs.

---

[1] Note that copper is currently not on the European Union's list of critical materials. The Copper Alliance uses the term "essential material" in relation to copper. Copper is included in this paper as a critical material as demand for it may be affected significantly.

# SCARCITY INDICATORS: SHORT-TERM AND LONG-TERM ASPECTS

Prices reflect scarcity. But such scarcity may occur on a timescale of months or years. Once prices are high, mining activity increases and supply expands. Once scarcity is resolved, prices tend to fall. Such market dynamics have been reflected in the price in recent years (Daily Metal Prices, 2021):

- In the case of lithium, a price peak of 27 US dollars per kilogramme (USD/kg) occurred at the end of 2017, followed by a rapid decline and a price trough of 6 USD/kg in summer 2020, followed by a recovery to 14 USD/kg in July 2021. Prices rose again quickly in recent months.
- Neodymium has hovered around 60 USD/kg for a long time and climbed to 120 USD/kg in 2021. with a 20% price increase in October.
- Nickel started at 10 USD/kg in 2017 and rose continually to nearly 20 USD/kg in 2021.
- Cobalt started at 30 USD/kg in 2017, reached more than 90 USD/kg in 2018, only to drop back to 30 USD/kg in 2019; it recovered in 2021, reaching more than 50 USD/kg.
- Copper has for a long time hovered at 6-7 USD/kg, only to rise to 10 USD/kg in 2021.

This brief price overview suggests that prices tend to fluctuate and that price increases can be followed by dramatic declines. But it is remarkable that prices have risen markedly for all these metals in recent months and years, and in some cases to levels that have not been seen before. There is clearly a link with rapidly growing demand, which is related to energy transition.

It is unclear what the price dynamics will be going forward. Prices can continue to rise and eventually limit demand growth, or supply can rise fast enough in response to higher prices, so the trend is reversed.

The recent price increases have raised considerable interest from the investor side, and the energy transition naysayers have jumped on the bandwagon as well. The term “greenflation” has been introduced for rising prices of metals and minerals such as copper, aluminium and lithium that are essential to solar and wind power, electric cars and other renewable technologies, and it has been argued that greenflation makes limiting the worst effects of global warming less likely (Sharma, 2021).

Price is one type of criticality indicator; supply diversity is another. The rare earth metals, whose main use is in permanent magnets, are dominated by a single supplier (China). The Chinese government has constrained exports twice (to Japan and the United States), and this is a cause for concern and action among consumer countries, as new electromobility applications are at the core of large economies (Slav, 2021). Efforts are ongoing to diversify the supply. Cobalt is another example, with supply concentrated in the Democratic Republic of the Congo. Supply chains subject to political instability or supply chains with serious environmental and social governance issues will be a cause of supply risk sooner or later. Diversity of supply and emphasis on the local benefits of mining operations reduce the supply risk and can therefore be used as indicators of lesser criticality. However, a particular challenge for energy transition is that the supply of certain critical elements needs to be ramped up fast, so today’s situation may not be a good indicator of the issues going forward.

Longer term, reserve and resource data provide insights regarding availability, and a comparison of potential demand and availability provides insights regarding scarcity. Such comparisons are dynamic, as resources and reserves may increase as exploration and mining technology progresses. Subsea metal nodules or even asteroid mining are examples of breakthrough solutions that may one day affect supply substantially (Box 1).

### **Box 1:** Reserves versus resources

As defined by the Committee for Mineral Reserves International Reporting Standards, "A Mineral Resource is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction. A Mineral Reserve is the economically mineable part of a Measured and/or Indicated Mineral Resource" (CIM, 2014).

Technology can change the quantities of reserves and resources substantially, as well as the permitting. Seabed metal nodules are key resources that have not yet been mined; the prospects are not clear, but such mining could substantially change the supply outlook for several critical materials. The Clarion-Clipperton Zone – which stretches from Mexico to Hawaii and covers more than 4 million square kilometres of seabed – is particularly rich in nodules, with estimates suggesting there is six times more cobalt and three times more nickel there than in the world's entire land-based reserves. To date, more than 20 exploration contracts have been awarded by the International Seabed Authority (ISA), the United Nations body responsible for controlling mining on international waters. The Pacific Island state of Nauru – one of ISA's 167 member states – utilised Article 15 in the 1994 Implementation Agreement of the United Nations Convention on the Law of the Sea. This clause allows a State to request that the ISA complete the regulations allowing for deep-sea mining within two years. The ISA, which has been developing and negotiating these regulations since 2011, will now work towards finalising the regulations by July 2023 (McKie, 2021).

# STRATEGIES TO MITIGATE CRITICAL MATERIALS DEPENDENCIES

Governments have experience with oil and gas supply issues. A lot can be learned from the responses that have been developed in this context. Establishment of stockpiles, supply diversification and producer-consumer dialogue are among the key aspects.

A number of strategies exist to reduce supply risks related to critical materials. These strategies are well known from circular economy concepts and industrial ecology (*e.g.* Gielen, 1999):

- Ramp up supply and ensure a global free market. A market that has sufficient depth without dominant parties on the supply and demand side can prevent disruptions. Diversifying supply thus reduces dependence on one or a few dominant suppliers. However, this is easier said than done. Large-scale mining projects often take years to develop, and a successful outcome is not guaranteed. The interests of national governments that hold resources, the local interests and the project developer's interests often do not coincide, and dialogue is essential to find mutually agreeable solutions.
- Develop national supply. This may come at a certain cost, as such supply may be more expensive due to the resource being of lesser quality or the scale of mining operations being smaller. In a free market, such a solution cannot be forced; it likely requires government intervention in the market and some form of standards and certification, as well as market regulation, to ensure uptake. The experience with global supply chain disruptions caused by COVID-19 has emphasised the vulnerabilities that come with dependency.
- Substitute critical materials with other less critical materials. This strategy has been deployed, for example, in the case of battery cathode design (see the Battery chemistry trends section). Often, there is a trade-off between technical performance and the criticality of materials supply. Equipment suppliers will respond to criticality with adjustments in their product design. However, such adjustments may take time as production lines and supply chains need to be adjusted. A structured inclusion of materials criticality in energy transition decision-making processes can help avoid problems in the future.
- Develop stockpiles and long-term supply contracts for critical materials. Physical stockpiles and contractual arrangements can help prevent sudden disruptions. Enterprises are used to hedge commodity price disruptions. Governments hold strategic oil and gas reserves; they could extend this approach to hold strategic reserves of critical materials. However, such reserves are suited to disruptions on a scale of months; they are not a solution for longer term structural issues. It should also be noted that some countries such as the United States had strategic materials stockpiles in the past.
- Raise the efficiency of materials use. For example, efforts are ongoing to reduce the rare earth element content of permanent magnets through enhancements in the production process. Also, the silver content of solar photovoltaic (PV) has significant room for improvements in materials efficiency. Normally, suppliers will seek such solutions as they also help reduce manufacturing costs, but greater public and private research, design and development efforts can help accelerate such efficiency gains.

- Redesign products. While use of permanent magnets is widespread for wind turbines and electric cars, alternatives exist that avoid the use of permanent magnets altogether. In many cases, such product redesign can be applied. Even in batteries where the use of lithium as the lightest metal seems predetermined, a combination of batteries and ultracapacitors can reduce battery requirements substantially (McFadden, 2020). Solutions continue to evolve, and government research, design and development programmes can help accelerate these solutions.

- Increase recycling of critical materials. This strategy can help reduce demand for primary materials, and important efforts are aimed at the recycling of wind turbines and solar PV panels, as well as batteries (Frangoul, 2021; IRENA, 2016; UCS, 2021). But it must be acknowledged that the build-up of the massive capital stock needed will take time and materials. Recycling will trail energy-transition-generated demand for materials for decades to come. Therefore, significant new mining activity will be needed.

# MATERIAL DEMAND PROJECTIONS AND PROSPECTS

The supply characteristics of critical materials differ markedly. Therefore, each material requires a specific approach to deal with supply issues. Table 1 provides an estimate for current mining volumes of critical materials and the need to ramp up to 2050 in a 1.5°C pathway (see IRENA (2021a) for the characteristics of this pathway). The assessment of demand growth is complex because it depends not only on the demand for energy transition but also on the demand in all other market segments. For example, a large share of copper, as well as bronze, is used for information cables and water pipes. Total growth in demand for copper will therefore also depend on the demand trends for these market segments. Nickel has similar market characteristics, while demand for lithium, cobalt and neodymium is dominated by their use for energy applications.

Recycling and a closed loop economy are receiving a lot of attention as a solution for scarcity. While recycling can play an important role in the long term, and can help reduce accumulation of toxic elements in the natural environment, it can do little to resolve scarcity issues in the short and medium term for two reasons: the long life of the products in which these critical materials are used and the need to accumulate a stock of products in use. Therefore, the energy transition will require a supply of new primary materials in the decades to come, which implies a growth of mining. This is especially the case for new minerals and metals that have not been in wide use before, such as lithium, neodymium and cobalt. The situation is different for copper and nickel, which are already widely deployed and have other fields of application.

The volumes involved also vary widely for different critical materials (Table 1). In 2021, the copper supply and demand is a thousand times larger than the neodymium supply and demand. Given similar prices per unit of weight, this difference in volume indicates the comparative economic importance of different critical materials. Well-established materials with a range of applications in energy and elsewhere, such as copper, will be less impacted in relative terms by the energy transition than materials with very specific energy applications, such

**Table 1:** Current supply and projected 2050 demand for a 1.5°C scenario

| | 2020 [Mt/yr.] | 2050 [Mt/yr] | COMMENT | SOURCE |
|---|---|---|---|---|
| **Copper** | 30[a] | 50-70 | Energy is only part of current demand and future demand growth | Elshkaki *et al.*, 2016; ICSG, 2021a |
| **Nickel** | (2019) 2.54 | 5-8 | Today, mainly used for stainless steel | Elshkaki *et al.*, 2017 |
| **Lithium (LCE)** | (2019) 0.41 | 2-4 | Batteries are the main field of application | Moore and Bullard, 2021 |
| **Cobalt** | 0.14 | 0.5-0.6 | Batteries will be the main field of application in the future | Hund *et al.*, 2020; Tsiropoulos *et al.*, 2018 |
| **Neodymium** | 0.03 | 0.2-0.5 | Permanent magnets will be the main field of application in the future | Barrera, 2021; Alves Dias *et al.*, 2020; Deetman *et al.*, 2018 |

**LCE:** lithium carbonate equivalent.

a. Includes 8.5 Mt recycling and 21.5 Mt primary production from ore.

as lithium and neodymium. However, in absolute terms, the need for increased copper supply will dwarf that of all other critical materials combined.

In relative terms, demand growth is most pronounced for neodymium, followed by lithium and cobalt. The impact on copper demand is less pronounced. The question is whether supply growth can meet the increased demand. To answer this question, it is important to understand the supply characteristics, which differ markedly by material. Therefore these materials will be discussed individually.

## COPPER

Copper can be found in different types of deposit. Porphyry deposits account for about 60% of the world's copper. In these deposits, copper ore minerals are disseminated in igneous intrusions. A second key deposit type is sediment-hosted stratabound copper deposits, in which copper is concentrated in layers in sedimentary rocks. These account for about 20% of the world's identified copper. The remaining 20% are other types of deposits. The mean undiscovered totals for porphyry and sediment-hosted deposits are 3 100 Mt and 400 Mt, respectively, resulting in a global total of 3 500 Mt of copper. Identified copper resources are currently estimated at 2 100 Mt. Therefore, total copper resources (undiscovered plus identified) amount to 5 600 Mt (ICSG, 2015). Given that 21 Mt of primary copper was produced in 2020 (ICSG, 2021a), we will not run out of copper any time soon. However, the development of new mines takes time, and supply shortages might occur in the coming years as demand ramps up quickly. Around 24 Mt refined copper is produced from ore and scrap annually while more than 5 Mt copper scrap are directly melted and reused.

Also, the effort required to extract the remaining copper continues to increase. Copper mines use deposits ranging from 0.4% to around 2% (w/w) copper content (Warren Centre, 2020), with an average of 0.6% copper (Pistilli, 2021). The copper concentration has been declining over time, and therefore the effort needed and the tailings created per tonne of copper have been increasing. Leaching (solvent extraction) has emerged as a new technology for the treatment of low-quality ores and tailings, and it accounts now for 16% of global refined copper production (ICSG, 2021a). The primary copper mining activity creates more than 3 Gt of mine tailings every year. Copper mining is widely spread, with a significant concentration in the Andes and Rocky Mountains, as well as in the African Copper Belt. Chile alone hosts around a quarter of today's world primary production. In 2019, China accounted for less than 10% of world copper mining but for 39% (USGS, 2021) to almost 50% (ICSG, 2021a) of copper smelter production. The country is also the largest market for copper. The geographical concentration on the processing side is therefore more pronounced than on the mining side.

In 2018, around 8.5 Mt of copper scrap was recycled: 4.54 Mt of fabrication scrap and 4.0 Mt of end-of-life scrap. A big gap remains between the 13 Mt of copper that is released from use every year and the 4 Mt that is actually recycled (Copper Alliance, 2020). Higher scrap recovery rates will reduce the need for primary production.

## NICKEL

Nickel ore can be divided into sulphide ore bodies and laterite soils. In the coming years, hydrometallurgical processing of laterites to produce nickel metal and chemicals is forecasted to increasingly gain importance. Currently, about one-third of global nickel supply is from recycling.

The US Geological Survey (USGS) estimates around 89 Mt in nickel reserves (DERA, 2021b). Resources in classical (subsoil) ore deposits are estimated at almost 300 million tons (Mudd and Jowitt, 2014). When it comes to future resources, there are also believed to be additional significant nickel deposits in the sea. Manganese nodules, which are found on the deep-sea floor, contain significant amounts of various metals, including nickel. Recent estimates indicate that there are more than 290 million tons of nickel contained in such deposits (Mistry, 2020).

Globally, more than 2 000 projects are currently being developed with nickel as either the main product or a by-product. Nearly 300 of these projects are currently in operation, in commissioning or in advanced exploration. Approximately 2.54 Mt of nickel was extracted from both underground and open-pit mines in 27 countries on six continents in 2019. The main nickel-producing regions were Southeast Asia and Oceania,

### **Box 2:** Subsea metals mining

There are three types of deep-sea ocean mineral of commercial interest: polymetallic nodules, seafloor massive sulphides and polymetallic crusts.

Polymetallic nodules were the first of the seafloor minerals to be discovered. These nodules are of commercial interest for their high manganese content. Seafloor massive sulphides are formed by undersea volcanos and generally lie in shallower water than manganese nodules. The deposits of copper, zinc, gold and silver are the materials of commercial interest in these areas. Many, if not most, of these potential fields are located in the Pacific Ring of Fire and within coastal states' exclusive economic zones or outer continental shelf. Finally, polymetallic crusts are also found in relatively shallow water within coastal states' exclusive economic zones. These crusts form a hard pavement on the seabed up to 25 centimetres thick. The minerals of commercial interest are cobalt, titanium, platinum and some rare earth minerals (Lipman and Yu, 2019).

Ultramafic-hosted mid-ocean ridges are highest in copper content (SPC, 2013). A set of ten samples in the Bismarck Sea (Papua New Guinea) found up to 10% copper content in these deposits. However, they are also biologically diverse, and mining would destroy the habitat.

Pacific Ocean nodules have the highest average manganese, nickel and copper contents, and Atlantic Ocean nodules have the highest average iron content. The average manganese, nickel and copper contents generally increase toward the equator in both hemispheres. Nickel and copper are concentrated in nodules located at a depth below 2 900 to 3 000 metres. However, the cobalt content of such nodules is generally less than about 0.6% (McKelvey *et al.*, 1983).

Three rarely overlapping types of nodule of possible economic interest can be recognised: (1) nodules containing more than about 1% combined nickel and copper, which only exceptionally contain more than 0.5% cobalt and 35% manganese; (2) nodules containing more than 0.5% cobalt, which rarely contain more than 1% combined nickel and copper and 35% manganese; (3) nodules containing more than 35% manganese, which only exceptionally contain more than 0.5% cobalt, although they average nearly 1.1% combined nickel and copper (McKelvey *et al.*, 1983).

Current economic interest in nodule mining is focused on the Clarion-Clipperton Zone in the northeastern equatorial Pacific Ocean, the largest known area in which nodules average 1.8% or more combined nickel and copper. Several other areas in which nodules are rich in these metals are found in the Pacific and Indian Oceans and may be viewed as targets for exploration. There may be other kinds of metal-rich areas, some of which may have potential economic value (McKelvey *et al.*, 1983).

The United Nations Convention on the Law of the Sea, which established the International Seabed Authority, came into force in 1994. Starting in 2016, the Authority began drafting the Regulations on the Exploitation of Mineral Resources, which must be in place before any commercial mining operations can commence (Bloomberg, 2021; SPC, 2013).

together accounting for more than 62% of global supply in 2019. The single largest producing country was Indonesia. The majority of new mine production until 2025 is expected to come from Australia and Indonesia. Global nickel refined production reached about 2.39 Mt in 2019. By far the most important products were nickel pig iron and nickel metal, together accounting for three-quarters of refined production. Seventy-one per cent of all nickel is used for stainless steel. In 2019, China and Indonesia accounted for half of global refined production. In 2019, global nickel consumption amounted to about 2.4 Mt. Chinese demand was the highest worldwide, followed by Indonesia. Indonesian nickel refining activities were negligible until 2016 but have quickly increased to make the country the second-largest nickel refiner worldwide (DERA, 2021b). Lithium-ion batteries may account for a quarter to a fifth of global nickel demand by 2025 (0.5-0.7 Mt/yr) (DERA, 2021b).

## LITHIUM

Total worldwide lithium production in 2019 was 77 000 tonnes of lithium, or 410 000 tonnes in lithium carbonate equivalent (LCE) (USGS, 2020). BloombergNEF projects the consumption of lithium to range between 1.3 million tonnes and 2.0 million tonnes LCE (240 000-375 000 tonnes lithium) by 2030, a three- to fivefold increase from 2019 levels (BloombergNEF, 2021a). One of the main drivers of this projected increase in lithium demand is its use in EVs (Kelly *et al.*, 2021).

Production of lithium carbonate from brine-based resources accounts for about 40% of world production, and this is supplemented by production from ore-based (spodumene) resources. USGS (2020) indicates lithium reserves of 17 Mt and 80 Mt in lithium resources (inferred, indicated, measured; about 400 Mt LCE), more than half brine based (Argentina, the Plurinational State of Bolivia, and Chile) and the remainder largely spodumene ore based (Australia, Canada, China and the United States). Both types of production are expanding rapidly. As brine production entails significant groundwater drainage, it is unclear to what extent this production can expand in the desert areas in South America, where it is currently practised. New resources continue to be identified, such as a recent announcement in Germany: lithium ore reserves are being developed in Saxony and geothermal resources in the Upper Rhine valley (NS Energy, 2021a, 2021b). In a US context, the Salton Sea in California alone could produce 0.6 Mt of lithium per year – more than today's global production. In this case, geothermal energy could be deployed for evaporation energy (Cantú, 2021).

Seawater also contains lithium. However, at this moment it is not economic to extract lithium from seawater as the concentration is too low.

## COBALT

The principal terrestrial (land-based) types of cobalt deposit, which represent most of world's cobalt mine production, include primary magmatic nickel-cobalt sulphides, primary and secondary stratiform sediment-hosted copper-cobalt sulphides and oxides, and secondary nickel-cobalt laterites. The total terrestrial cobalt resource (reserves plus other resources) plus past production, where available, is calculated to be 25.5 million metric tons. Additional resources of cobalt are known to occur on the modern seafloor in aerially extensive deposits of iron-manganese nodules and iron-manganese crusts (USGS, 2017).

Around 62% of all cobalt was used for lithium-ion batteries in 2020. Today, 98% of cobalt is a by-product of copper and nickel mining (Global Energy Metals, 2021). As demand for cobalt is projected to grow much faster than demand for nickel and copper, more dedicated mining will be needed. Cobalt deposits can be found throughout the world and are most prominent in the African Copper Belt, with over 60% of global cobalt production from a single country: the Democratic Republic of the Congo (Global Energy Metals, 2021).

## NEODYMIUM

The name “rare earth” refers to a group of rare earth elements, also called rare earth metals and rare earth oxides. This group of 17 chemical elements[2] is moderately abundant in the Earth’s crust and has unique properties. The 40 largest exploration projects indicate over 3 000 Mt of inferred resources (at various grades) in more than 15 countries, and 11 mines were in operation in 2017 (USCRS, 2020).

Rare earth metal production was on the rise again in 2020, jumping to 240 kilotonnes (kt) worldwide. The principal economic sources of rare earth elements are minerals and clays. These resources contain different types of rare earth metals, and these are co-produced. Neodymium is typically 10-18% of the rare earth content of commercial deposits of the light rare earth minerals bastnäsite and monazite. Although the main mining areas are in China, others are found in Australia, Brazil, India, Sri Lanka and the United States. Global reserves of neodymium are estimated at about 8 million tonnes, making it the second most abundant rare earth element after cerium. So the resource is adequate, but short- and medium-term growth in supply may pose a challenge.

According to the USGS, Greenland holds the largest reserves of undeveloped rare earth deposits, particularly neodymium. This offers the prospect of supply growth. However such mining is controversial. One of the geopolitical issues has been that mining and processing is dominated by China. Supply security for rare earth metals is high on the agenda of countries that plan to expand EV use (see the Geopolitical aspects section). However, developing mines and processing capacity outside of China has so far been hampered by economics, environmental concerns and the occurrence of radioactive uranium and thorium by-products in many deposits.

Rare earths, notably neodymium and dysprosium, are widely used for permanent magnets in electric generators (*e.g.* wind turbines) and in electric motors (for EVs). A megawatt of wind turbine capacity may require around 500 kg of permanent magnets (notably, for offshore turbines); a typical EV requires around 3 kg of magnets. Globally, these applications could require around 150 kt of annual permanent magnet production by 2030 and generate around 50 kt of demand for rare earth elements.[3]

Neodymium-iron-boron (NdFeB) magnets, because of their high energy products, lend themselves to compact designs that result in innovative applications and lower manufacturing costs. In commercial sintered NdFeB magnets, neodymium is usually partially substituted by other rare earth elements including praseodymium, dysprosium and terbium (Advanced Magnets, 2021). Because neodymium and praseodymium usually co-exist in ore and these two elements have similar physical and chemical properties, it is more economic to produce praseodymium-neodymium alloy instead of pure neodymium metal from ore and to use this alloy as the raw material of the magnet. In general, the total rare earth element content is around 30 wt% in the magnet, and its material cost accounts for around 70% of the total magnet cost or even more (Advanced Magnets, 2021).

The dysprosium supply is even more constrained than the neodymium supply. For neodymium magnets to perform at elevated temperatures, significant amounts of dysprosium are added (up to 12 wt%). However, in terms of relative abundance in the Earth’s crust, dysprosium constitutes less than 1% of all rare earth elements (Constantinides and De Leon, 2011). As a consequence, the dysprosium supply cannot expand fast enough to meet the growing demand for high-temperature neodymium magnets for EVs. Therefore, alternative additives need to be found.

---

[2] Seventeen elements are commonly considered to be rare earth metals, 15 within the lanthanoid group of elements, as well as yttrium and scandium. Rare earth metals are often discussed or categorised as light rare earth elements or heavy rare earth elements. The light rare earth elements are lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium and gadolinium. The heavy rare earth elements are terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium (USCRS, 2020).

[3] Assuming 35 million EVs and 3 kg magnets per EV, plus 100 GW wind turbines with permanent magnets (50% market share) at 0.5 kt magnets per gigawatt.

Rare earth permanent magnet applications accounted for 29% of total demand in 2020, the largest single end use. By 2030, rare earth magnet applications are forecast to account for approximately 40% of total demand, raising the potential for a tight supply-demand balance for key magnetic rare earth elements (Alves Dias *et al.*, 2020; Barrera, 2021).

## CRITICALITY CHARACTERISTICS VARY AND THEREFORE SOLUTIONS VARY

This section has shown that critical materials are diverse. Copper mining dwarfs mining of the other critical materials discussed. But the development of new mines is challenging. In some cases, mining and processing is concentrated in a few countries (*e.g.* for cobalt, nickel, and rare earth elements), which raises geopolitical concerns. Lithium resources seem more widely spread, but a massive ramp-up will be needed over a short period to satisfy demand for batteries.

It is beyond this paper to discuss the resources, mineral deposits and mining aspects in more detail. However, this brief discussion shows that the issues that need to be tackled are different for different critical materials. In principle, the resources are in place to support the energy transition. But as demand for certain critical materials is projected to increase substantially, there is a need to ramp up mining substantially, which may take time. In the meantime, imbalances between supply and demand can result in strong price fluctuations, and the concentration of resources, mining and processing in certain countries can create new geopolitical risks.

# HOW WILL INNOVATION AFFECT DEMAND FOR CRITICAL MATERIALS?

The following discussion will focus on five specific applications:

- batteries for EVs
- permanent magnets for wind turbines
- solar PV technology trends
- permanent magnets for EVs
- electricity grids.

The analysis will show that:

- Demand for critical materials will increase substantially as demand increases for new products that are needed for energy transition.
- Material efficiency and technical innovation are promising for alleviating shortages in critical materials supply in the long term. However, the existing global supply structure for critical materials, along with the intensifying geopolitical and environmental constraints, could inhibit a rapid energy transition in the short and medium term (Li *et al.*, 2020).
- Innovation based on materials substitution and product redesign can change materials requirements substantially, and in many cases, we already know what alternatives are available on the market today.
- Engineering performance results, in many cases, in preference for critical materials deployment. Substitution yields, in certain cases, a lower performance, but this may be acceptable.
- Equipment manufacturers do generally not design their products with potential future scarcity in mind. However, they respond to price increases.

## BATTERY CHEMISTRY TRENDS

Electric cars require batteries. The battery capacity requirement is largely determined by the car weight and the drive range. Battery needs also depend on the energy efficiency of the vehicle (notably, the capability of recuperative braking energy). Today's electric cars show a wide range of electricity use, from 100 watt-hours per kilometre to nearly 300 watt-hours per kilometre (Electric Vehicle Database, 2021). This affects the drive range for a given battery size.

The car battery weight is a function of the battery storage capacity and the weight per unit of battery. Today's cars require 7-10 kg of battery per kilowatt-hour (kWh), with an outlook of less than 5 kg in the near future

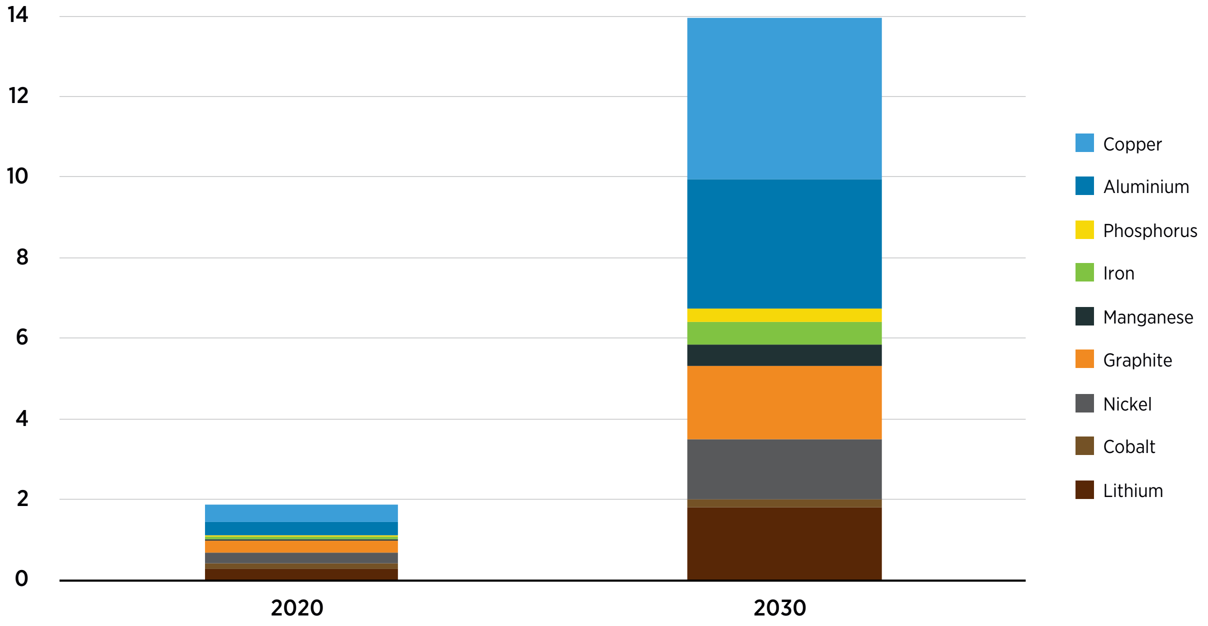
(Lima, 2020).[4] Assuming 5 kg/kWh and 100 million electric car sales (today's car market volume), a 50 kWh battery on average yields 25 Mt of batteries needed per year. Commercial vehicles (delivery trucks, buses, heavy duty trucks, etc.) must be added. This is a significant volume and one of the main challenges for energy transition in terms of need for critical materials. To put it otherwise, every car requires 250 kg of battery materials.

The smallest element of a battery is a cell. The cell consists of a cathode, an anode, electrolyte in between and a casing (typically aluminium). To safely and efficiently manage the countless battery cells mounted in one EV, the cells are installed in modules and packs. Simply put, cells, modules and packs are units of gathered batteries. A cluster of cells makes up a module, and a cluster of modules makes up a pack. A pack includes a battery management system and a cooling device, which control and manage the batteries' temperature, voltage, and so on. A separate charging device may be needed (Samsung SDI, 2021).

The BloombergNEF estimate of demand for battery materials is shown in Figure 1, amounting to 14 Mt by 2030, a sevenfold increase from the demand level in 2020 (BloombergNEF, 2021a). The figure shows the important role of copper, aluminium and graphite in the battery materials mix, while most attention is focused on lithium, cobalt and nickel, which make up about a fifth of the battery weight. While the growth numbers in the figure are impressive, certain metals such as copper, aluminium, iron, manganese and nickel have a wide range of applications. So, while battery demand for these metals may grow substantially, this does not mean that mining needs to grow at the same rate.

The battery chemistry is somewhat flexible, most notably the cathode chemistry (Figure 2 provides a typical breakdown). The share of nickel, manganese and cobalt in the cathode can go from 333 to 811 (respectively, one-third weight shares each, or 80% nickel, 10% manganese and 10% cobalt). The cathode represents the bulk of the weight in the cell.

**Figure 1:** Projections of demand for battery materials



**Adapted from:** BloombergNEF, 2021a.

---

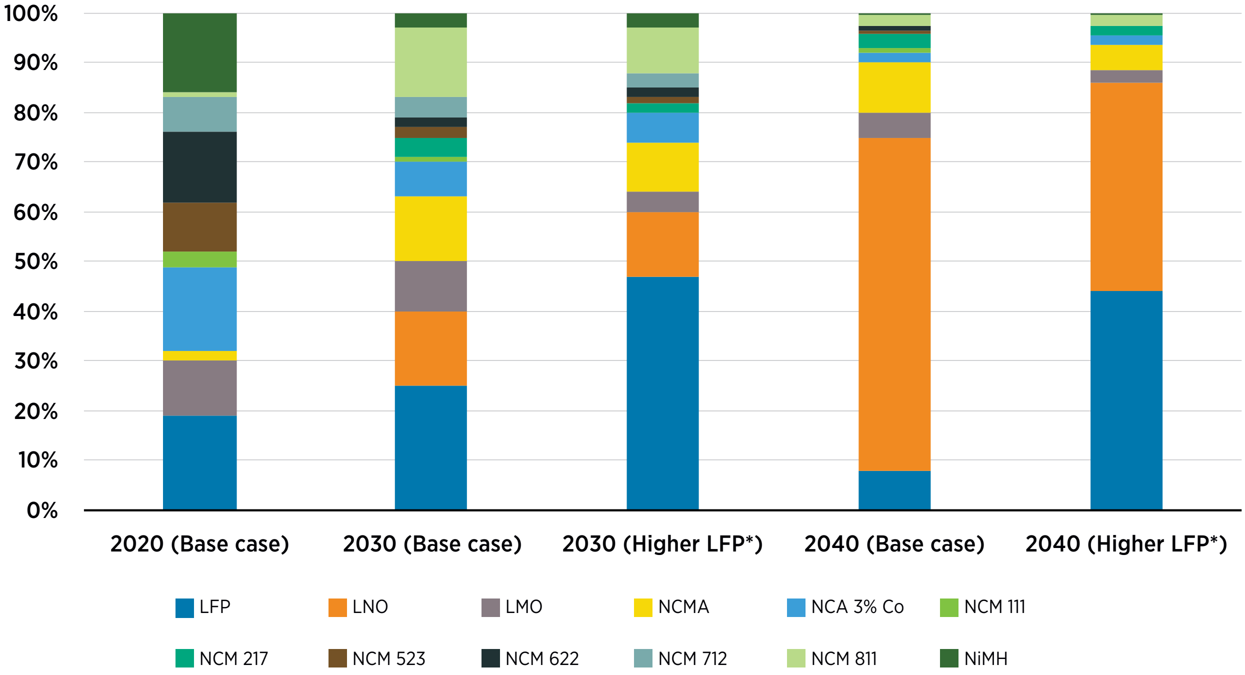
[4] Today's battery cells reach 4 kg/kWh (Masias *et al.*, 2021); lab-scale cells with a solid lithium anode and a new type of electrolyte reach 2 kg/kWh (Wu *et al.*, 2021).

Car makers could switch to lithium iron phosphate (LFP) chemistry, which would reduce the performance of some EVs, particularly their range. But this would avoid the use of critical materials. In an LFP scenario, LFP's share of stationary storage deployments in 2030 jumps from 23% to 53%, while the share of highest nickel chemistries would decline (Mining Review Africa, 2021). Other scenarios indicate up to a 45% LFP share (Figure 2). Finally, there is a possibility of solid-state batteries that use solid lithium as the anode, thus avoiding graphite and nearly doubling energy intensity and eliminating the need for cooling, which reduces demand for copper and aluminium. However, the prospects for such solid-state batteries are still unclear.

Average battery prices are expected to further decline, inching closer to the coveted tipping point of 100 USD/kWh. This puts pressure on battery suppliers and car manufacturers to increase performance and reduce material needs in order to reduce production cost. At present, cathode metals make up 30-45% of the overall battery material costs, depending on the type of composition under consideration. The need for longer-range EVs and the decoupling of battery costs from the ever-volatile cobalt prices have already prompted manufacturers to increasingly shift toward higher-nickel compositions. This is also a driver for LFP cathode use (already widely deployed in China), thus reducing demand for nickel and cobalt (Figure 2).

The most common anode material is graphite. It constitutes the largest input of raw materials (Figure 3). Two types of graphite are used in lithium-ion batteries: naturally mined flake graphite processed into spheres, and synthetic graphite produced from petroleum coke and tar pitch at very high temperatures (Timofeeva, 2018). New research suggests that one way to reduce battery costs and increase energy storage capacity may be to use silicon nanoparticles instead of graphite in lithium-ion anodes. Various other approaches are being tried; it remains to be seen which one will succeed. While it is likely that graphite alternatives will emerge, the timing is unclear.

**Figure 2:** Cathode material scenarios, 2020-2040

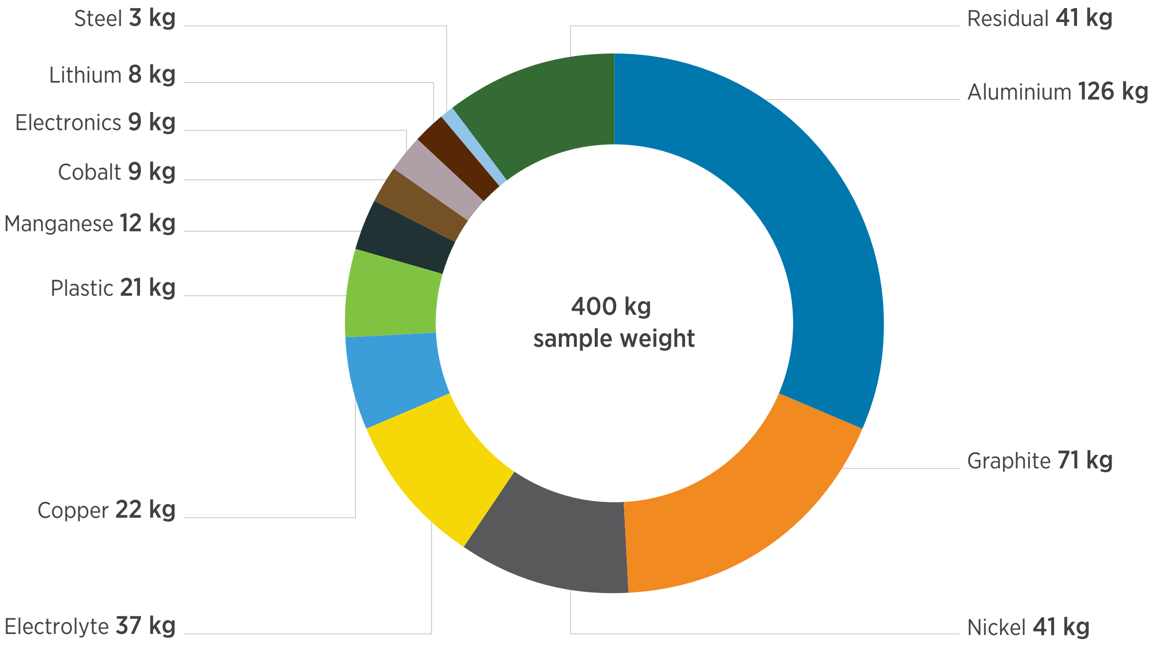


LFP: lithium iron phosphate ($LiFePO_4/C$); LMO: lithium manganese oxide ($LiMn_2O_4$); LNO: lithium nickel oxide ($LiNiO_2$); NCA: lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$); NCM: lithium nickel cobalt manganese oxide ($LiNiCoMnO_2$); NCMA: lithium nickel cobalt manganese aluminium oxide; NiMH: nickel metal hydride.

* In China and EU27.

**Adapted from:** Willuhn, 2021.

**Figure 3:** Typical car battery pack composition



**Adapted from:** Volkswagen, 2021.

Typically, 1 kWh of energy storage requires 0.28 kg of lithium metal equivalent, only about 2-3% of the battery weight. Almost a third of the weight of a lithium-ion battery is made up of aluminium (casing); the weight of the graphite anode accounts for around another 18%. The cathode weight (nickel, cobalt and manganese) is also significant, at around 15% (Figure 3). Cathode metals alone weigh 1.25-2.33 kg/kWh, depending on the battery chemistry (BloombergNEF, 2021b).

Chinese companies have developed lithium-boron batteries with an LFP cathode based on low-cost abundant materials. This reduces the cost from 140-160 USD/kWh to 85 USD/kWh. The battery is also safer due to the materials composition (Sanderson, 2021). The only drawback is that the weight per unit of energy of the cell material doubles, so the range decreases. Still, for city vehicles this may be acceptable. There is a possibility of improving LFP battery chemistry, for example through the addition of silicon to the graphite anode (Jaroni *et al., 2019*).

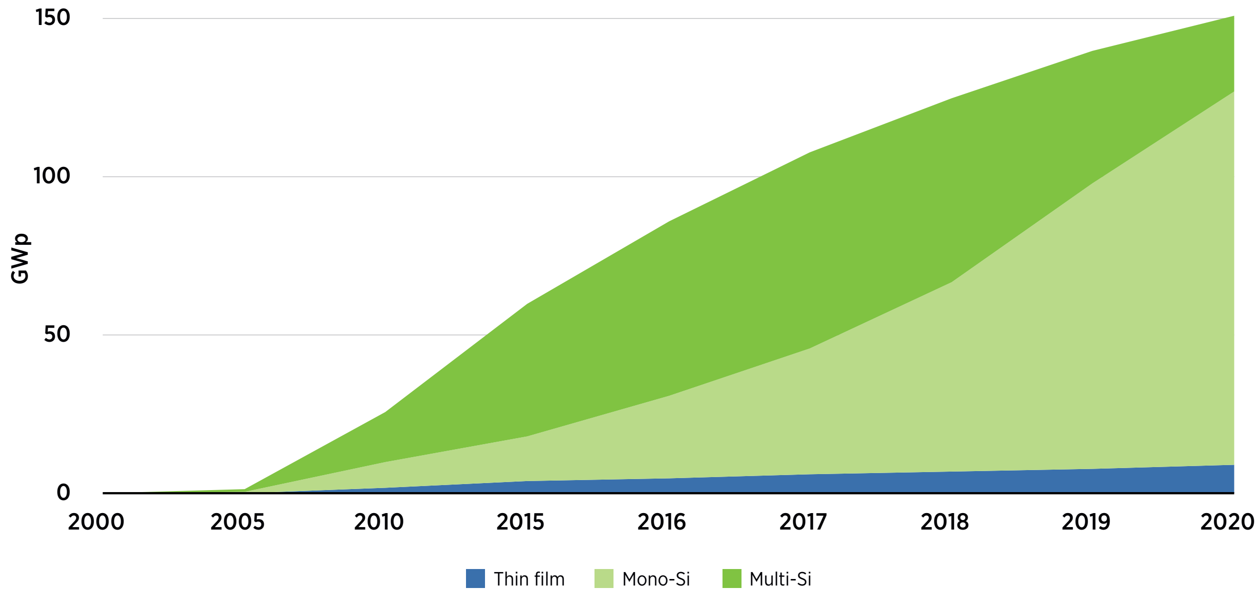
The Chinese company BYD has developed the so-called blade LFP battery (Sanderson, 2021). While most car batteries contain cells placed together into a module and then a pack, in this alternative design, long thin battery cells are placed directly into a battery pack. Through this design, the company can pack 50% more cells into the battery pack compared to conventional LFP batteries. Because of the reduction in casing, this approach saves space and makes up for some of the inherent cell weight and range disadvantages.

## SOLAR PV TRENDS

Already, solar PV manufacturing is an important use of copper and silver. Around 10% of global silver use is for solar PV, and the cost of silver accounts for 10% of the PV module manufacturing cost (Bellini, 2021). However, improvement in materials efficiency has the potential to reduce this by half to three-quarters over the coming decade.

Basically, three solar PV technologies exist: thin film, monocrystalline silicon and multicrystalline silicon. The trend in recent years has been away from multicrystalline silicon and thin film toward monocrystalline silicon (Figure 4). Recently, silicon multijunction solar cells, such as IIIV/silicon, IIVI/silicon, chalcopyrite/silicon, and perovskite/silicon, have become popular and are getting closer to economic competitiveness (Yamaguchi *et al.*, 2021). Such stacked cells will change the materials requirements. At this point, it is not clear which concept will be the most successful, but multijunction solar cell technology with efficiency beyond the limits of silicon seems to have a clear advantage. However such designs can raise silver demand substantially. Key questions remain regarding the combination of materials and the timing of such a transition (Yamaguchi *et al.*, 2021). As Figure 4 illustrates, this can have a rapid impact on the technology mix in the market.

**Figure 4:** Trends in PV module manufacturing, 2000-2020



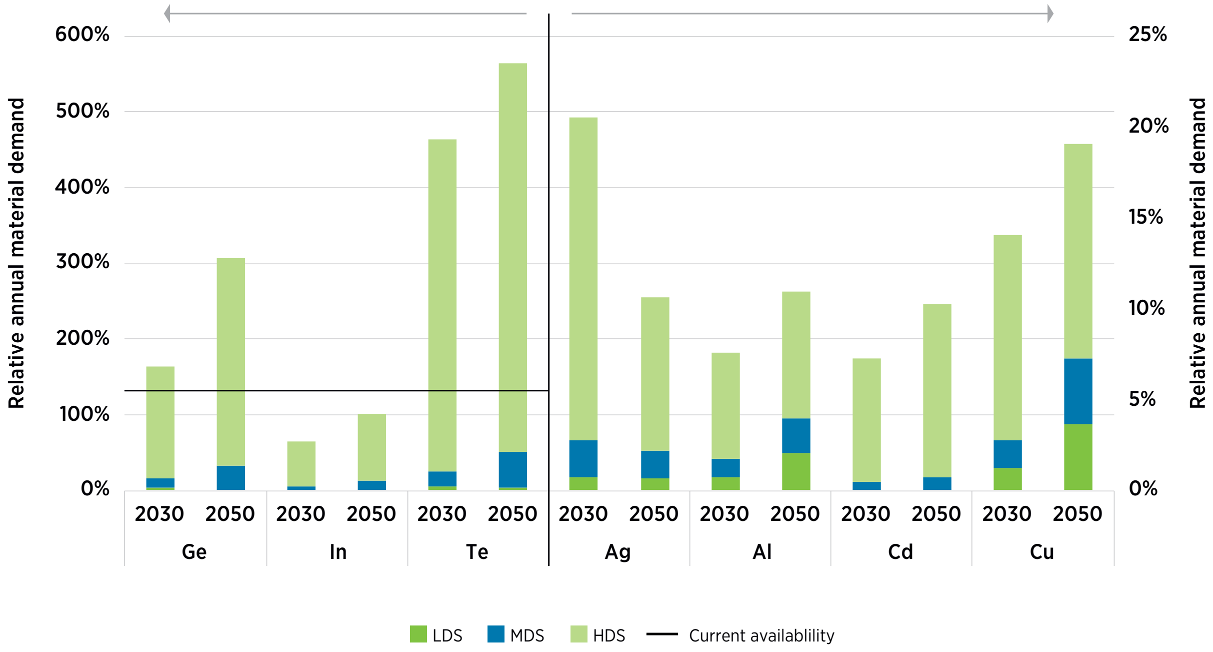
Mono-Si = monocrystalline silicon; Multi-Si: multicrystalline silicon.

**Adapted from:** Fraunhofer ISE, 2021.

The European Commission's Joint Research Centre has assessed three scenarios for solar PV material needs going forward in which the share of thin film develops linearly to 1%, 10% and 23% of demand by 2050 (corresponding to a low-demand scenario, a mid-demand scenario and a high-demand scenario). The annual installed solar PV capacity increases to 200 GW, 300 GW and 700 GW per year in the low-demand, mid-demand and high-demand scenarios, respectively. The higher end is roughly consistent with the IRENA 1.5°C scenario. The results (Figure 5) suggest that a high-demand scenario in combination with a rising share of thin film could increase demand for germanium and telluride substantially (three to six times the total demand today), while demand for aluminium, cadmium, copper and silver would see an increase equivalent to 10-20% of the total demand today (silver demand for solar PV already accounts for 10% of total global demand today) (Bellini, 2021). Going forward, efficiency gains in silver use will limit growth in demand for materials (Marsh, 2021).

The current trend is not towards thin film technology but monocrystalline silicon. Therefore, the mid-demand scenario is probably a better indicator, with a much smaller impact on demand for materials. The relative material demand in the high-demand versus the mid-demand scenario shows the importance of product composition in minimising future demand for critical materials.

**Figure 5:** Global annual PV material demand in 2030 and 2050 compared with current demand levels, in low-, mid- and high-demand scenarios



LDS: low-demand scenario; MDS: mid-demand scenario.

**Adapted from:** Carrara *et al.*, 2020.

## PERMANENT MAGNET TRENDS IN WIND TURBINES

There are increasing concerns about conflicts between the supply of rare earth elements (mainly neodymium, praseodymium and dysprosium) and the global expansion of wind power. Li *et al.* (2020) found that the significant increase in demand for rare earth elements driven by the ambitious 2050 global wind power targets cannot be achieved without an 11- to 26-fold expansion in rare earth production.

Ren *et al.* (2021) indicate an 18-fold increase in demand for rare earth elements in China in 2050 compared with 2020 and a cumulative demand for neodymium and dysprosium amounting to 1.6-3.3% and 1.4-2.8% of the country's reserves, respectively. It was indicated that recycling will play an important role after 2050 as a secondary supply of metal for Chinese wind power, but the study lacked noteworthy impacts on short-term future outlooks.

Various studies have assessed the material content of wind turbines and substitution strategies (*e.g.* Lacal-Arántegui, 2015; Marx, 2018; Pavel *et al.*, 2017). Carrara *et al.* (2020) state:

> There are two main technical designs of wind turbine suitable for use in onshore and offshore applications: direct drive and gearbox. The two types have significantly different constructions, differing in generator design, drivetrain system and grid connection solutions. As a result, both the mass and the material content differ greatly between the two.
>
> Gearbox configurations are offered with a choice of medium-speed (> 80 rpm) and high-speed (> 900 rpm) drives, further split into designs that contain a permanent magnet (medium-speed hybrid drives that employ both gearboxes and permanent magnets, and lower-speed drives with low magnet content) and ones with electromagnet generators (high-speed induction generators with multistage gearboxes). As it is heavy and requires maintenance, the gearbox design is less competitive in larger plants and offshore solutions.

> Direct-drive turbines, on the other hand, can be based on permanent magnet generators (e.g. Siemens and General Electric models), or can incorporate an electrically excited generator (e.g. Enercon direct-drive turbine models). In the latter case, they are produced without permanent magnets.
>
> A key advantage of direct-drive permanent magnets is that by eliminating the gearbox they enable a reduction in size, and thus a reduction in the turbine's overall weight, increasing its attractiveness in offshore applications.

Hybrid drives also exist. Hybrid drives use smaller permanent magnets than their direct-drive equivalents, making them less reliant on rare earth elements.

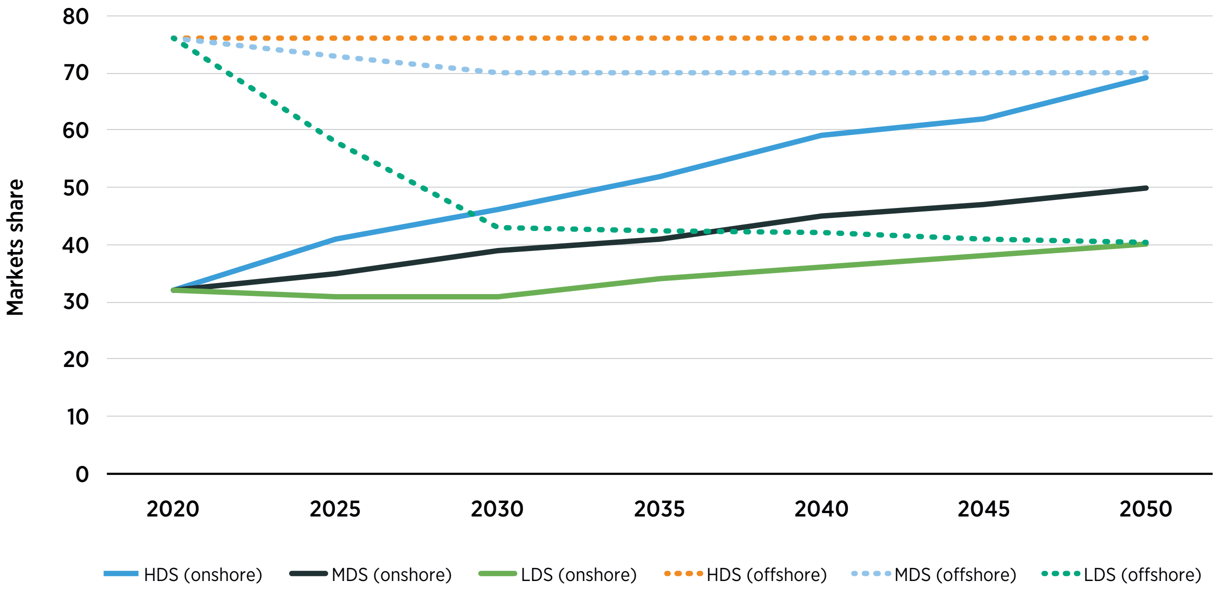
> In the future, direct-drive turbines could additionally be based on high-temperature superconductors (HTS). Gains associated with this technology include improvements in performance owing to a decrease in weight and savings in terms of neodymium and dysprosium consumption. However, moving towards this option, in particular at offshore locations where it can be most beneficial, depends on further cost reductions and technological progress. (Carrara *et al.*, 2020)

In 2018, permanent magnet turbines accounted for 76% of the world offshore market. Gear box–double fed induction generator turbines accounted for 52% of global market onshore; permanent magnet drives accounted for 32% in 2018. However, the share of permanent magnet drives has been rising.

The scenarios assume a convergence for onshore and offshore; however, the range is wide: from 40-70% permanent drive share.

Carrara *et al.* (2020) developed three scenarios for the use of permanent magnets in wind turbines (Figure 6, Table 2).

**Figure 6:** Scenarios for use of permanent magnets in wind turbines



HDS: high-demand scenario; LDS: low-demand scenario; MDS: mid-demand scenario.

**Adapted from:** Carrara *et al.*, 2020.

The following breakdown was applied: neodymium accounts for about 29%, dysprosium for 4%, boron for 1% and iron for 66% of the weight of a rare earth permanent magnet.

**Table 2:** Material usage estimates (t/GW) for different types of wind turbine

| MATERIAL | RANGE | DD-EESG | DD-PMSG | GB-PMSG | GB-DFIG |
|---|---|---|---|---|---|
| **Concrete** | 243 500-413 000 | 369 000 | 243 000 | 413 000 | 355 000 |
| **Steel** | 107 000-132 000 | 132 000 | 119 500 | 107 000 | 113 000 |
| **Polymers** | 4 600 | 4 600 | 4 600 | 4 600 | 4 600 |
| **Glass/carbon composites** | 7 700-8 400 | 8 100 | 8 100 | 8 400 | 7 700 |
| **Aluminium** | 500-1 600 | 700 | 500 | 1 600 | 1 400 |
| **Boron** | 0-6 | 0 | 6 | 1 | 0 |
| **Chromium** | 470-580 | 525 | 525 | 580 | 470 |
| **Copper** | 950-5 000 | 5 000 | 3 000 | 950 | 1 400 |
| **Dysprosium** | 2-17 | 6 | 17 | 6 | 2 |
| **Iron (cast)** | 18 000-20 800 | 20 100 | 20 100 | 20 800 | 18 000 |
| **Manganese** | 780-800 | 790 | 790 | 800 | 780 |
| **Molybdenum** | 99-119 | 109 | 109 | 119 | 99 |
| **Neodymium** | 12-180 | 28 | 180 | 51 | 12 |
| **Nickel** | 240-440 | 340 | 240 | 440 | 430 |
| **Praseodymium** | 0-35 | 9 | 35 | 4 | 0 |
| **Terbium** | 0-7 | 1 | 7 | 1 | 0 |
| **Zinc** | 5 500 | 5 500 | 5 500 | 5 500 | 5 500 |

DD: direct drive; DFIG: double fed induction generator; EESG: electrically excited synchronous generator; GB: gearbox; PMSG: permanent magnet synchronous generator.

**Adapted from:** Carrara *et al.*, 2020.

The total materials consumption is around 15 000 t/GW if concrete, steel, cast iron, polymers, aluminium and glass or carbon composites are left out. So, if 300 GW per year is installed, that equals around 4.5 Mt of critical materials per year. That amount is much smaller than the amount of materials needed for EVs (around 25 Mt per year for batteries alone, plus motors and cables).

## PERMANENT MAGNETS IN EVS

Permanent magnets are also used in EVs. According to Roskill around a quarter of permanent magnets will be used in transport this year. However EVs are gradually becoming one of the largest "consumers" of NdFeB magnet production – mostly for electric motors (although not all types of traction motor use magnets). According to Adamas Intelligence's forecast (2021), in 2030, EVs alone will be responsible for around 25% of NdFeB consumption. Traction motors (for passenger and commercial vehicles, as well as bikes, scooters and motorcycles) will take 23% of the NdFeB market. EVs also use magnets in micromotors, sensors and speakers (the remaining 2%) (Kane, 2020).

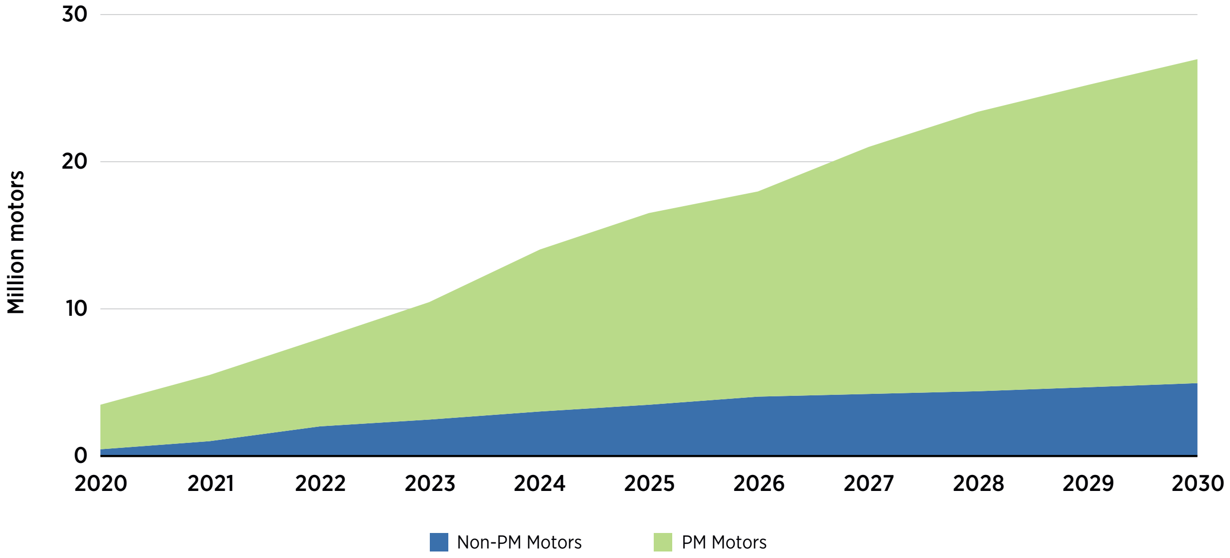
For the time being, the optimisation of power-to-weight ratio in motors and generators remains possible with the use of rare earth NdFeB magnets. Tesla switched to a mix of induction and permanent magnet motors as the latter boosted the models' driving range by 10%. Typical hybrid electric vehicles incorporate a 1-1.5 kW/kg motor, and according to BMW its i3 EV motor pushes out 2.5 kW/kg (Onstad, 2021).

Renault and Tesla have already employed wound rotor and induction motor technologies, respectively, eliminating rare earth magnets. These and other technologies, notably switched reluctance motors and the replacement of rare earth magnets with low-cost ferrites, can perhaps form the basis of even higher performance traction motors in the future. Companies trying to cut their use include Japan's third-largest car maker, Nissan, which is scrapping rare earth magnets from the engine of its new Ariya model. Germany's BMW did the same for its iX3 electric SUV this year, and the world's two biggest automakers, Toyota and Volkswagen, are also cutting back on the minerals. Manufacturers accounting for 46% of total light vehicle sales in 2020 have said they have scrapped, plan to eliminate, or are scaling down rare earth magnets in EVs (Onstad, 2021).

The average hybrid or electric vehicle uses between 2 kg and 5 kg of rare earth magnets, depending on the design. The neodymium magnets in a typical EV weigh up to 3 kg (Onstad, 2021).[5] The permanent magnets in hybrid and EV motors cost more than USD 300 per vehicle, or up to half the cost of the motor (Onstad, 2021). Rare earth magnets feature in various car components (Fears, 2021), but the motors account for the bulk of use.

However, the rate at which production needs to expand depends on the assumptions for EV production in 2030 (between 20 and 40 million), the share of cars with permanent magnets, and the magnet weight per car. The expectation is that most cars will use permanent magnets (Figure 7). Multiplying the two yields a wide range of demand for NdFeB, between 30 kt and 120 kt, for EVs in 2030 (Kane, 2021). However, the most significant bottleneck in supplying higher demand for permanent magnet generators and traction motors is the upper limit temperature performance and the associated cost and availability of the dysprosium. It is here that the technological breakthroughs are going to be most important (Onstad, 2021).

**Figure 7:** Projections for rare earth permanent magnet (PM) use in electric vehicles, 2020-2030



Note: Estimates of motors used in battery and fuel cell electric vehicles. PM motors are axial flux permanent magnet and surface-mounted permanent magnet. Non-PM motors are current-excited wound synchronous and induction.

**Adapted from:** Onstad, 2021.

---

[5] The European Raw Materials Alliance (2021) assumes 1.5 kg of rare earth magnets per vehicle but states that the magnet mass in EVs using this motor technology will most likely increase.

## ELECTRICITY GRIDS AND COPPER USE

Electricity grids are an important market segment for copper. Worldwide, around a third of all copper is used for electricity grids: nearly 21% of all copper is used for electrical power wiring in buildings; another 13% is used for power transmission and distribution (Table 3).

However, subsea cables and underground transmission cables do exist, and their use is expanding. Aluminium has 61% of the conductivity of copper but has only 30% of the weight of copper. An aluminium wire needs a 1.5 times larger cross-section to pass the same current as a copper wire but is half the weight. Weight is one of the most important parameters for high-voltage power lines that transmit power over long distances. Therefore, only aluminium wires are used in main overhead power lines (Aluminiumleader, 2021).

Global electricity grids can be split into transmission grids (high-voltage direct and alternating current lines) and distribution grids (low and medium voltage). The setup differs somewhat, but most transmission grids use overhead lines. Overhead lines are typically made from aluminium. Underground transmission cables can be made from copper or from aluminium – there is no technical weight advantage. Current technology permits underground transmission cable systems as high as 1100 kilovolts. Aluminium and copper are used for distribution wiring depending on the country, but copper dominates building wiring everywhere for reasons of safety (fire hazards) (Black, 1995).

Distributed renewables can result in a higher demand for underground and subsea grid connections and transformers, which can raise the demand for copper. Wind turbines also need copper. Copper is used in the wind turbine itself but, more importantly, in the power line that connects the wind turbine to the grid and in the transformers. A UK study (Falconer, 2009) found that around one-third of the copper is in the turbine and two-thirds is in the cabling between the turbine and the substation, giving a total of 5.64 t/MW. This effect is even more pronounced for offshore turbines, with around 5 t/MW for the turbine nearshore and up to 15 t/MW for a turbine 100 km offshore. The same study says that continental Europe specifies aluminium for underground cables onshore, which reduces copper needs by two-thirds. In the upgrade of the terrestrial transmission grid, it can be assumed that most overhead lines and underground cables will continue to be made of aluminium. But submarine interconnections to integrate more offshore wind generation into the system can be a large driver for copper, especially with copper-intensive direct current lines and converters (Debusscher *et al.*, 2019). So standards can make a big difference to intensity of materials use and deserve a close look.

A case study for Europe found that energy transition to 2050 in the European Commission's High Renewables scenario means adding 22 Mt of copper to the European Union's 82.1 Mt of copper in use. This represents an increase of about 27% of the currently used amount. Annual consumption would increase over time and be 25% higher in 2035 (0.9 Mt/yr), but this consumption increase would drop in later years. Renewable power generation, distribution grids and EVs dominate the additional demand for copper. EVs are expected to become about two to three times more copper intensive than combustion cars: at least 44 kg with new expected battery technologies, compared with 22 kg with current internal combustion powertrains. However, if a decline in total vehicle demand is accounted for due to changing lifestyle and other factors, growth in demand for copper could be limited (Debusscher *et al.*, 2019).

**Table 3:** Copper use (semi-applications) in 2020

| SECTOR | APPLICATION | USE [kt/yr] | SHARE [%] |
|---|---|---|---|
| **Building construction** | Plumbing | 1 345 | 4.6 |
| | Aircon tube | 235 | 0.8 |
| | Roofs, gutters, etc. | 323 | 1.1 |
| | Communication wiring | 247 | 0.8 |
| | Electrical power wiring, etc. | 6 069 | 20.6 |
| **Infrastructure** | Power transmission and distribution | 3 859 | 13.1 |
| | Telecom | 834 | 2.8 |
| **Industrial** | Transformers & motors | 1 782 | 6.1 |
| | Non-electrical | 1 682 | 5.7 |
| **Transport** | Harnesses, motors, batteries | 2 234 | 7.6 |
| | Radiators & tubing | 225 | 0.8 |
| | Railroad and ships | 1 317 | 4.5 |
| **Other** | Consumer products | 2 538 | 8.6 |
| | Aircon/refrigeration | 2 376 | 8.1 |
| | Industrial/commercial electronics, computers | 1 395 | 4.7 |
| | Ammunition, clothing, coins | 2 977 | 10.1 |
| **Total** | | 29 438 | 100.0 |

**Note:** Applications shaded grey have an energy transition link.

**Source:** ICSG, 2021b; IWCC/ICA, 2020.

Today's power generation includes about 30% renewables. This percentage needs to increase to around 90% by 2050, with more than 60% of all power coming from solar PV and wind. Therefore, we need 8 000 GW of wind and 15 000 GW of solar PV by 2050. This requires, on average, 250 GW of wind and 350 GW of solar capacity additions per year between now and 2050. By 2030, a threefold increase is needed from 2020 levels (IRENA, 2021b).

Such rapid growth may impact copper markets. Copper demand from onshore and offshore wind turbines may grow to 2 Mt/yr. Compared with today's copper demand of 30 Mt/yr, this represents a 7% growth – not trivial, but not a showstopper. When considering solar PV, copper needed for power generation grows by 4 Mt/yr. However, power generation represents only part of total mineral and metal needs. Power grids and EVs are two other key growth markets for the energy transition in which copper is widely used.

Automotive applications account for around 9% of today's copper use. EVs can double or even quadruple copper use, compared with internal combustion engine vehicles (LePan, 2018). Given a production volume of 100 million cars, this would require 4-8 Mt of copper per year, equivalent to 1428% of today's copper use. But innovation may reduce this need. The battery pack alone accounts for around 40 kg of copper; additional copper cabling and wiring in motors accounts for the remainder of the metal's increased use. But copper needs can vary widely for battery packs, and the composition continues to evolve rapidly (McKinsey, 2021). BloombergNEF projects 4 Mt of copper demand for lithium-ion batteries by 2030 (Figure 1). That is around 13% of today's copper supply, a significant growth area.

Copper is unique in that the metal's use is ubiquitous in the energy transition. Higher prices will promote higher recycling rates: today, half of post-consumer copper waste is lost, while a third of production is based on recycling (ICSG, 2021b). Also, mining of old mine tailings offers the potential for quick ramp-up of copper supply. Material substitution can also ease supply bottlenecks. For example, aluminium can replace copper in electricity wiring. The technical properties are not exactly the same, but aluminium is today widely used for transmission and distribution grids.

# GEOPOLITICAL ASPECTS

As energy transition has moved to the top of the global political agenda, supply of critical materials has become an issue of high geopolitical importance (Global Commission, 2019). Geopolitical aspects include new future trade patterns and the ability of single or select players to build a dominant position in certain critical materials markets that can be used to control prices or supply. The most recognised way of ensuring supply security is through diversity of supply. Neodymium and cobalt therefore seem the most sensitive components at this moment. However, solutions exist to reduce dependencies.

Projections of future critical material needs are subject to much uncertainty. First, demand for new products is projected to ramp up rapidly. Whether this happens at the speed commensurate with a 1.5°C pathway will depend on the implementation of policies that put newly formulated objectives for decarbonisation by mid-century into practice. Second, the analysis in this paper has shown that considerable leeway exists to substitute critical materials. However, this often comes at a cost in economic or performance terms. Also, such substitution cannot happen overnight. Equipment manufacturers and governments need to consider carefully if they want to accept the risk of new supply dependencies. Finally, for many critical materials, a massive ramp-up will be needed, and it is likely that the sources of supply will change. For example, lithium rock mining has been established as a supplement to brine leaching, and cobalt is today 98% produced as a by-product of copper and nickel mining – dedicated mines for cobalt will be needed going forward. Such fundamental changes in supply also broaden the resource base and reduce potential geopolitical issues.

Although rare earth deposits are found on all continents, China produces more than 90% of all globally used rare earth metals. Besides its economic dominance, China has also gained unique know-how related to rare earth element processing technologies. While its share in rare earth mining has been declining in recent years, it also produces close to 90% of the world's permanent magnet alloys, and Chinese manufacturing of permanent magnets themselves is on the rise (Rane Worldview, 2019). Based on China's dominant position in rare earth markets, other countries such as Australia, Japan, the United States, and several across Europe are increasingly concerned about a stable rare earth supply and their increasing dependence on China (Jaroni *et al.*, 2019). Various strategies have been deployed by importing countries to reduce this dependency, so far with limited success.

In the case of copper, a decline in resource quality in combination with a growth of demand due to energy transition means that the mining effort will have to increase. To some extent, aluminium can substitute for copper in electricity grids. The main challenge in growing copper supply in the coming years is the need to bring new mines into operation. Such mines often face considerable local opposition. At the same time, they often represent billions in investments, and mining companies are wary of the risk in the light of past copper price fluctuations. Whereas transition advocates call for expanded supply, the mining industry is wary due to experience with past supply cycles.

Investors expect a bonanza. Stock prices of copper and lithium miners are up, and new projects are being explored feverishly. This is much needed because development of new mines can take decades and is fraught with uncertainties. The Resolution copper mine in the US state of Arizona is such a case, with USD 2 billion invested over the past 30 years without any copper produced so far (Klemetti, 2019). Separately, the Rio Tinto Group's planned USD 2.4 billion lithium-borate mine in Serbia faces tough questions and calls for further environmental guarantees. Such new mining activities must be managed properly, and local and national concerns must be taken seriously. Rio Tinto's iron mining activities destroyed an important prehistoric site in Australia in 2020 and made headlines worldwide, tarnishing the mining behemoth's reputation for years to come. Such negligence must be avoided, and mine tailings need to be managed properly. Local populations also expect the creation of local jobs and economic development from mining projects. Seabed metal mining is an area to watch closely in this context (Bloomberg, 2021).

Another type of supply risk relates to the geographical distribution of supply. China has built a dominant position for rare earth element supply but also for many other minerals and metals. Supply chains are being reviewed in the light of vulnerabilities that have become visible in recent years and rising geopolitical tensions. There is a role for governments in managing this process, with a clear trade-off between low-cost supply from abroad on the one hand and geopolitical concerns on the other.

Geopolitics is a matter for governments, but the consumers of critical materials are also aware and can take measures; for example, car companies ensure materials supply through contracts. There is a role for governments to secure supply of critical materials. Today, various countries operate their own agencies that assess critical materials supply (USGS, Deutsche Rohstoffagentur, Joint Research Council, etc.), but an international body is lacking. The establishment of such a body could be considered.

The Critical Materials Institute is a US Department of Energy Innovation Hub led by Ames Laboratory that seeks to accelerate innovative scientific and technological solutions to develop resilient and secure supply chains for rare earth metals and other materials critical to the success of clean energy technologies (Ames Laboratory, 2021). The US Department of State has established the Energy Resources Governance Initiative to promote sound mining sector governance and resilient energy mineral supply chains (IRENA and USDoS, 2020). The Initiative will also promote resilient and secure energy resource mineral supply chains. Rare earth metals are specifically mentioned in this context.

The European Commission 2020 Communication on Critical Raw Materials announced the launch of an industrial alliance dedicated to securing a sustainable supply of raw materials in Europe (European Commission, 2020). By bringing together all relevant stakeholders along strategic value chains and industrial ecosystems, the alliance will initially focus on the most pressing needs, namely to increase the European Union’s resilience in the rare earth element and permanent magnet value chains (European Commission, 2021; ERMA, n.d.). A rare earth strategy document was released in 2021 (Gauß *et al.*, 2021). Also, the Joint Research Centre of the European Commission has a well-established programme to track critical raw materials (Bobba *et al.*, 2020).

Japan also has an active policy to ensure supply of critical materials such as rare earth metals (Hui, 2021).

In conclusion, governments are aware of the critical materials issue, but there is a lack of co-ordination. It is therefore recommended to enhance international governance for critical materials.

# CONCLUSIONS

Energy transition is critical for the future of humankind. The risks associated with climate change dwarf those associated with critical materials supply, and the current discourse on materials scarcity as a showstopper is misleading. However, attention to critical materials is warranted. Energy transition will affect mineral and metal consumption substantially. But these new supply challenges can be resolved. The energy transition is here to stay and will create new economic opportunities. On the supply side, long-term resource availability is less of a concern than the capability to ramp up supply in the near and medium term.

Whereas some alarming analyses have pointed to scarcity problems and some investors see a bonanza in critical materials, the reality is more nuanced. First of all, it is critical not to lump materials but to maintain sufficient detail in the assessment of scarcity issues. Second, its critical to look at the growth of total materials demand, as energy transition is often just one demand component and an exclusive focus on energy transition may distort the broader picture.

The right policy frameworks and design decisions today can avoid scarcity problems in the future. Also, in many cases, the issue is not the resource availability but the capacity to ramp up production. The rapid rollout of electromobility and battery production that we witness today will certainly put a strain on mineral and metal supply in the years to come. But these problems can be overcome. The energy transition is here to stay, and it will create new economic opportunities.

The rapid expansion of electromobility in particular raises questions about materials scarcity, while renewable power generation and power grids contribute to a lesser degree. The rapid transition we are currently witnessing from internal combustion engines to EVs results in a rapidly increasing demand for battery materials (lithium, nickel and cobalt) and copper, as well as permanent magnets (which has implications for neodymium and dysprosium demand). This is the prime source of the supply shortfalls and price increases that can be witnessed at present. It is likely that this new market dynamic will be maintained for some years. However, this rapid demand increase will not be maintained after 2030. Other market segments such as production of wind turbines and solar PV panels may double or even quadruple, but their net impact on demand for critical materials is much more subdued. However, permanent magnets are also needed for certain types of wind turbine. Grid investment will need to rise in years to come, and the main impact will relate to demand for copper, notably for underground cables in distribution networks. Demand for copper may also increase as electrification of a range of energy services accelerates.

There is a need for a more precise and transparent assessment of needs and intervention. Every mineral and metal is different in terms of its supply issues, its demand side potential for substitution and its likely demand growth due to energy transition. While long lists of strategic minerals exist, not all of those minerals are essential for the energy transition. Materials with unique properties such as neodymium, copper and lithium seem, for now, more critical than graphite, cobalt and indium, where alternatives exist. There is a need to better understand the material requirements of the energy transition in the light of the rapid innovations that are taking place on the production side.

Many of these critical resources are found in remote locations, where mining can offer a welcome source of new, sustainable economic activity. But experience shows that this will not happen on its own. A more precise and transparent assessment of needs and potential government interventions is required. Every mineral and metal is different, and the specific issues need to be understood to manage the transition properly.

Some strategic minerals have unique engineering properties that make substitution challenging; in other cases the impact is more marginal and substitutes exist with limited impact on performance. It will be important not to dilute policy efforts too much across many different materials as this may weaken effectiveness. On the supply side, resource availability is less of a problem than the capability to ramp up supply. The rapid expansion of electromobility, particularly, raises questions for this decade, while renewable power generation and power grids seem less of an issue.

Projections of future critical material needs are subject to much uncertainty. First, demand for new products is projected to ramp up rapidly. Whether this happens at the speed commensurate with a 1.5°C pathway will depend on the implementation of policies that put newly formulated objectives for decarbonisation by mid-century into practice. Second, the analysis in this paper has shown that considerable leeway exists to substitute critical materials. However, this often comes at a cost in economic or performance terms. Also, such substitution cannot happen overnight. Equipment manufacturers and governments need to consider carefully if they want to accept the risk of new supply dependencies. Finally, for many critical materials, a significant ramp-up will be needed if the market takes off as expected, and it is likely that the sources of supply will change. For example, lithium rock mining has been established as a supplement to brine leaching, and cobalt is today 98% produced as a by-product of copper and nickel mining – dedicated mines for cobalt will be needed going forward. Such fundamental changes in supply also broaden the resource base and reduce potential geopolitical issues.

Whereas recycling is often touted as a solution to the problem of access to critical materials, this notion is misguided. Recycling can help avoid waste management problems, and it can help develop circular economy concepts on a timescale of decades or centuries, but it cannot be the source of supply needed to build up the materials stock required for the global economy in the coming years.

The topic of critical materials has been on government agendas for some time. All major economies have study groups and try to develop strategies to reduce dependencies. However, these are not developed in concert and often they obstruct one another, for example in developing access to strategic supply sources. Access to critical materials is clearly an issue of rising geopolitical importance.

Therefore, a global approach to strategic minerals makes sense but is currently lacking. Individual car companies and other equipment manufacturers that ensure their strategic supplies through contracts may help mitigate short-term price and supply risks, but this will not resolve the geopolitical issues. There is a role for international agencies, notably IRENA as the sole world energy transitions agency with truly global membership, to bring countries together on this topic and facilitate the management of supply.

Governments should consider issues related to critical materials as they design their energy transition strategies. It cannot be left to the market alone to deal with future dependencies, especially in a world that is increasingly multipolar. Governments must set clear policy objectives and regulations if critical materials supply is considered essential. This may include development of strategic materials stockpiles and active support for the development of specific secure supply routes where this is deemed essential. A structured global dialogue, facilitation of free trade and diversification of suppliers are constructive and fruitful responses to geopolitical challenges.

# REFERENCES

**Adamas Intelligence** (2021), *Rare Earth Magnet Market Outlook to 2030*, Adamas Intelligence, Toronto and Amsterdam, www.adamasintel.com/report/rare-earth-magnet-market-outlook-to-2030.

**Advanced Magnets** (2021), "Introduction to basic composition and microstructure of sintered NdFeB magnet", www.advancedmagnets.com/introduction-to-basic-composition-and-microstructure-of-sintered-ndfeb-magnet.

**Aluminiumleader** (2021), "Aluminium in power-engineering", www.aluminiumleader.com/application/electrical_engineering.

**Alves Dias, P., *et al.*** (2020), *The Role of Rare Earth Elements in Wind Energy and Electric Mobility*, EUR 30488 EN, Publications Office of the European Union, Luxembourg.

**Ames Laboratory** (2021), "Critical Materials Institute", www.ameslab.gov/cmi.

**Barrera, P.** (2021), "Rare earths market update", Investing News Network, https://investingnews.com/daily/resource-investing/critical-metals-investing/rare-earth-investing/rare-earths-market-update.

**Bellini, E.** (2021), "Silver accounts for 10% of PV module costs", *PV Magazine*, www.pv-magazine.com/2021/03/04/silver-currently-accounts-for-10-of-pv-module-costs.

**Black, W.** (1995), "Trends in the use of copper wire & cable in the USA", Copper Development Association, www.copper.org/resources/market_data/trends_cable.html.

**Bloomberg** (2021), "Subsea mining SPAC's rush for underwater metals comes with deep risks", *GCaptain*, https://gcaptain.com/subsea-mining-startups-spac-soac.

**BloombergNEF** (2021a), "BloombergNEF ups battery demand forecast", *Canadian Mining Journal*, www.canadianminingjournal.com/news/bloombergnef-ups-battery-demand-forecast.

**BloombergNEF** (2021b), *Electric Vehicle Outlook 2021*, https://about.bnef.com/electric-vehicle-outlook.

**Bobba, S., *et al.*** (2020), *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study*, Publications Office of the European Union, Luxembourg, https://ec.europa.eu/docsroom/documents/42881.

**Cantú, A.M.** (2021), "In search of 'Lithium Valley': why energy companies see riches in the California desert", *The Guardian*, www.theguardian.com/us-news/2021/sep/27/salton-sea-california-lithium-mining.

**Carrara, S., *et al.*** (2020), *Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy System*, EUR 30095 EN, Publications Office of the European Union, Luxembourg.

**CIM** (2014). "CIM definition standards", Canadian Institute of Mining, Metallurgy and Petroleum, www.bcsc.bc.ca/-/media/PWS/Resources/For_Companies/Mining/CIM_DEFINITION_STANDARDS_MAY_10_2014.pdf.

**Constantinides, S., and J. De Leon** (2011), "Permanent magnet materials and current challenges," Arnold Magnetic Technologies, Rochester, www.arnoldmagnetics.com/wp-content/uploads/2017/10/Permanent-Magnet-Materials-and-Current-Challenges-Constantinides-and-DeLeon-PowderMet-2011-ppr.pdf.

**Copper Alliance** (2020), "Global copper stocks and flows in 2018", https://copperalliance.org/about-copper/stocks-and-flows.

**Daily Metal Prices** (2021), "Metal spot price charts", www.dailymetalprice.com/metalpricecharts.php?c=li&u=kg&d=1200.

**Debusscher, D., *et al.*** (2019), *Copper as a Key Driver in the Energy Transition*, European Copper Institute, Brussels, www.coppertransition.eu.

**Deetman, S., *et al.*** (2019), "Modelling global material stocks and flows for residential and service sector buildings towards 2050", *Journal of Cleaner Production*, Vol. 245, Elsevier, Amsterdam, https://doi.org/10.1016/j.jclepro.2019.118658.

**Deetman, S., *et al.*** (2018), "Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances", *Environmental Science and Technology*, Vol. 52/8, pp. 4950–4959, https://dx.doi.org/10.1021%2Facs.est.7b05549.

**DERA** (2021a), *Rohstoffe für Zukunftstechnologien 2021*, DERA Rohstoffinformationen 50, Deutsche Rohstoffagentur, Berlin.

**DERA** (2021b), *Rohstoffrisikobewertung: Nickel*, DERA Rohstoffinformationen 48, Deutsche Rohstoffagentur, Berlin.

**Electric Vehicle Database** (2021), "Energy consumption of full electric vehicles", https://ev-database.org/cheatsheet/energy-consumption-electric-car.

**Elshkaki, A., B. Reck and T. Graedel** (2017), "Anthropogenic nickel supply, demand, and associated energy and water use", *Resources, Conservation & Recycling*, Vol. 125, pp. 300-307, https://doi.org/10.1016/j.resconrec.2017.07.002.

**Elshkaki, A., *et al.*** (2016), "Copper supply, demand and associated energy use to 2050", *Global Environmental Change*, Vol. 39, pp. 305-315, https://doi.org/10.1016/j.gloenvcha.2016.06.006.

**ERMA** (European Raw Materials Alliance) (n.d.), https://erma.eu.

**European Commission** (2021), "Critical raw materials", https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en.

**European Commission** (2020), *Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability*, European Commission, Brussels, https://ec.europa.eu/docsroom/documents/42849.

**Fabre, A.** (2019), "Evolution of EROIs of electricity until 2050: estimation and implications on prices", *Ecological Economics*, Vol. 164, https://doi.org/10.1016/j.ecolecon.2019.06.006.

**Falconer, I.** (2009), "Metals required for the UK's low carbon energy system: the case of copper usage in wind farms", http://docs.wind-watch.org/Copper%20use%20in%20wind%20farms.pdf.

**Fears, P.** (2021), "Rare earth magnets in electric vehicle motors", Bunting, www.buntingeurope.com/rare-earth-magnets-in-electric-vehicle-motors.

**Frangoul, A.** (2021), "Wind turbine giant Siemens-Gamesa claims world fist in blade recycling", *CNBC*, www.cnbc.com/2021/09/07/wind-energy-giant-siemens-gamesa-claims-world-first-in-blade-recycling.html.

**Fraunhofer ISE** (2021), *Photovoltaics Report*, Fraunhofer Institute for Solar Energy Systems, Freiburg, www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

**Gauß, R., *et al.*** (2021), *Rare Earth Magnets and Motors: A European Call for Action*, European Raw Materials Alliance, Berline, https://eitrawmaterials.eu/wp-content/uploads/2021/09/ERMA-Action-Plan-2021-A-European-Call-for-Action.pdf.

**Gielen, D.J.** (1999), *Materialising Dematerialization*, PhD thesis, Delft University of Technology.

**Gielen, D. and C. Papa** (2021), Materials for the energy transition, International Renewable Energy Agency and ENEL, Abu Dhabi and Rome, www.irena.org/newsroom/expertinsights/2021/Nov/Materials-shortage-will-not-stop-the-energy-transition.

**Global Commission on the Geopolitics of Energy Transformation** (2019), *A New World: The Geopolitics of Energy Transformation*, International Renewable Energy Agency, Abu Dhabi, http://geopoliticsofrenewables.org/Report.

**Global Energy Metals** (2021), "Cobalt supply", www.globalenergymetals.com/cobalt/cobalt-supply.

**Hui, M.** (2021), "Japan's global rare earths quest holds lessons for the US and Europe", *Quartz*, https://qz.com/1998773/japans-rare-earths-strategy-has-lessons-for-us-europe.

**Hund, K., *et al.*** (2020), *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*, World Bank, Washington, DC, https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf.

**ICSG** (2021a), *The World Copper Factbook 2020*, International Copper Study Group, Lisbon, www.icsg.org/index.php/component/jdownloads/finish/170/3046.

**ICSG** (2021b), "Selected data", International Copper Study Group, www.icsg.org/index.php/statistics/selected-data.

**ICSG** (2015), "Long term availability of copper", International Copper Study Group, www.icsg.org/index.php/the-world-of-copper/71-uncategorised/114-long-term-availability-of-copper.

**IEA** (2021), *The Role of Critical Minerals in Clean Energy Transitions*, International Energy Agency, Paris, www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

**IRENA** (2021a), *World Energy Transitions Outlook: 1.5°C Pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.

**IRENA** (2021b), "World adds record new renewable energy capacity in 2020", International Renewable Energy Agency, Abu Dhabi, www.irena.org/newsroom/pressreleases/2021/Apr/World-Adds-Record-New-Renewable-Energy-Capacity-in-2020.

**IRENA** (2016), *End-of-Life Management: Solar Photovoltaic Panels*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

**IRENA and US Department of State** (2020), *Joint Virtual Workshop on Minerals Criticality & the Energy Transition: Summary of Key Insights from the Discussions*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Events/2020/Jun/Mineral-Criticality-and-the-Energy-Transition/Mineral-Criticality_Summary-report_final.pdf.

**IWCC and ICA** (2020), "Global copper semis end-use reports", International Wrought Copper Council, London, and International Copper Association, Washington, DC, www.coppercouncil.org/iwcc-statistics-and-data.

**Jaroni, M., B. Friedrich and P. Lemathe** (2019), "Economical feasibility of rare earth mining outside China", *Minerals*, Vol. 9/10, p. 576, https://doi.org/10.3390/min9100576.

**Kane, M.** (2020), “A quarter of NdFeB magnet production will be used in EVs by 2030”, *InsideEVs*, https://insideevs.com/news/439469/quarter-of-ndfeb-production-used-evs-2030.

**Kelly, J., *et al.*** (2021), “Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries”, *Resources, Conservation and Recycling*, Vol. 174, https://doi.org/10.1016/j.resconrec.2021.105762.

**Klemetti, E.** (2019), “North America is about to get its largest copper mine”, *Discover*, www.discovermagazine.com/environment/north-america-is-about-to-get-its-largest-copper-mine.

**Lacal-Arántegui, R.** (2015), “Materials use in electricity generators in wind turbines – state-of-the-art and future specifications”, *Journal of Cleaner Production*, Vol. 87, pp. 275283, https://doi.org/10.1016/j.jclepro.2014.09.047.

**Lee, J., and M. Bazilian** (2021), “As the planet burns, a new Cold War over critical minerals”, *The Hill*, thehill.com/blogs/congress-blog/politics/567394-as-the-planet-burns-a-new-cold-war-over-critical-minerals.

**LePan, N.** (2018), “How much copper is in an electric vehicle?” *Visual Capitalist*, www.visualcapitalist.com/how-much-copper-is-in-an-electric-vehicle.

**Li, J., *et al.*** (2020), “Critical rare-earth elements mismatch global wind-power ambitions”, *One Earth*, Vol. 3/1, pp. 116125, https://doi.org/10.1016/j.oneear.2020.06.00.

**Lima, P.** (2020), “Comparison of different EV batteries in 2020 (update)”, PushEVs, https://pushevs.com/2020/04/04/comparison-of-different-ev-batteries-in-2020.

**Lipman, A., and A. Yu** (2019), “Will 2020 be the year for subsea mining?” *Marine Technology News*, www.marinetechnologynews.com/news/subsea-mining-596722.

**Marsh, J.** (2021), “How much silver is needed for the solar panel industry?” *ResourceWorld*, https://resourceworld.com/how-much-silver-is-needed-for-the-solar-panel-industry.

**Marx, A.** (2018), *An In-Depth Comparative Study of Direct Drive versus Gearbox Wind Turbines*, MSc thesis, KTH Stockholm, www.diva-portal.org/smash/get/diva2:1293881/FULLTEXT01.pdf.

**Masias, A., J. Marcicki and W.A. Paxton** (2021), “Opportunities and challenges of lithium ion batteries in automotive applications”, *ACS Energy Letters*, Vol. 6, American Chemical Society, Washington, DC, pp. 621630, https://doi.org/10.1021/acsenergylett.0c02584.

**McFadden, C.** (2020), “Could ultracapacitors replace batteries in future electric vehicles?” *Interesting Engineering*, https://interestingengineering.com/could-ultracapacitors-replace-batteries-in-future-electric-vehicles.

**McKelvey, V.E., N.A. Wright and R.W. Bowen** (1983), *Analysis of the World Distribution of Metal-Rich Subsea Manganese Nodules*, US Geological Survey, Reston, https://pubs.er.usgs.gov/publication/cir886.

**McKie, R.** (2021), “Is deep-sea mining a cure for the climate crisis or a curse?” *The Guardian*, www.theguardian.com/world/2021/aug/29/is-deep-sea-mining-a-cure-for-the-climate-crisis-or-a-curse.

**McKinsey** (2021), “Building better batteries: insights on chemistry and design from China”, www.mckinsey.com/industries/automotive-and-assembly/our-insights/building-better-batteries-insights-on-chemistry-and-design-from-china.

**Mining Review Africa** (2021), “China maintains grip on battery chemical industry”, www.miningreview.com/battery-metals/china-maintains-grip-on-battery-chemical-industry-in-h12021.

**Mistry, M.** (2020), "Is there enough nickel? Reserves, resources and recycling", Nickel Institute, https://nickelinstitute.org/blog/2020/january/reserves-resources-and-recycling-is-there-enough-nickel.

**Moore, J., and N. Bullard** (2021), *BloombergNEF Executive Factbook*, BloombergNEF, https://assets.bbhub.io/professional/sites/24/BNEF-2021-Executive-Factbook.pdf.

**Mudd, G., and S. Jowitt** (2014), "A detailed assessment of global nickel resource trends and endowments", *Economic Geology*, Vol. 109, pp. 18131841, https://doi.org/10.2113/econgeo.109.7.1813.

**NS Energy** (2021a), "Zinnwald lithium project", www.nsenergybusiness.com/projects/zinnwald-lithium-project.

**NS Energy** (2021b), "Vulcan lithium project", www.nsenergybusiness.com/projects/vulcan-lithium-project.

**Onstad, E.** (2021), "China frictions steer electric automakers away from rare earth magnets", *Reuters*, https://www.reuters.com/business/autos-transportation/china-frictions-steer-electric-automakers-away-rare-earth-magnets-2021-07-19.

**Pavel, C., *et al.*** (2017), "Substitution strategies for reducing the use of rare earths in wind turbines", *Resources Policy*, Vol. 52, Elsevier, Amsterdam, pp. 349357, https://doi.org/10.1016/j.resourpol.2017.04.010.

**Pistilli, M.** (2021), "Types of copper deposits in the world", *Investing News*, https://investingnews.com/daily/resource-investing/base-metals-investing/copper-investing/types-copper-deposits-world.

**Rane Worldview** (2019), "The geopolitics of rare earth elements", https://worldview.stratfor.com/article/geopolitics-rare-earth-elements.

**Ren, K., *et al.*** (2021), "Bridging energy and metal sustainability: insights from China's wind power development up to 2050", *Energy*, Vol. 227, 120524.

**Samsung SDI** (2021), "The composition of EV batteries: Cells? Modules? Packs? Let's understand properly!" www.samsungsdi.com/column/all/detail/54344.html.

**Sanderson, H.** (2021), "Battery technology gives China and opening in electric vehicles", *Financial Times*, www.ft.com/content/fcbc860b-51cd-40d8-b65f-db97ce9adc57.

**Sharma, R.** (2021), "'Greenflation' threatens to derail climate change action", *Financial Times*, www.ft.com/content/49c19d8f-c3c3-4450-b869-50c7126076ee.

**Slav, I.** (2021), "Europe's rare earth dependency dilemma", *RT*, www.rt.com/business/516348-europe-rare-earth-dependency-dilemma.

**SPC** (2013), *Deep Sea Minerals: Sea-Floor Massive Sulphides, a Physical, Biological, Environmental, and Technical Review*, Secretariat of the Pacific Community, Nouméa, http://dsm.gsd.spc.int/public/files/meetings/TrainingWorkshop4/UNEP_vol1A.pdf.

**Timofeeva, E.** (2018), "Raw material supplies for growing battery production", Influit Energy, www.influitenergy.com/supply-chain-and-raw-materials-for-growing-battery-production.

**Tsiropoulos, I., D. Tarvydas and N. Lebedeva** (2018), *Li-Ion Batteries for Mobility and Stationary Storage Applications: Scenarios for Costs and Market Growth*, EUR 29440 EN, Publications Office of the European Union, Luxembourg, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113360/kjna29440enn.pdf.

**UCS** (2021), *Electric Vehicle Batteries: Addressing Questions about Critical Materials and Recycling*, Union of Concerned Scientists, Cambridge, MA, https://ucsusa.org/sites/default/files/2021-02/ev-battery-recycling-fact-sheet.pdf.

**USCRS** (2020), *An Overview of Rare Earth Elements and Related Issues for Congress*, United States Congressional Research Service, Washington, DC, https://crsreports.congress.gov/product/pdf/R/R46618.

**USGS** (2021), "Copper", in *Mineral Commodity Summaries*, US Geological Survey, Reston, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-copper.pdf.

**USGS** (2020), "Lithium", in *Mineral Commodity Summaries*, US Geological Survey, Reston, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-lithium.pdf.

**USGS** (2017), "Cobalt", in *Critical Mineral Resources of the United States – Economic and Environmental Geology and Prospects for Future Supply*, US Geological Survey, Reston, https://pubs.usgs.gov/pp/1802/f/pp1802f.pdf.

**Volkswagen** (2021), "From old to new – battery recycling in Salzgitter", www.volkswagen-newsroom.com/en/stories/from-old-to-new-battery-recycling-in-salzgitter-6782.

**Warren Centre, The** (2020), *Zero Emission Copper Mine of the Future*, University of Sydney, www.sydney.edu.au/content/dam/corporate/documents/faculty-of-engineering-and-information-technologies/industry-and-government/the-warren-centre/zero-emissions-copper-mine-of-the-future-report-the-warren-centre.pdf.

**Willuhn, M.** (2021), "Nickel and dime batteries to LFP", *PV Magazine*, No. 3, pp. 6063.

**Wu, F. *et al.*** (2021), "Dual-anion ionic liquid electrolyte enables stable Ni-rich cathodes in lithium-metal batteries", *Joule*, Vol. 5/8, pp. 21772194, https://doi.org/10.1016/j.joule.2021.06.014.

**Yamaguchi, M. *et al.*** (2021), "Multi-junction solar cells paving the way for super high-efficiency", *Journal of Applied Physics*, Vol. 129/24, 240901, https://doi.org/10.1063/5.0048653.

IRENA

International Renewable Energy Agency

**www.irena.org**

© IRENA 2021