

Minerals for Climate Action:

The Mineral Intensity of the
Clean Energy Transition

CLIMATE-SMART MINING FACILITY

Kirsten Hund, Daniele La Porta, Thao P. Fabregas, Tim Laing, John Drexhage



Climate **Smart** Mining

© 2020 International Bank for
Reconstruction and Development/
The World Bank

1818 H Street NW
Washington, DC 20433
Telephone: 202-473-1000
www.worldbank.org

This work is a product of the staff of The World Bank with external contributions. The findings, interpretations, and conclusions expressed in this work do not necessarily reflect the views of The World Bank, its Board of Executive Directors, or the governments they represent.

The World Bank does not guarantee the accuracy of the data included in this work. The boundaries, colors, denominations, and other information shown on any map in this work do not imply any judgment on the part of The World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

This report was supported by the Climate-Smart Mining Initiative of the World Bank Group. The Climate-Smart Mining Initiative is supported by Anglo American, the Netherlands Ministry of Foreign Affairs, and Rio Tinto. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ) also supported the development of this report. We would also like to thank Jane Sunderland (editor) and Mark Lindop (designer).

Rights and Permissions

The material in this work is subject to copyright. Because the World Bank encourages dissemination of its knowledge, this work may be reproduced, in whole or in part, for noncommercial purposes as long as full attribution to this work is given.

Any queries on rights and licenses, including subsidiary rights, should be addressed to:

World Bank Publications
The World Bank Group
1818 H Street NW
Washington, DC 20433,
USA

Fax: 202-522-2625

Table of Contents

Foreword	7
Acknowledgments	8
Abbreviations	9
Executive Summary	11
Methodology - Estimating Mineral Demand	19
Overall Methodology	19
Recycling, Reuse	25
Global Warming Potential	26
Model Uncertainty	28
The Role of Minerals in the Clean Energy Transition	31
Renewable Energy and Storage Forecast	32
Mineral Intensity of Clean Energy Technologies	37
Solar Photovoltaic	38
Wind	45
Geothermal	51
Concentrated Solar Power	55
Energy Storage	59
Emerging Energy Technologies	65
Overall Mineral Demand up to 2050	71
Mineral Recycling, Reuse	80
Global Warming Potential of Energy Technologies, Minerals	87
GWP of Energy Technologies	87
GWP of Minerals	88
Conclusion	93
Rising Overall Demand for Minerals	93
Mineral Demand Vulnerability and Risks	93
Role of Recycling and Reuse	95
Emissions Mitigation and Reduction Opportunities	95
Risks Beyond the Model	97
Next Steps and Actions	99
Annex A: About Climate-Smart Mining	101
Annex B: Methodology	102
Annex C: Uncertainties	107
References	108

Figures

Figure ES.1	Projected Annual Average Demand of Minerals up to 2050 Under the IEA Energy Technology Perspective Scenarios	11	Figure 3.11	Cumulative Demand for Neodymium from Wind Technologies Under Present Technology and Material Use Reduction Under 2DS Through 2050	49
Figure ES.2	Total Molybdenum Demand by Energy Technology Through 2050 Under 2DS	12	Figure 3.12	Share of Mineral Demand from Geothermal Under 2DS Through 2050	51
Figure ES.3	Cumulative Demand for Indium from Solar PV Subtechnologies Compared to Base Share Under 2DS Through 2050	13	Figure 3.13	Cumulative Demand for Minerals Needed for Geothermal Through 2050	52
Figure ES.4	Aluminum Recycling Projections Relative to Annual Aluminum Demand Under 2DS Through 2050	14	Figure 3.14	Total Titanium Demand by Energy Technology Through 2050 (2DS, Base Scenario)	52
Figure ES.5	Cumulative Global Warming Potential from Extraction and Processing of Minerals, Not Including Operations, Using Cradle-to-Gate Through 2050 Under 2DS	15	Figure 3.15	Share of Mineral Demand from Concentrated Solar Power Under IEA 2DS Through 2050	55
Figure 1.1	Technology Coverage in the Model	22	Figure 3.16	Cumulative Demand for Minerals Needed for Concentrated Solar Power Through 2050	56
Figure 1.2	Methodology for Estimating Demand of Minerals for 2050 Energy Technology Scenarios	23	Figure 3.17	Total Silver Demand by Technology Through 2050 (2DS, Base Scenario)	56
Figure 1.3	Schematic of Global Warming Potential Component of Model	28	Figure 3.18	Li-ion Battery	60
Figure 2.1	Estimated Installed Capacity in 2050 Across the Technology-Based Mitigation Scenarios	33	Figure 3.19	Share of Mineral Demand from Energy Storage Under IEA 2DS Through 2050	61
Figure 2.2	Expected Growth in Energy Storage Through 2050	35	Figure 3.20	Cumulative Demand for Minerals Needed for Energy Storage Through 2050	62
Figure 3.1	Share of Mineral Demand from Solar Photovoltaic Under the IEA 2DS Through 2050	40	Figure 3.21	Cumulative Demand for Minerals from Li-ion Battery Scenarios Under 2DS Through 2050	63
Figure 3.2	Cumulative Demand for Minerals Needed for Solar Photovoltaic Through 2050	40	Figure 3.22	Cumulative Demand for Lithium from Energy Storage Under Present Technology and Material Use Reduction Through 2050 Under 2DS, B2DS	64
Figure 3.3	Total Aluminum Demand by Energy Technology Through 2050 (2DS, Base Scenario)	41	Figure 3.23	Carbon Capture Storage	65
Figure 3.4	Total Indium Demand by Energy Technology Through 2050 (2DS, Base Scenario)	41	Figure 3.24	Solid-State Battery	66
Figure 3.5	Cumulative Demand for Indium from Solar PV Subtechnologies Compared to Base Share Under 2DS Through 2050	42	Figure 3.25	Floating Offshore Wind	68
Figure 3.6	Evolution of the Wind Turbine	45	Figure 3.26	Hydrogen Fuel Cell	69
Figure 3.7	Share of Mineral Demand from Wind Under IEA 2DS Through 2050	46	Figure 4.1	Cumulative Demand for Minerals for Energy Technologies (Without Storage) Through 2050 Only Under 4DS, B2DS, and REmap	71
Figure 3.8	Cumulative Demand for Minerals Needed for Wind Through 2050	47	Figure 4.2	Relative Change in Demand for Minerals from Energy Technologies (Without Storage) Through 2050 Under RTS, Ref, B2DS, and REmap, Compared to Base Scenario	72
Figure 3.9	Total Zinc Demand by Energy Technology Through 2050 (2DS, Base Scenario)	47	Figure 4.3	Projected Annual Mineral Demand Under 2DS Only from Energy Technologies in 2050, Compared to 2018 Production Levels	73
Figure 3.10	Cumulative Demand for Neodymium from Wind Subtechnologies Compared to Base Share Under 2DS Through 2050	48			

Tables

Figure 4.4	Total Copper Demand by Energy Technology Through 2050 Under 2DS	75	Table 1.1	Energy Technologies Included in This Study	20
Figure 4.5	Total Molybdenum Demand by Energy Technology Through 2050 Under 2DS	75	Table 1.2	Minerals Identified in the Literature Review for Inclusion in the Scenario Study	20
Figure 4.6	Cumulative Copper and Molybdenum Demand Through 2050 (2DS, Base Scenario)	76	Table 1.3	Technology-Based Mitigation Scenarios	21
Figure 4.7	Demand Risk Matrix Under 2DS	78	Table 1.4	Assumed Subtechnology Shares in 2050	24
Figure 4.8	Impact of Recycling on Cumulative Demand for Aluminum and Copper Under 2DS Through 2050	81	Table 1.5	Assumed Lifetime of Technologies	24
Figure 4.9	Impact of Recycling on Cumulative Demand for Nickel Under 2DS Through 2050	82	Table 1.6	End-of-Life Recycling Rates and Recycled Content Rates	25
Figure 4.10	Impact of Recycling on Cumulative Demand for Cobalt and Lithium Under 2DS Through 2050	82	Table 2.1	Shortened Technology-Based Mitigation Scenarios from IEA and IRENA	32
Figure 4.11	Impact of Reuse on Cumulative Demand for Lithium Under 2DS Through 2050	83	Table 3.1	Mapping Minerals with Relevant Low-Carbon Technologies	37
Figure 5.1	Cumulative GWP Through 2050 from "Cradle to Gate" Mineral Extraction and Processing, Operations of Renewable Electricity Generation, and Energy Storage Technologies Compared to Fossil Fuel Technologies Through 2050	87	Table 3.2	Share of Subtechnology Penetration in Solar PV Market Compared with Base Share Under 2DS	42
Figure 5.2	Total Cumulative Emissions from Cradle to Gate for Energy Technologies Through 2050 Under 2DS Compared to the Demand Index (MtCO ₂ e)	89	Table 3.3	Share of Subtechnology Penetration in Wind Market Compared with Base Share	48
Figure 5.3	Cumulative GWP from Extraction and Processing of Minerals, Not Including Operations, Using Cradle-to-Gate by Technology Through 2050 Under 2DS	91	Table 3.4	Batteries and Their Subtechnologies Covered in the Ref, 2DS, and B2DS	61
Figure A.1	Climate-Smart Mining Building Blocks	101	Table B.1	Implication of Clean Energy Transition on Mineral Demand Challenges	103
Figure B.1	Lithium Prices, 2010–2019	106	Table B.2	2018 Mineral Production and 2050 Projected Annual Demand from Energy Technologies	103

Box

Box 5.1	Reducing Emissions from Aluminum Production Demand from Energy Technologies	90
----------------	---	-----------



Foreword

The data presented in this report speak for themselves: Ambitious climate action will bring significant demand for minerals. Limiting global warming to at or below 1.5°C–2°C, to realize a low-carbon future, requires a large-scale transition to clean energy. Manufacturing solar panels, wind turbines, and batteries will shape the supply and demand for critical minerals for the foreseeable future. Doing so will have significant implications for a wide variety of industries and for mineral-rich developing countries. These countries stand to benefit from the rise in demand for minerals but also need to manage the material and climate footprints associated with increased mining activities.

This report's findings make it clear that all stakeholders along the mineral and renewable energy supply chains have a vital role to play in the transition to a cleaner energy system to achieve Sustainable Development Goal 7 (Affordable and Clean Energy for All), while ensuring that it does not come at the cost of the climate, the environment, and people, particularly communities directly affected by mining activities.

In 2017, the World Bank published *The Growing Role of Minerals and Metals for a Low Carbon Future*, concluding that a low-carbon future will not be possible without minerals. This report makes that case even stronger, but with a new emphasis on how technology improvements and recycling could impact mineral demand up to 2050. For the first time, the global warming potential of different low-carbon technologies were analyzed in comparison with fossil-fuel-based energy systems. We also present a new framework to capture the risks associated with the demand for specific critical minerals.

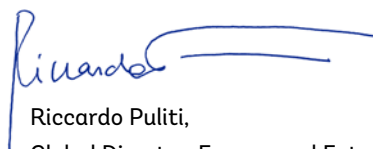
This report intends to provide policy makers, mineral producers, renewable energy developers, climate negotiators, and civil society organizations with a data-driven understanding of how the shift to a cleaner energy system could impact mineral demand. It also provides a forward-looking outlook on the actions each stakeholder can take to minimize the carbon and material footprints of such a significant shift.

The mineral intensity of low-carbon technologies should not be overlooked. We know that to date, the mining industry consumes up to 11 percent of the global energy use, while 70 percent of mining projects from the six largest mining companies operate in water-stressed regions. Increasing demand for minerals and metals would only push these figures higher unless we adopt a radically different, climate-smart approach. Understanding these new, climate-related risks will be critical for all stakeholders involved in renewable energy and battery technology supply chains—from extraction to the end use of any given mineral or metal.

While the mineral intensity of renewable energy has its challenges, our research shows that, even if low-carbon technologies are more mineral intensive, they only account for a fraction (6 percent) of emissions generated by fossil fuel technologies. This means that the deployment of renewable energy is essential in helping us meet the Paris Agreement, even if it means that more minerals will be needed to get there.

To address these challenges, the World Bank launched the Climate-Smart Mining Initiative to ensure that minerals for the clean energy transition are produced and supplied sustainably and responsibly, while enabling developing countries to benefit from this seismic shift. The goal is to ensure that mineral-rich developing countries are well prepared to meet this growing demand with the smallest possible carbon footprint, while safeguarding the environment and people.

I am confident that, with the adoption of climate-smart mining, we can make the clean energy transition possible without endangering the climate and the environment. By working together to reduce the carbon and material footprints of minerals, we can support the large-scale deployment of renewable energy and battery storage technologies required to meet ambitious climate targets and achieve a low-carbon future that benefits everyone.



Riccardo Puliti,
Global Director, Energy and Extractive Industries
World Bank

Acknowledgments

This report was developed by the Climate-Smart Mining Team of the World Bank's Energy and Extractive Global Practice. The team was led by Daniele La Porta and Kirsten Hund. The primary authors and research team consisted of Thao P. Fabregas (formerly Nguyen), Dr. Tim Laing (University of Brighton), and John Drexhage. Emmanouela Markoglou and Clare Murphy-Mcgreevy provided communications support. Aisha I. Agily and Helen Ba Thanh Nguyen provided organizational support.

The team is grateful for the input and contributions received from the following individuals: Ivan Jacques, Michael McCormick, Marcelo Mena-Carrasco, Peter Mockel, Remi Pelon, Sven Ulrich Renner, Benjamin Sprecher (Leiden University), Ester van der Voet (Leiden University), and Sean Whittaker.

We would like to thank the experts who provided feedback during the modeling phase: Matthew Eckelman (Northeastern University), Jagabanta Ningthoujam (Rocky Mountain Institute), Phillip Nuss (German Environment Agency), and Kohji Tokimatsu (Tokyo Institute of Technology).

The report's model was built from the original publication *The Growing Role of Minerals and Metals for a Low Carbon Future* and benefited from insight, feedback and data from a number of other esteemed colleagues. Our sincerest thanks go to all of them.

Lastly, the team greatly appreciates the input and guidance from Christopher Sheldon and Riccardo Puliti.

Abbreviations

2DS	2-degree scenario (IEA)
4DS	4-degree scenario (IEA)
B2DS	beyond 2-degree scenario (IEA)
CCS	carbon capture and storage
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CSP	concentrated solar power
CO₂	carbon dioxide
CO₂e	carbon dioxide equivalent
EOL	end of life
GHG	greenhouse gas
Gt	gigatons
GW	gigawatts
GWh	gigawatt-hours
GWP	global warming potential
ICMM	International Council on Mining and Metals
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	levelized cost of energy
Li-ion	lithium-ion
Mt	million tons
MW	megawatts
NDC	Nationally Determined Contribution
NMC	nickel manganese cobalt oxide
OECD	Organisation for Economic Co-operation and Development
PV	photovoltaic
RC	recycled content
Ref	reference scenario (IRENA)
REmap	renewable energy roadmap scenario (IRENA)
RTS	reference technology scenario (IEA)
SDG	Sustainable Development Goal

All dollars are U.S. dollars unless otherwise indicated.



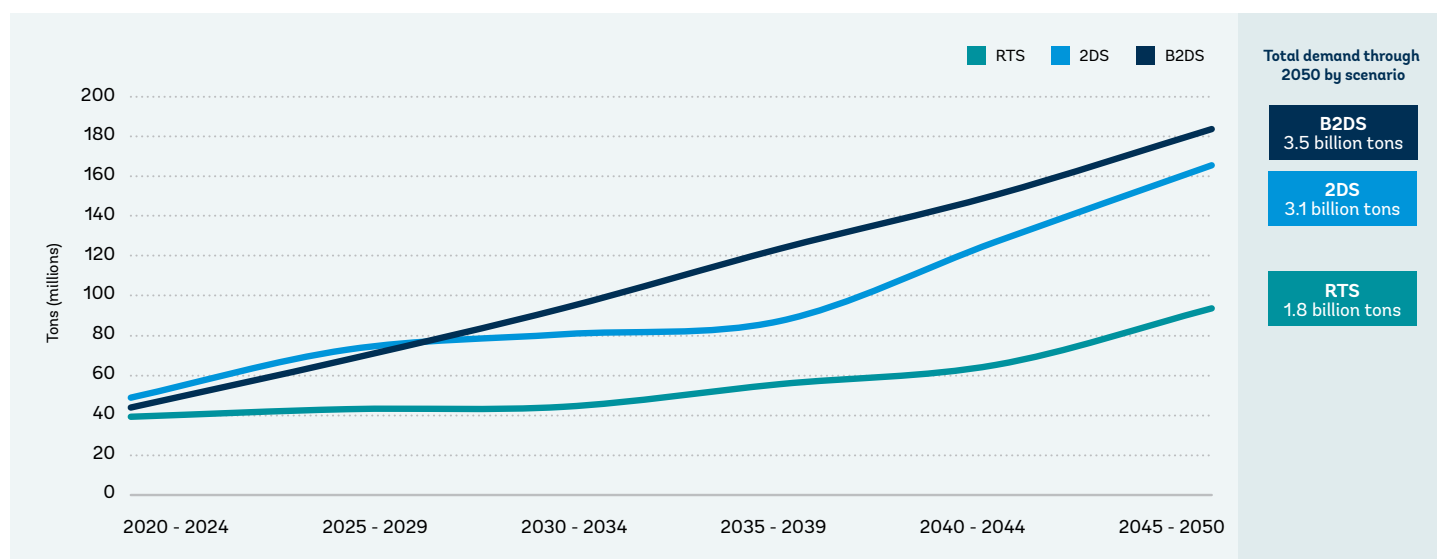
Executive Summary

1. A low-carbon future will be very mineral intensive because clean energy technologies need more materials than fossil-fuel-based electricity generation technologies. Greater ambition on climate change goals (1.5°C–2°C or below), as outlined by the Paris Agreement, requires installing more of these technologies and will therefore lead to a larger material footprint.¹

Low-carbon technologies, particularly solar photovoltaic (PV), wind, and geothermal, are more mineral intensive relative to fossil fuel technologies. For example, about 3,000 solar panels are needed for 1 megawatt (MW) of capacity of solar PV; this means that a 200 MW solar PV project could be as big as 550

American football fields (Mathis and Eckhouse 2020). Under a 2-degree scenario (2DS),² production of graphite, lithium, and cobalt will need to be significantly ramped up by more than 450 percent by 2050—from 2018 levels—to meet demand from energy storage technologies.³ Though demand for some base minerals, like aluminum and copper, appears to be smaller in percentage terms, their absolute production figures are significant, at 103 million tons and 29 million tons by 2050, respectively. These projections do not include the associated infrastructure needed to support the deployment of these technologies (for example, transmission lines) or the physical parts (like the chassis⁴ of newly built electric vehicles).⁵ Because of the material intensity of low-carbon technologies, any potential shortages in mineral supply could impact the speed and scale at which certain technologies may be deployed globally.

Figure ES.1 Projected Annual Average Demand of Minerals up to 2050 Under the IEA Energy Technology Perspective Scenarios



Note: "Minerals" refers to the 17 minerals included in this analysis plus steel, but excluding concrete. Steel has been included because of the size of demand for the alloy from energy technologies. Average annual demand is the mean demand for minerals across the time periods given. The higher mineral demand under the 2DS compared with the B2DS before 2030 can be explained by the higher overall generation capacity projected by the IEA to be needed in the 2DS compared with the B2DS. This is especially true of solar photovoltaic in the 2DS in these time periods. Subsequently, the plateau in mineral demand in the 2DS is caused by a relatively slower penetration of renewable generation, followed by a rapid increase in storage capacity from 2035 onward. 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, RTS = reference technology scenario.

- 1 This report does not intend to forecast what will happen, but instead provide a range of scenarios to explore the future global energy system and how different policy choices and technology improvements could affect overall mineral demand up to 2050.
- 2 2DS—along with B2DS (beyond 2-degree scenario) and RTS (reference technology scenario)—refers to one of the scenarios developed in the International Energy Agency (IEA) *Energy Technology Perspectives 2017*. Please refer to chapter 1 for additional information.
- 3 These projections may be conservative and will most likely be larger in a 1.5°C-degree scenario, which demands solutions to be implemented faster, and at a larger scale.
- 4 "Chassis" refers to the frame of car and associated components.
- 5 Steel figures have not been included in this analysis because of potential double counting issues.

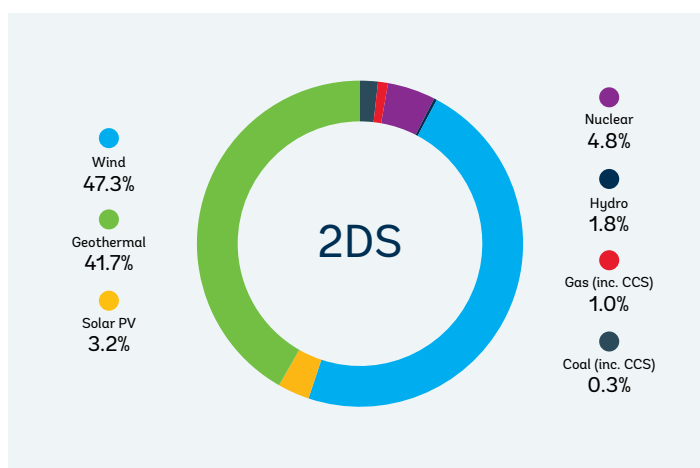
2. Each mineral carries a different demand risk depending on whether it is cross-cutting (needed across a range of low-carbon technologies) or concentrated (needed in one specific technology). Absolute production numbers and relative increases in demand for each mineral may also play a role in their ability to meet supply as well as have climate and environmental implications.

Cross-cutting minerals, such as copper, chromium, and molybdenum, are used across a wide variety of clean energy generation and storage technologies and have stable demand conditions. This is because these minerals do not depend on the deployment of any one specific technology within the clean energy transition. Molybdenum and copper, for instance, are used in more than eight clean energy generation and storage technologies; thus, even if technological improvements, costs reductions, and deployment of new emerging technologies were to take place, these changes would have little impact on the overall demand for them. For copper, the greatest share of demand comes from solar PV and wind, but demand may be underestimated as it does not include the transmission infrastructure needed to connect these new technologies to electricity grids.

Concentrated minerals, such as lithium, graphite, and cobalt, are needed only for one or two technologies and therefore possess higher demand uncertainty as technological disruption and deployment could significantly impact their demand. These minerals are primarily used in energy storage and have the highest demand figures relative to 2018 production levels. With energy storage having the highest level of uncertainty post-2030 given the number of energy storage subtechnologies currently at the research and development (R&D) and pilot stages, as well as different policy choices and market forces, concentrated minerals have the highest level of demand risk, particularly for producers of these minerals.

Beyond cross-cutting versus concentrated, some minerals face higher levels of changes in demand from the shift to a low-carbon future. Graphite and lithium demand are so high that current production would need to ramp up by nearly 500 percent by 2050 under a 2DS just to meet demand. Demand for aluminum for energy technologies in 2050, on the other hand, makes up only 9 percent of current production levels, but aluminum is used across a broad range of technologies, making it less susceptible to changes in technology deployment, and it has the highest absolute levels of demand from any of the minerals in this analysis. Understanding these different demand risks is crucial for mining and energy industries that must be adaptive to rapidly evolving energy technologies. To facilitate the understanding of the relationship between cross-cutting and concentrated minerals, as well as the different levels of demand, this report has developed a demand risk matrix (figure 4.7) that can be used by stakeholders and policy makers, allowing minerals to be categorized based on their demand risk profile.

Figure ES.2 Total Molybdenum Demand by Energy Technology Through 2050 Under 2DS



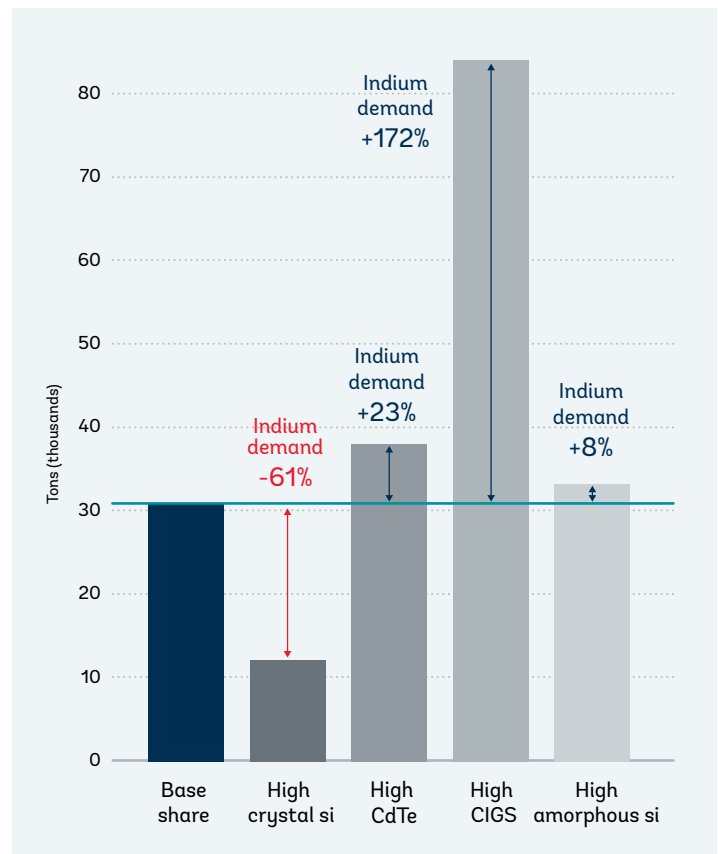
Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, PV = photovoltaic.

3. Technology and subtechnology choice, material substitution, and technological improvements will shift the demand for individual minerals under different low-carbon scenarios. Still, any lower-carbon pathway will increase the overall demand of minerals.

Under a 2DS, solar PV will account for the majority of aluminum demand from energy technologies (87 percent), while wind and geothermal will account for most zinc and titanium demand, at 98 percent and 64 percent, respectively. Solar PV and wind, combined, account for 74.2 percent of all copper demand, while battery storage accounts for all graphite and lithium demand in this analysis. Each energy technology has different mineral compositions, leading to demand features that can vary significantly from one technology to another.

Substitution effects, such as efficiency improvements, could have strong impacts on the demand for individual minerals, like indium, based on which subtechnology within a technology ends up being most widely deployed up to 2050. Factors that could drive substitution effects include market dynamics, availability of minerals, technological improvements, and costs. The technology pathway that will emerge to decarbonize electricity production will shape the minerals that will experience the largest increases in demand. It is possible that new technologies such as floating offshore wind, green hydrogen, or solid-state batteries may change the shape of the future energy system. These technologies require different minerals and carry different mineral demand implications, but given that they are generally more material intensive than their fossil-fuel-based counterparts, overall demand for minerals will still increase.

Figure ES.3 Cumulative Demand for Indium from Solar PV Subtechnologies Compared to Base Share Under 2DS Through 2050



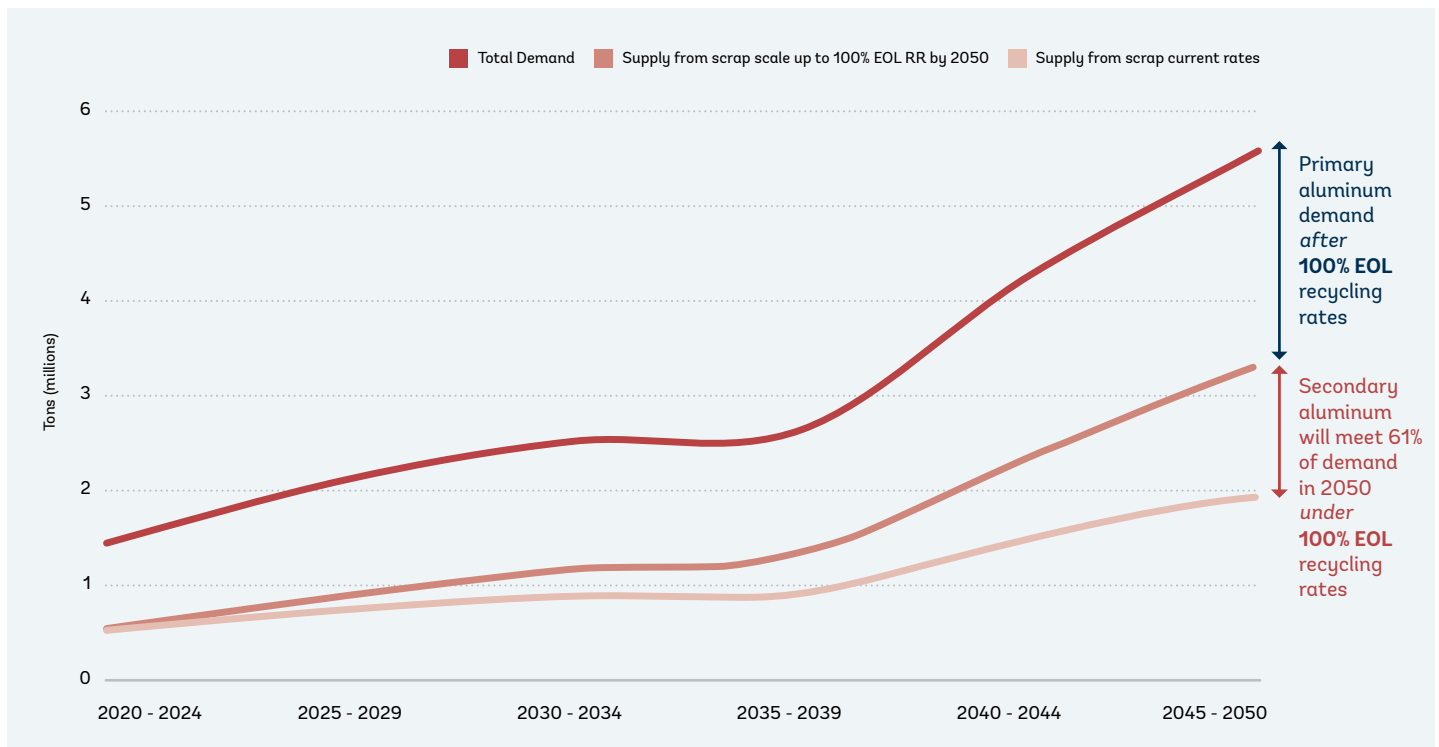
Note: 2DS = 2-degree scenario, amorphous Si = amorphous silicon, CdTe = cadmium telluride, CIGS = copper indium gallium selenide, crystal Si = crystalline silicon, PV = photovoltaic.

4. While the recycling and reuse of minerals can play a key role in reducing emissions, mining will still be required to supply the critical minerals needed to produce these low-carbon technologies, even with large future increases in recycling rates.

Recycling and reuse will have a role in meeting future mineral demand, but primary mineral demand from mining will still be needed. Recycling rates vary greatly for all minerals due to costs and technical issues. The challenge with meeting most of the demand from recycling is partly due to lack of existing material to recycle and reuse, along with costs and technological barriers (for example, some technologies may not be easily recyclable due to design). Facilitating recycling and reuse is a vital part

of the low-carbon transition, but policy measures will need to incentivize action in this area while promoting awareness of the economic and environmental challenges associated with the processes of recycling. Future increases in recycling rates can play an important role in mitigating increases in demand for raw materials, as can reuse of components for energy storage technologies, such as lithium-ion batteries, and refurbishment of equipment, such as wind turbines. Even if these challenges in the mineral recycling sector can be overcome, there is still a need to meet remaining primary demand in the most effective and environmentally and socially responsible manner. It will be crucial for importers of these critical minerals with ambitious climate targets, particularly in developed countries, to work closely with mineral producers in developing countries to decarbonize and reduce the material impacts associated with increased extractive activities.

Figure ES.4 Aluminum Recycling Projections Relative to Annual Aluminum Demand Under 2DS Through 2050



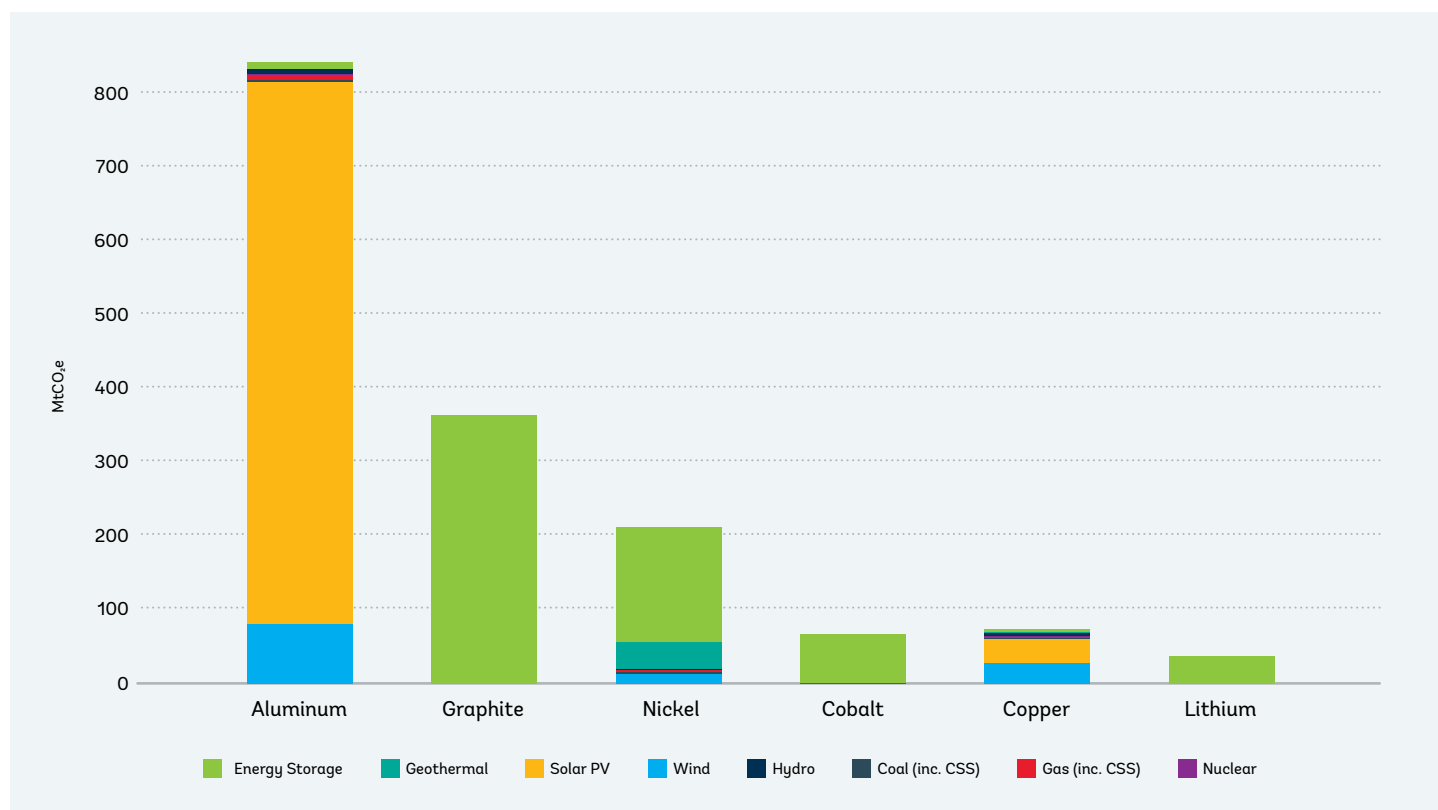
Note: EOL recycling rates are assumed to increase annually to meet 100 percent EOL by 2050. This means that secondary aluminum meets an increasing amount of aluminum demand over time. 2DS = 2-degree scenario, EOL = end of life, RR = recycling rates.

5. Despite the higher mineral intensity of renewable energy technologies, the scale of associated greenhouse gas emissions is a fraction of that of fossil fuel technologies. However, the carbon and material footprints cannot be overlooked.

While increasing the share of renewable energy is one of the most effective ways of decarbonizing the electricity sector, the countries who have committed to the Paris Agreement need to address the mineral intensity of clean energy technologies. Emissions from the production and operation of renewable energy and storage technologies are just 6 percent of coal and gas generation under

a 2DS. They account, however, for about 16 gigatons of carbon dioxide equivalent (GtCO₂e) emissions up to 2050—similar to the 2018 emissions of the United States and China—without factoring in the emissions from transporting minerals between processing and manufacturing facilities. Together, aluminum, graphite, and nickel production for energy technologies account for a cumulative 1.4 GtCO₂e up to 2050, nearly equivalent to the total 2018 carbon dioxide emissions from France, Germany, and the United Kingdom combined.⁶ Greening the power sector and battery production requires that upstream and downstream emissions-related challenges from clean energy technologies be meaningfully addressed through policy and innovation while integrating these emissions reductions into countries' Nationally Determined Contributions under the Paris Agreement.

Figure ES.5 Cumulative Global Warming Potential from Extraction and Processing of Minerals, Not Including Operations, Using Cradle-to-Gate Through 2050 Under 2DS



Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, MtCO₂e = million tons of carbon dioxide equivalent.

6 Data retrieved from the 2019 Global Carbon Atlas: <http://www.globalcarbonatlas.org/en/CO2-emissions>.

6. Limiting the carbon footprint of minerals needed for the clean energy transition may offer double wins, helping to boost economic growth and reduce environmental risks in resource-rich developing countries. It will also enable the transition to a 1.5°C–2°C pathway, in line with the Paris Agreement, Sustainable Development Goal (SDG) 7, “access to affordable, reliable, sustainable and modern energy for all,” and SDG 13, taking “urgent action to combat climate change and its impacts.”

Taking a holistic approach toward increasing climate ambition in developed, emerging, and developing countries, as well as in producers and consumers of minerals, involves understanding and analyzing the full supply chain of low-carbon technologies, from mineral extraction to the end of life of these technologies. Thus, upstream and end-of-life activities of clean energy technologies must be taken into account to ensure that (1) the mining industry can meet increasing demand up to 2050 using sustainable and responsible practices; (2) governments and the private sector address the emissions associated with increased

mineral production while ensuring a continued, stable, and affordable supply of these minerals to support a low-carbon transition; and (3) innovation across the whole supply chain is leveraged to ensure low-carbon technologies can be easily disassembled and safely disposed of, and the mineral contents recycled to partially meet this new demand.

Limiting greenhouse gas emissions throughout the clean energy technology supply chain could offer double wins, helping boost economic growth as well as reducing climate and environmental risks in resource-rich developing countries that are positioned to supply these minerals. If, however, the mitigation of emissions and other potentially harmful environmental and social effects are not achieved from increased mineral production, there is a risk that clean energy technologies may not maintain the same level of support they have today for climate action. Therefore, it is vital that the production and disposal of these technologies do not come at the expense of people and the environment. The mining sector has an important role in the clean energy transition, contributing to SDG 7, and can play a crucial role in the global fight against climate change (SDG 13, Paris Agreement). Ensuring that innovation takes a center stage in decarbonizing and encouraging responsible mineral production would equally contribute to SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production).



7. The **Climate-Smart Mining Initiative** addresses these challenges by working together with governments, development partners, industries, and civil society to minimize the new emissions from a low-carbon transition and work closely with resource-rich developing countries to responsibly supply these strategic minerals for clean energy technologies.

Combining climate-smart mining with an overview of the different demand risks of minerals, via the demand risk matrix, provides a framework for climate, energy, and mining stakeholders to understand and mitigate risks associated with providing a stable supply of minerals while limiting the carbon and material footprints of increased climate ambition. Each stakeholder along the supply chain has a role to play:

- **Climate stakeholders:** With minerals playing a vital role in enabling the clean energy transition, it will be crucial for members of the climate community to work closely with producers of those minerals—including resource-rich developing countries and the mining industry—to ensure that these emissions are mitigated. Mineral-rich countries that make it a priority to reduce emissions from mineral production, through *climate-smart mining* practices, could assess options to integrate their decarbonization efforts in their Nationally Determined Contributions under the Paris Agreement.
- **Clean energy stakeholders:** The energy sector also has an important role to play in ensuring that the low-carbon technologies they are deploying are being produced sustainably and responsibly while taking into account the waste management of these technologies once they reach end of life, in 10, 20, or 30 years from today. The mining sector accounts for 2–11 percent of the world’s total energy consumption, so it will be important for the energy sector to work closely with mineral producing countries and miners to ensure that minerals are produced using clean sources of energy and *climate-smart mining* practices.
- **Mining stakeholders:** The mining community should position itself as a contributor to SDG 7 by ensuring that the carbon and material footprints associated with the minerals they supply are minimized. Innovation is necessary to reduce the amount of energy, water, and land needed to extract these minerals and reduce the sector’s carbon and environmental footprints. Without putting into place measures that address these challenges, such as adapting *climate-smart mining* practices, it will be difficult for the mining sector to position itself as a champion and enabler of the clean energy transition.





Methodology

Estimating Mineral Demand

The methodology in this report is based on a spreadsheet-based model that derives the total global demand of relevant minerals and metals (together referred to as “**minerals**”) from electricity generation and energy storage up to 2050.⁷ The electricity generation and energy storage scenarios (together referred to as “**technology-based mitigation scenarios**”) use data from the International Energy Agency’s (IEA) *Energy Technology Perspectives 2016* and *Energy Technology Perspectives 2017* and the International Renewable Energy Agency’s (IRENA) *2019 Global Energy Transformation: A Roadmap to 2050*, to identify the amount of minerals that would be required under each scenario to supply clean energy technologies.

While the analysis estimates mineral demand from energy storage as well as geothermal, solar, wind, and conventional energy technologies, it does not take into account the global supply of minerals available to date to meet demand, nor the new mineral demand that will come from new global transmission infrastructure needed to electrify a low-carbon world (for example, connecting renewable energy projects to existing transmission infrastructure and creating new charging stations for electric vehicles). It also does not consider the current and future price of energy technologies, nor the price of minerals required for the energy transition. In other words, this report exclusively analyzes the amount of minerals that will be needed to supply a specific subset of clean energy technologies (listed below) regardless of price and whether today’s mineral supply worldwide would be able to meet this new demand up to 2050.

Overall Methodology

The methodology was developed using primary and secondary research to build a robust model to determine potential mineral demand stemming from the clean energy transition. A literature scoping study and interviews with clean energy experts were conducted to review mineral use in electricity generation and energy storage technologies for clean and conventional energy. This information was then used to develop the assumptions used in the model to estimate annual mineral demand. These annual demands were then aggregated into cumulative demand up to 2050. Key assumptions in the model included technology-based mitigation scenarios based on IEA and IRENA outlooks; technology and subtechnologies required to reach those scenarios; assumed life spans of those technologies; and the minerals required to supply a megawatt of electricity or a megawatt-hour of energy storage from each technology included in the model. The model has static and dynamic elements. The capacity required for each energy technology and subtechnology varies from year to year, depending on the relevant technology-based mitigation scenarios. Other aspects, such as the minerals required to supply a megawatt or megawatt-hour of electricity or energy storage, and the life spans of the technologies, remain static in the model, although the sensitivity of results to altering the first of these assumptions is tested.

Literature Scoping Study

The approach included identifying the subtechnologies within each energy technology necessary to include in the analysis to derive mineral demand (see table 1.1). For example, many variants of solar PV panels exist on the market today, and each has slightly different mineral requirements. Wind turbines can come in a number of different models, too, and onshore and offshore wind turbines require different amounts of minerals. *Subtechnologies* are these different types of solar panels, wind turbines, or batteries.

The report then identified a list of 17 minerals for inclusion in the analysis (see table 1.2).

⁷ This report builds on the World Bank’s previous report, *The Growing Role of Minerals and Metals for a Low Carbon Future* (June 2017), and adopts a similar methodology. The analysis covers 17 elements and minerals: Sixteen are produced and used after various amounts of extraction and processing, while one, graphite, is a particular form of carbon.

Table 1.1 Energy Technologies Included in This Study

Energy technologies									
Clean energy (electricity generation)	Technology	Subtechnology	Energy storage	Technology	Subtechnology	Conventional energy (electricity generation)	Technology	Subtechnology	
	Concentrated solar power	n.a.		Battery: Automotive	Split between Li-ion, lead acid, and other		Coal	Coal-fired electricity generation	
	Hydro-electricity	n.a.		Battery: Decentralized	Split between Li-ion, lead acid, and other			Coal-fired electricity generation + CCS	
	Geothermal	n.a.		Battery: Grid-scale	Split between Li-ion, lead acid, redox flow, and other		Gas	Gas-fired electricity generation	
	Nuclear	n.a.						Gas-fired electricity generation + CCS	
	Solar PV	Solar PV – CdTe							
		Solar PV – crystal silicon							
		Solar PV – CIGS							
		Solar PV – amorphous silicon							
	Wind	Offshore							
Onshore									

Note: The mineral demand for the technologies listed here have been included in the overall mineral demand results for this study. CCS = carbon capture and storage, CdTe = cadmium telluride, CIGS = copper indium gallium selenide, Li-ion = lithium-ion, n.a. = not applicable, PV = photovoltaic.

Data collected from the literature review also included the amount of elements and minerals (henceforth referred to as minerals) needed (see table 1.2) to build a megawatt of capacity of a particular subtechnology; this has been typically expressed by the mineral's weight, in kilograms, of installed megawatt (kg/installed MW). For example, one data source may report the zinc required to build a 3 MW wind turbine, while another source gives the zinc needed for a 5 MW turbine. These numbers have been standardized to give the amount of zinc needed to produce 1 MW of a wind turbine.

Different estimates were collected, and for each mineral-subtechnology pairing—such as zinc for offshore wind or lithium for Li-ion batteries—a low, median, and high value were chosen. These different values were used in the model to produce an estimated range of mineral demand. The midpoint of this range is reported in this analysis.

Table 1.2 Minerals Identified in the Literature Review for Inclusion in the Scenario Study

1	Aluminum	10	Manganese
2	Chromium	11	Molybdenum
3	Cobalt	12	Neodymium
4	Copper	13	Nickel
5	Graphite	14	Silver
6	Indium	15	Titanium
7	Iron	16	Vanadium
8	Lead	17	Zinc
9	Lithium		

Technology-Based Mitigation Scenarios

As mentioned above, “**technology-based mitigation scenarios**” refers to the electricity generation and energy storage scenarios up to 2050 that were drawn from the IEA and IRENA. More specifically, this report uses six technology-based mitigation scenarios to estimate mineral demand (table 1.3).

An important distinction to make about the IEA and IRENA scenarios is that the 2017 IEA scenarios include outlook on both electricity generation and energy battery storage penetration, while the IRENA scenarios and the IEA 4DS exclusively focus on electricity generation. In other words, the IRENA scenarios and IEA 4DS do not report the penetration of energy storage in the clean energy transition.

While the 4DS is not used in the models for the IEA’s 2017 ETP scenarios or in IRENA’s 2019 scenarios, it has been retained here as the base scenario, which is defined as the state of affairs where there is marginal progress toward a low-carbon transition. This is done not because a 4DS is likely or normative, but to compare the relative demand for relevant minerals between a future with and without low-carbon technology penetration in the global energy system.

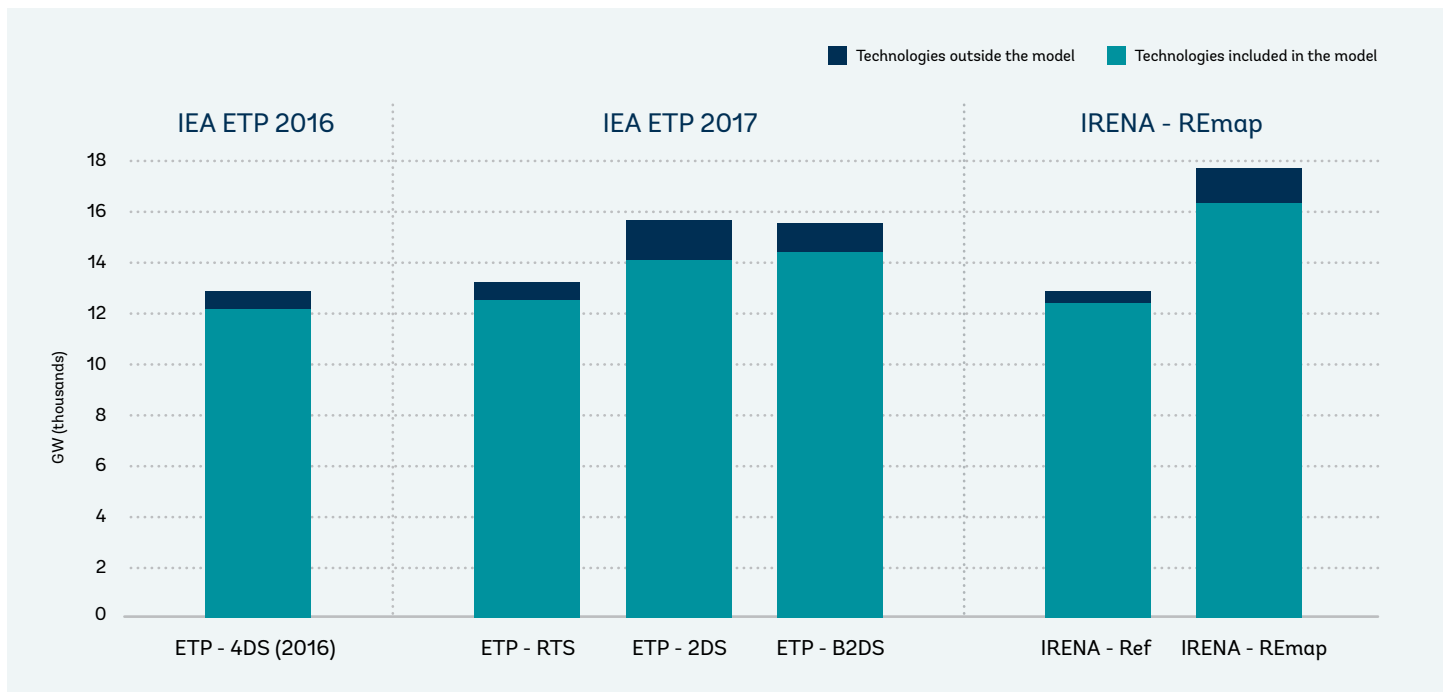
The IEA and IRENA also hold the view that the state of technology capacity is already sufficient to meet even the most ambitious of the global temperature scenarios. That said, neither agency speculates on the relative availability of the materials required to actually implement that scale of low-carbon technology penetration.

Table 1.3 Technology-Based Mitigation Scenarios

Technology-Based Mitigation Scenarios			
	Scenario acronym	Source	Scenario description
1	4DS (Base scenario)	4-degree scenario from the IEA ETP (2016) report	Base scenario , where the world carries on a current trajectory, makes minor improvements in shifting energy system away from fossil fuel sources
2	RTS	Reference technology scenario from the IEA ETP (2017) report	Assumes all countries will implement their Nationally Determined Contributions (NDCs), as proscribed under the Paris Agreement, resulting in an average temperature increase of 2.7°C by 2100
3	2DS	2-degree scenario from the IEA ETP (2017) report	Scenario with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100
4	B2DS (Most ambitious scenario in the IEA report)	Beyond 2-degree scenario from the IEA ETP (2017) report	Scenario with a 50% chance of limiting average future temperature increases to 1.75°C by 2100
5	Ref	Reference scenario from IRENA (2019a)	Similar to the IEA’s RTS, it accounts for actions, commitments made under current/planned policies, including NDCs. Rise in temperatures would be at least 2.6°C by 2100
6	REmap (Most ambitious scenario in IRENA)	Renewable energy roadmap scenario from IRENA (2019a)	Ambitious scenario that limits the rise in global temperature to “ well below ” 2°C above preindustrial levels by 2100

Note: IEA = International Energy Agency, IRENA = International Renewable Energy Agency, ETP = Energy Technology Perspectives.

Figure 1.1 Technology Coverage in the Model



Source: IEA 2016, 2017; IRENA 2019a.

Note: 2DS = 2-degree scenario, 4DS = 4-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, ETP = Energy Technology Perspectives, GW = gigawatt, Ref = reference scenario, REmap = renewable energy roadmap scenario.

The electricity generation technologies included in the model—clean and conventional—account for the vast majority of future generated electricity in both the IEA and IRENA scenarios (figure 1.1). A very small share of electricity generation is not included, mainly electricity generated from oil-based power stations, biomass power plants, and wave and ocean electricity-generating facilities. These technologies were excluded owing to the lack of publicly available data on the minerals needed for them.

The majority of clean energy technologies, particularly solar PV but also wind (onshore and offshore), are expected to be deployed in developing countries because of large projected increases in electricity demand and accompanying increasing economic development, coupled with significant renewable energy resources, particular solar, in many of these countries. For example, in the IEA's 2DS, installed capacity of solar PV and wind is 117 percent higher in non-Organisation for Economic Co-operation and Development (OECD) countries than in OECD countries by 2050.

For solar PV specifically, the picture is even more striking, with solar PV in non-OECD countries being 208 percent of that in OECD countries.

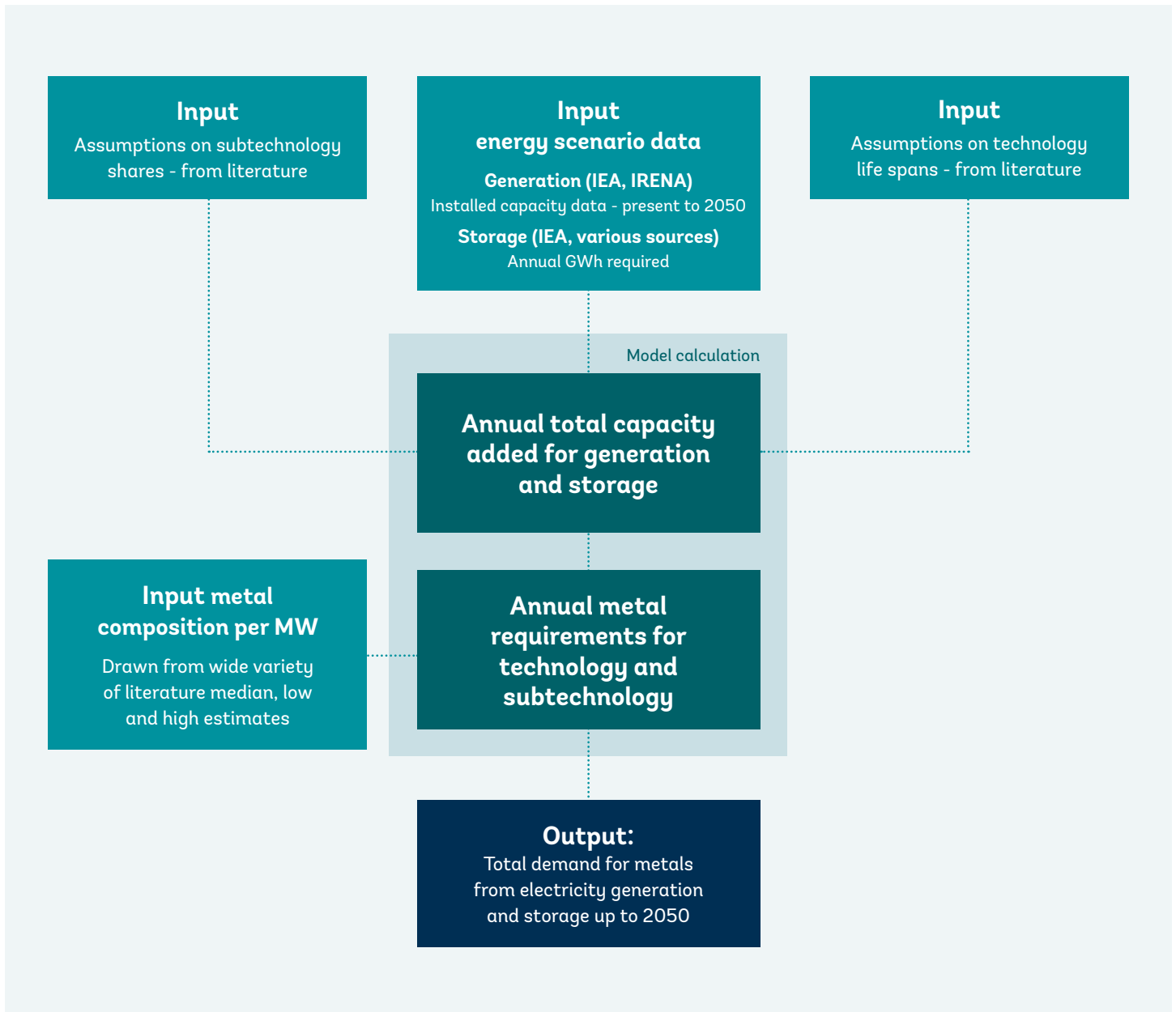
Modeling Inputs

The model approach is shown in figure 1.2. The core inputs are fourfold:

- Technology-based mitigation scenarios developed by the IEA and IRENA
- Technology and subtechnology shares required to meet those scenarios
- Assumed life spans on relevant technologies
- A range of estimates minerals required to supply a megawatt of electricity

Figure 1.2 breaks down the steps used in estimating mineral demand under a range of climate scenarios based on the IEA data.

Figure 1.2 Methodology for Estimating Demand of Minerals for 2050 Energy Technology Scenarios



These four inputs were combined into the model to create two more comprehensive categories of data:

I. Estimated capacity additions for electricity generation and energy storage technologies by 2050.

II. Estimated annual mineral requirements in supplying these technologies, which were then summed through 2050 to derive the final calculations of total demand for minerals from electricity generation and energy storage.

Table 1.4 lays out the penetration of different subtechnologies to 2050 that form the model's base scenario.

Table 1.4 Assumed Subtechnology Shares in 2050

Technology	Subtechnology	2050 Penetration
Energy storage (Automotive)	Lithium-ion	100%
Energy storage (Grid scale)	Lead acid	2.5% – 5% (depending on scenario)
Energy storage (Grid scale)	Lithium-ion	70% – 84% (depending on scenario)
Energy storage (Grid scale)	Redox Flow	2.8% – 3.7% (depending on scenario)
Energy storage (Grid scale)	Other ^a	9.8% – 25%
Energy storage (Decentralized)	Lithium-ion	33%
Energy storage (Decentralized)	Lead Acid	33%
Energy storage (Decentralized)	Other ^a	33%
Solar PV	Crystalline silicon	50%
Solar PV	Cadmium telluride	16.7%
Solar PV	Copper indium gallium selenide	16.7%
Solar PV	Amorphous silicon	16.7%
Wind	Direct drive	25%
Wind	Geared	75%

Note: In the breakdown of battery composition, the refurbishment of car batteries to grid/decentralized energy has not been accounted for in the estimated mineral demand under the various scenarios. It is discussed, however, in the section on reuse in chapter 4.

a. This category represents all other forms of grid-based and decentralized energy storage, such as pumped storage. As this represents a composite basket of technologies, there are no estimates on mineral requirements of this category.

The relative demand for minerals is also driven by the expected longevity of energy technologies. Table 1.5 breaks down the assumptions behind the expected life span of key zero-carbon technologies. In particular, the expected and shorter life span of 10 years for energy storage highlights the critical role it will play in determining the future minerals market. The life span for many of these technologies is likely to vary between subtechnologies and is also uncertain given that some of these technologies have not yet reached full-scale commercial deployment, yet alone the end of their projected life span. Should the life spans of the technologies be longer than projected, or be extended through refurbishment, then less of these technologies will need to be deployed over the time period of the model—for example, although the analysis conservatively assumes a life span of 20 years for wind, offshore wind is often designed with a lifetime of 25 years and some turbines have been in operation for more than 40 years. Should life spans be longer than anticipated, mineral demand from these technologies will be lower than estimated in this report's projections.

Table 1.5 Assumed Lifetime of Technologies

Technology	Assumed life span (years)
Concentrated solar power	30
Energy storage (all battery types)	10
Geothermal	30
Hydroelectricity	25
Nuclear	50
Solar photovoltaic	30
Wind	20
Coal	40
Coal + carbon capture and storage	40
Gas	30
Gas + carbon capture and storage	30

While the model relied on primary and secondary research, most of the model's assumptions are primarily based on publicly available data. The data are thus limited in a number of facets, not least that the data are obtained from a variety of different studies with different methodologies and scopes, and crucially different ages. Where possible, the data have been drawn from consistent sources, but this comes at the expense of some of the data being more recently dated. Additional assumptions made are outlined and discussed in annex B.

Recycling, Reuse

To build off the model described above to estimate mineral demand up to 2050 under the IEA and IRENA scenarios, additional analysis has been conducted on if and how mineral recycling and reuse could potentially affect estimated mineral demand. In its current form, the results generated provide estimates for the demand for end-use minerals in low-carbon energy technologies without considering whether those minerals come from primary or secondary minerals. A brief analysis was conducted on five minerals—aluminum, cobalt, copper, nickel, and lithium—to examine the impact of recycling on primary mineral demand, while the impact of reuse was examined for lithium only.

Primary mineral is considered to be newly mined material, while secondary mineral is considered to be recycled material. There are two commonly reported rates for recycling: (1) **end of life (EOL)**, which gives how much of a mineral is recycled at the end of its use in a product; and (2) **recycled content (RC)**, which gives the percentage of secondary material that goes into end-use demand for a mineral.

EOL and RC rates are not equal, and the former is higher than the latter (see table 1.6). The primary reason for this difference is the availability of scrap. Take the example of aluminum: Between 42 and 70 percent of aluminum is recycled at the end of its life, with rates as high as 90 percent in some countries;⁸ the industry is also well developed in recycling the scrap that it obtains. Yet the recycled content of new aluminum products has been estimated at between 34 and 36 percent. This is because the availability of scrap is simply not enough to meet the growing demand for

aluminum. In addition, some recycling processes cause losses in the material itself and it may not be technically or economically feasible to recover material suitable for recycling from some applications. This is especially the case now with Li-ion batteries (Church and Wuennenberg 2019), helping explain the low recycling rates for lithium (table 1.6). RC rates are also an average across all industries, and with certain minerals, recycled material provides a suboptimal performance. For example, the cobalt used in batteries needs to be extremely pure, limiting the use of recycled material for that particular use (Bomgardner and Scott 2018), while it is extremely difficult to recycle the fiberglass used in wind turbine blades (Martin 2020). These reasons imply that even if EOL rates could reach 100 percent (implying that all possible scrap was captured, recycled, and could be reused), RC rates are unlikely to reach 100 percent without significant reductions in overall demand for these minerals.

Table 1.6 End-of-Life Recycling Rates and Recycled Content Rates

Mineral	End-of-life recycling rates	Recycled content rates
Aluminum	42%–70%	34%–36%
Cobalt	68%	32%
Copper	43%–53%	20%–37%
Lithium	<1%	<1%
Nickel	57%–63%	29%–41%

Source: UNEP 2011.

To estimate the impact of current and potential future recycling rates on the demand for primary minerals, a two-step methodology is adopted. First, it is assumed that current EOL and RC recycling rates persist to 2050. Given these levels of recycled content, the balance between primary and secondary mineral production is estimated using the RC rates and the overall level of demand for the mineral estimated in the model. The implicit assumption here is that the minerals used in energy technologies had the same balance between primary and secondary production as minerals used across all applications.

8 See "Quality and Value," (webpage), Aluminum for Future Generation, for more information: <http://recycling.world-aluminium.org/review/quality-value/>

The impact that increasing future recycling rates have on primary demand is then examined. Estimates of future recycling rates are sparse, both for EOL and RC. To understand the scale of a large future increase in recycling efforts, the following assumptions are made for four of the minerals studied (aluminum, cobalt, copper, and nickel):

- **Current recycling rates:** Estimates of current EOL and RC rates are drawn from the literature, taken as the midpoint of the range of values collected.
- **New scenario – scaling up EOL recycling rates:** EOL recycling rates are scaled up to 100 percent by 2050. This is likely to be unrealistic because of some losses remaining in the system, but it demonstrates an ambitious increase in recycling efforts.
- **Availability of scrap material:** The same ratio of scrap material availability to overall mineral demand remains the same.
- **Impact on RC rates:** RC rates therefore follow the same ratio to EOL rates, as demonstrated today, and RC rates for 2050 are estimated using the same ratios.
- **Determining primary, secondary mineral production:** RC rates are used to estimate the balance between primary and secondary mineral production in each year.

This process is not possible to do for lithium given the mineral's negligible current estimated EOL and RC rates. Thus, scenarios of future lithium recycling rates are drawn from the literature.⁹

As for the estimates for mineral reuse, whereby components of the energy system are reused, this has the potential of, again, creating a difference between end-use and primary mineral demand. For example, there is discussion on repurposing Li-ion batteries from electric vehicles for stationary applications, such as the electricity grid. This impact of reuse is thus examined in the report to understand the impact of increasing reuse patterns on the model's estimated mineral demand from energy technologies.

Although this additional analysis does not intend to provide a complete picture of mineral recycling rates, it is an important area to explore to estimate whether current and future mineral

recycling and reuse would be sufficient to meet the demand for minerals of clean energy technologies to achieve a low-carbon future. A key aspect not covered in this analysis is the role of refurbishment—for example, where all or component parts of energy technologies, such as wind turbines, are refurbished to extend their life span. The implications of this are, however, discussed in the section on reuse in chapter 4.

Global Warming Potential

This section focuses on the global warming potential (GWP) of clean energy technologies compared with fossil fuel technologies, partly using a life-cycle analysis. While the data are incomplete,¹⁰ initial results confirm that the additional extraction and processing of minerals will be appreciably less greenhouse gas (GHG)-intensive than a base scenario with the continued strong reliance on fossil fuels, with an estimated 615 gigatons of carbon dioxide (GtCO₂) being produced in the base scenario up to 2050, while moving to a 2DS involves an extra 6 GtCO₂ from building and operating renewable technologies, but it reduces emissions from fossil fuel generation by over 350 GtCO₂.

This GWP analysis does not cover the full life cycle of renewable electricity generation and energy storage technologies; it is limited to the operation of each technology. In other words, the GWP does not take into account the emissions associated with replacing and disposing energy technologies once they reach their end of life, nor does it take into account the transportation of renewable energy technologies, such as wind turbines, or the shipping of coal and gas. The intent of the GWP analysis is to produce an estimate of the GWP of shifting to a new and low-carbon energy system.

The basic approach is to examine the GWP in the extraction and processing of relevant minerals found in low-carbon technologies and then compare that with the GWP of the traditional fossil fuel-based electricity generation sources—namely, coal and gas. GWP refers to the relative amount of GHG emissions (the vast majority of which is carbon) used in the extraction, production, and processing of minerals, as well as the operation of these technologies. Nuclear

⁹ For example, Ziemann et al. (2018) provides projections for lithium recycling rates that are used in the analysis on recycling in chapter 4.

¹⁰ Calculations on the greenhouse gas (GHG) impact in the manufacturing of clean technologies in this study does not cover, for example, steel or cement; the GHG emissions associated with the production of infrastructure associated with the fossil fuel industry are also not examined.



energy has been excluded from this GWP analysis to focus on the issue of renewable energy versus fossil fuel production.

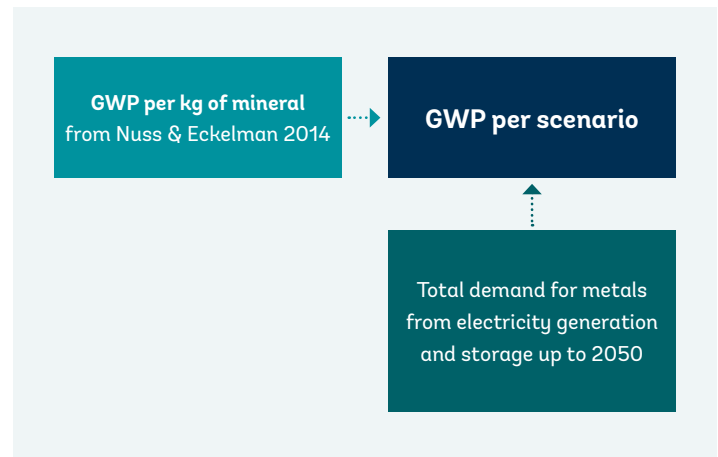
With respect to the specific minerals and metals covered in this study, the model draws on data from a paper by Nuss and Eckelman (2014). This paper gives consistent estimates of the amount of GWP of minerals in terms of carbon dioxide equivalent (CO₂e) from the direct and indirect emissions (for example, the emissions from the extraction and processing and estimates of the emissions associated with the type of electricity used in those processes). The authors estimate the relative GWP of these materials using a “**cradle-to-gate**” scope, thereby excluding transportation of the minerals and any emissions associated with their disposal.

There is little literature on the carbon footprint of energy technologies, and the data among the available sources vary vastly because of the different assumptions around extraction, processing, and operational emissions. For this analysis, the underlying data come from the period around 2008 and are thus not fully reflective of the situation today, and not for 2050. What has changed and is likely to further change, impacting the GWP per kilogram for the minerals in different ways, includes shifting electricity mix, reducing ore grades, relative prices of commodities,¹¹ and changing mining and production techniques.

The direction, and scale, of these changes will differ from mineral to mineral.¹² For example, iron will always have a relatively high GWP so long as it relies on coking ovens. Aluminum’s GWP, on the other hand, is very much predicated on the electricity source needed for its production. For example, its GWP is much smaller when the energy source for the aluminum production is hydroelectricity rather than electricity from coal power stations.

To produce the estimates, the total demand for minerals from the various energy technologies in the model are combined with the estimates of GWP per kilogram of mineral (figure 1.3). This then provides an estimate of the different GWPs arising from the minerals used in the technologies in the IEA 2DS.

Figure 1.3 Schematic of Global Warming Potential Component of Model



Note: GWP = global warming potential.

A range for each estimate was produced stemming from the range of the GWP per kilogram of mineral and the projected range of mineral demand. The numbers reported in this analysis are the midpoint of the range. This is discussed in more detail in annex B.

Model Uncertainty

Like many projections, there are uncertainties regarding future mineral demand from energy technologies, as it relies on a variety of different sources with different methodologies to derive forward-looking projections. These include the mineral composition of the energy technologies themselves; the share, and scale, of energy technologies that will be deployed in the future; which subtechnologies will actually be deployed within each energy technology; and the life span of technologies and future paths of recycling and reuse.

The model captures uncertainty around two of these elements: (1) mineral composition and (2) share, and scale, of energy technology penetration. It produces a range of demand for each mineral, and all results of this analysis are midpoints of the range of estimated mineral demand. The ranges of some of the minerals

¹¹ Relative prices are important because of the methodological choice of economic allocation rather than mass allocation for the GWP of production processes that produce two or more final metal products. For example, some forms of copper refining yield copper, silver, selenium, and tellurium. The question then becomes how to allocate the GWP from the copper refining process between the four minerals. Economic allocation, adopted by Nuss and Eckelman (2014), allocates the GWP on the basis of the revenue earned from the four minerals. Mass allocation allocates on the mass of the products obtained. Under the economic allocation methodology, large shifts in relative prices would shift the allocation of the GWP between the end-use metals.

¹² These issues have been explored in depth for seven specific metals in van der Voet et al. (2019). A further discussion of issues relating to the GWP sources can be found in annex B.

are considerable. For example, aluminum is used in solar PV for the frames; however, this service could be provided by synthetic or composite materials—and if or when aluminum is replaced, demand for that mineral could fall considerably.

The second aspect of uncertainty relating to the share and scale of energy technology penetration is captured by the use of various scenarios. Different scenarios from the IEA are used to capture the impact of wider deployment of low-carbon energy technologies. The four IEA scenarios are used to highlight the impact of greater climate ambition, demonstrating a clear trend that higher ambition leads to higher demand for minerals.

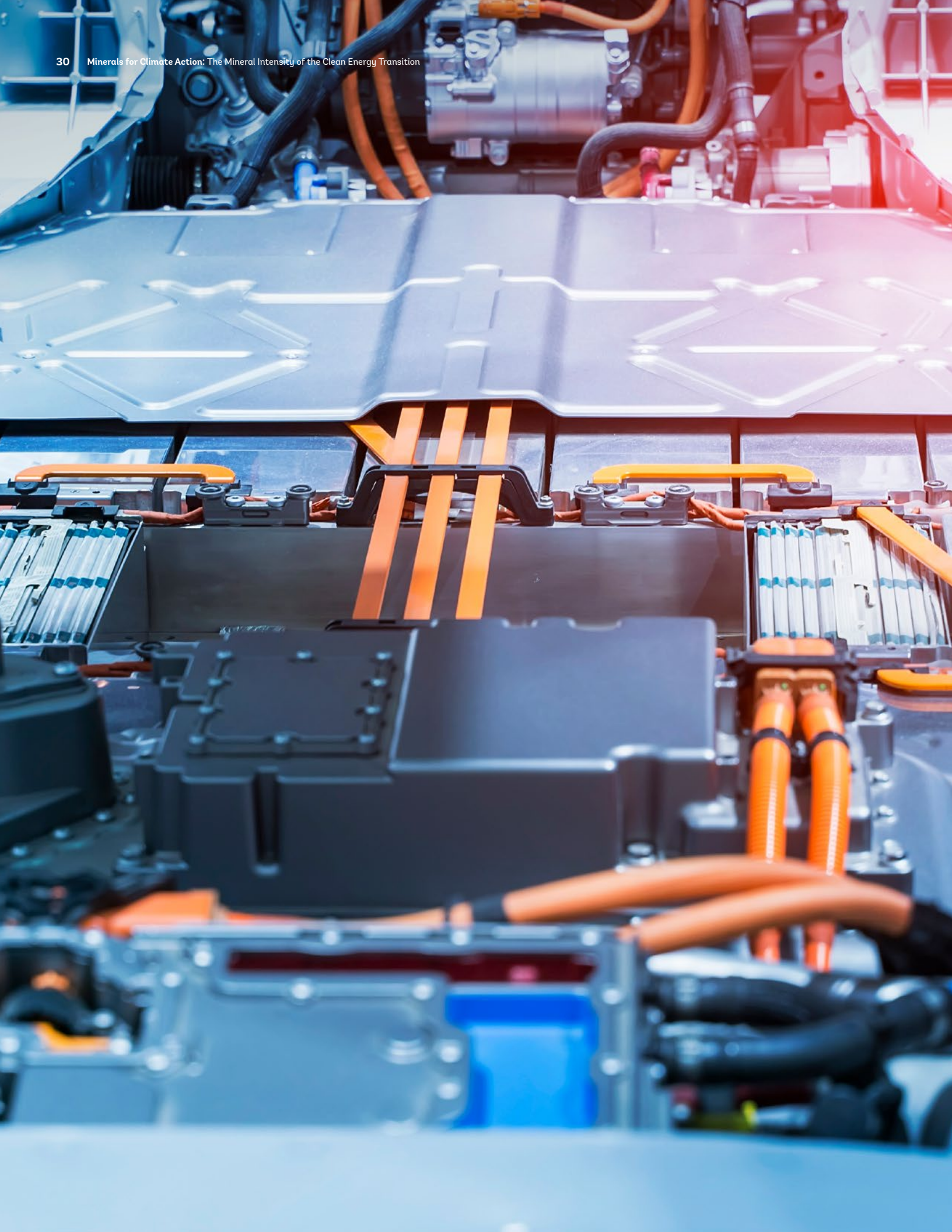
Within this greater ambition, however, are a number of potential technology pathways to meet the same level of emissions reductions. More focus could be placed on fossil fuel generation with carbon capture and storage, or on renewable deployment. Even within this second choice, there are options for more wind deployment, or more solar PV, higher rates of geothermal, or concentrated solar power. These choices do not necessarily mean higher or lower levels of overall demand for minerals, but they do imply demand for different minerals. This uncertainty is partially captured by the inclusion of scenarios from two different sources: the IEA and IRENA. The IEA scenarios see a greater role for carbon capture and storage, while the IRENA scenarios see greater renewable deployment. Comparing the results of these different groups of scenarios therefore highlights an aspect of this uncertainty.

The uncertainty over the emergence of new subtechnologies is also not captured in the model. The uncertainty over this element is likely to be much greater post-2030 than in the next decade, especially in the realm of energy storage, where a number of new technologies are emerging fast, such as solid-state Li-ion batteries as well as other types of flow batteries (for example, iron-based), and new developments in thermal electric and mechanical storage. Each of these technologies will have differing mineral compositions. Predicting which, if any, of these technologies will emerge is impossible, implying that post-2030 both the scale of storage and the mineral composition of energy storage is highly uncertain. This creates uncertainty over not only the amount of demand of minerals but the actual minerals

themselves that will be needed for the low-carbon transition. These different demand risks are addressed in the report through a demand risk matrix.

The potential implications for mineral demand from a range of emerging new technologies, including some of these new emerging storage technologies, are discussed in the Emerging Energy Technologies section in chapter 3. For additional information on uncertainty ranges, please refer to annex B.





The Role of Minerals in the Clean Energy Transition

The penetration of renewable energy in the energy sector will be crucial to achieve a low-carbon future. The energy sector today accounts for 41 percent of carbon emissions worldwide, or 13.6 GtCO₂e (IEA 2019a), and is expected to rise further as the global population grows, particularly in developing countries, and energy consumption rises because of this new demand.¹³ With renewable energy costs falling rapidly from clean energy technologies, such as solar PV and onshore wind at 0.08/kWh and 0.05/kWh in 2018 (IRENA 2019d), respectively, it is expected that these technologies will play a significant role in decarbonizing electricity production. However, the rapid deployment of these low-carbon technologies needed to reach a 2°C pathway, or below, will also mean that the demand for minerals needed to produce these technologies will rise.

The implications of rising mineral demand can be examined through multiple lens. On one hand, increasing extractive and processing activities *could* have serious environmental and social implications *if* these activities are not managed responsibly to meet this new demand from the increased deployment of renewable energy. As of today, the mining sector accounts for approximately 2–11 percent of total global energy consumption (Guilbaud 2016; CCSI 2018), while 70 percent of mining operations from the six largest mining companies are located in water-stressed countries (IFC and ICCM 2017). On the other hand, new demand for these “strategic” minerals could also provide new opportunities for resource-rich developing countries and enable them to meaningfully contribute to the clean energy transition.

Adopting climate-smart mining (World Bank 2019) practices would enable the mining sector to transform its current practices—through innovation and new partnerships with downstream companies and civil society organizations—to further reduce the overall sector’s carbon and environmental footprints. Providing adaptation measures (for example, water efficiency) and the incorporation of desalination can contribute to operational independence while improving relationships with the communities (Campero and Harris 2019). Integrating renewable energy into mining operations, for example, as well as employing energy efficiency measures could reduce at least 40 percent of total energy use in the crushing and grinding of minerals (Australia 2018). Providing demand estimates for a variety of minerals can illustrate the implications of various lower carbon pathways, and it is a crucial exercise to undertake as it provides a framework to ensure that the decarbonization of electricity generation does not end up shifting greenhouse gas (GHG) emissions from electricity production to upstream (extraction and processing) and EOL (disposal of energy technologies) activities.

This analysis estimates the amount of minerals that may be needed per clean energy technology—including their subtechnologies—to provide policy makers, private sector entities, and civil society organizations with the latest information available to support the low-carbon transition through a holistic approach. This includes estimating potential mineral demand under six technology-based mitigation scenarios from the IEA and IRENA while taking into account the role that recycling *could* have in meeting this new mineral demand. It does not intend to forecast what will happen, but instead provide a range of scenarios to explore the future global energy system and how different policy choices and technology improvements could affect overall mineral demand up to 2050. Failing to address concerns on materials use intensity and its relationship to increasing environmental and social impacts may cause a backlash that will question the appropriateness of some of these technologies in comparison to those that are conventional (Bloomberg 2019; Wade 2016).

¹³ Energy sector in this context refers to electricity and heat generation only. This category is further broken down by sector on the IEA website.

Renewable Energy and Storage Forecast

Renewable energy has been one of the largest growing sources of installed electricity generating capacity, growing from 1,058 GW in 2008 to 2,179 GW in 2018 (IRENA 2018), largely driven by government policies, regulations, and incentives as a means to decarbonize the energy sector and limit the negative impacts of a changing climate. Demand-side interventions, as well as economies of scale and technological developments on the supply side, have enabled renewable energy to become competitive with fossil-fuel-based technologies. For example, some countries have already begun transitioning away from support schemes (for example, feed-in-tariffs, or FiTs) to support renewable energy growth, to competitive auctions for long-term power purchase agreements (IEA 2019d, 154).

Policy choices, technology improvements, and these latest pricing trends combined indicate that the growth of renewable energy in the global electricity mix is here to stay, making renewable energy and storage forecasts a central point in this report's analysis to estimate mineral demand up to 2050. The IEA and IRENA scenarios for electricity generation and battery storage, including the subtechnology shares in those scenarios, also highlight the energy technology coverage in the model and break down key inputs used to better understand the minerals' role in the clean energy transition.

Technology-Based Mitigation Scenarios

As this report relies heavily on the IEA and IRENA **technology-based mitigation scenarios**, the six scenarios have been captured again in table 2.1 to provide a reference point for each assumption used to derive estimated mineral demand up to 2050.

Table 2.1 Shortened Technology-Based Mitigation Scenarios from IEA and IRENA

Technology-based mitigation scenarios			
	Scenario	Source	Scenario description
1	4DS (Base scenario)	IEA	Base scenario , where the world carries on a current trajectory and makes little improvement in shifting the energy system away from fossil fuel sources
2	RTS	IEA	Assumes all countries will implement their NDCs under the Paris Agreement, resulting in an average temperature increase of 2.7°C by 2100
3	2DS	IEA	Scenario with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100
4	B2DS	IEA	Scenario with a 50% chance of limiting average future temperature increases to 1.75°C by 2100
5	Ref	IRENA	Accounts for actions, commitments made under current/planned policies, including NDCs. Rise in temperatures would be at least 2.6°C by 2100
6	REmap	IRENA	Ambitious scenario that limits the rise in global temperature to "well below" 2°C above preindustrial levels by 2100

Note: 2DS = 2-degree scenario, 4DS = 4-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, NDC = Nationally Determined Contribution, Ref = reference scenario, REmap = renewable energy roadmap scenario.

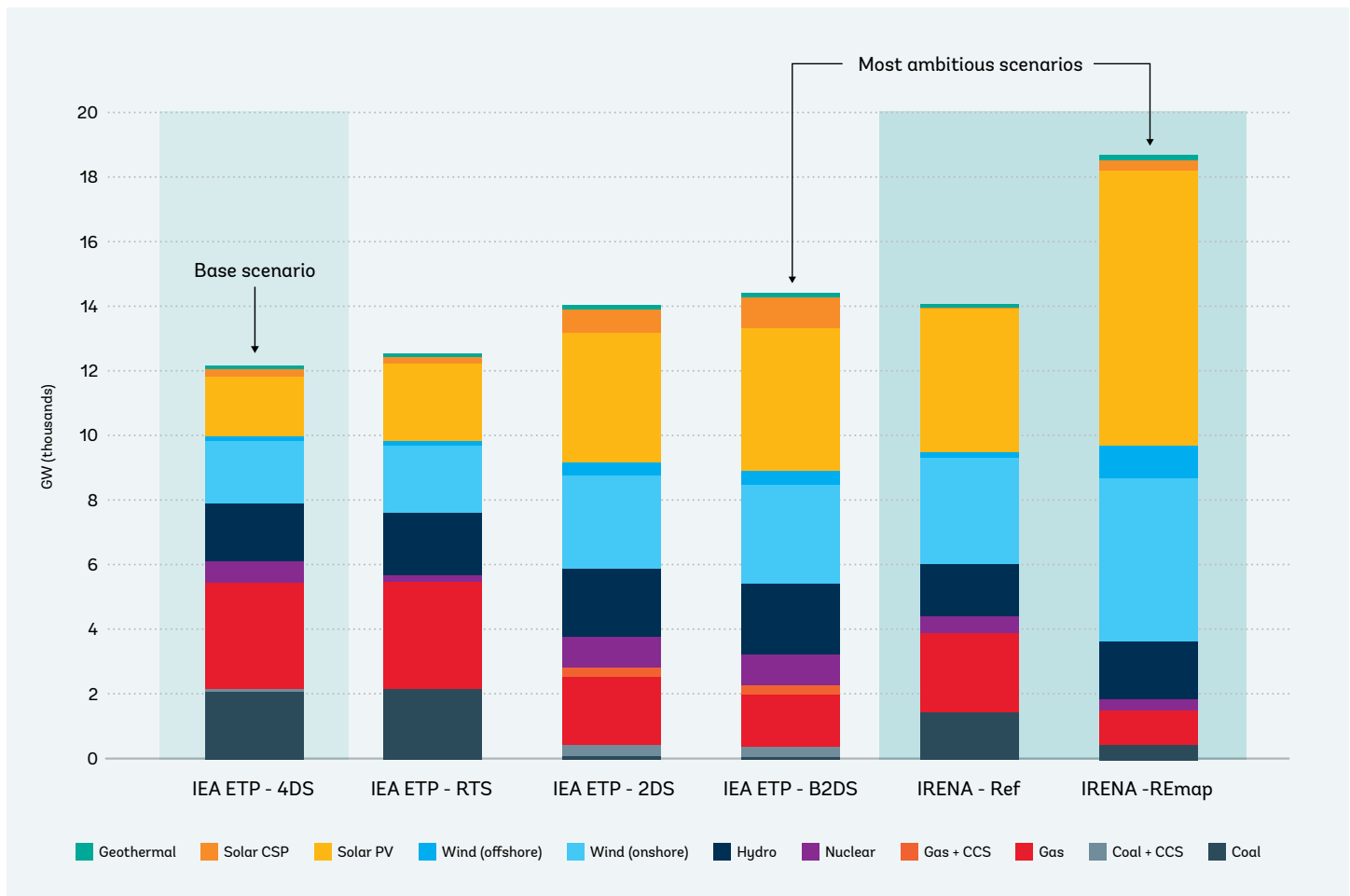
Electricity Generation: Installed Electrical Capacity in 2050

The IEA and IRENA use different assumptions about renewable energy penetration in their technology-based mitigation scenarios. For example, IRENA's REmap projections on renewable electricity penetration up to 2050 are higher than IEA's 2DS and B2DS, at 64 percent and 51 percent, respectively. These differences are due to a number of factors, including different global economic growth assumptions—IRENA assumes an annual global GDP growth of 3.2 percent; the IEA assumes 2.9 percent—and different assumptions

about the emergence of other low-carbon technologies such as carbon capture and storage (CCS).

The type of energy technology penetration in the global energy mix is relevant for minerals because they are required to supply transportation and nontransportation-related energy storage and renewable energy technologies. Figure 2.1 provides an overview of the relevant energy technologies expected to play a role in the global electricity production in the future; however, three technologies are excluded from this model—oil, biomass, and tidal—owing to the lack of data on their mineral composition.

Figure 2.1 Estimated Installed Capacity in 2050 Across the Technology-Based Mitigation Scenarios



Source: IEA 2016, 2017; IRENA 2019a.

Note: 2DS = 2-degree scenario, 4DS = 4-degree scenario, B2DS = beyond 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, ETP = Energy Technology Perspectives, IRENA = International Renewable Energy Agency, PV = photovoltaic, Ref = reference scenario, REmap = renewable energy roadmap scenario.



Under the base scenario (4DS), coal and gas with some CCS dominate the electricity sector, while the share of conventional energy gradually diminishes as the world becomes increasingly ambitious in its climate targets. Geothermal is seen to play a larger role under the base scenario than other reference scenarios (RTS and Ref), mainly because it was produced before the other scenarios. In the intervening period, the costs of variable renewable energy, such as solar PV and wind, have fallen dramatically, as have the costs of integrating these technologies into the grid, albeit not as dramatically as the latter. This has meant that in the later RTS and Ref scenarios, other renewables have become more attractive than geothermal energy.

From the base scenario, a decrease in coal is observed once the model moves toward the IEA's 2DS and B2DS, and away from the RTS and the 4DS. While coal decreases in the 2DS and B2DS, the share of CCS for gas and coal starts to appear in the electricity mix, albeit a very small share, whereas in the IRENA scenario, those technologies are not expected to materialize.

Renewables—particularly solar PV and wind—rise dramatically under those same IEA scenarios, but again, the IRENA models assume a much higher penetration of those two technologies than do the IEA models, which also assume increasing contributions from other nonemitting sources, including hydroelectricity and nuclear energy. The IRENA Ref scenario has higher levels of wind penetration than the IEA 2DS and B2DS. One of the key takeaways is the following: the more ambitious the scenario, the higher the penetration of renewable energy in the electricity mix for both the IEA and IRENA scenarios.



Energy Storage Projections

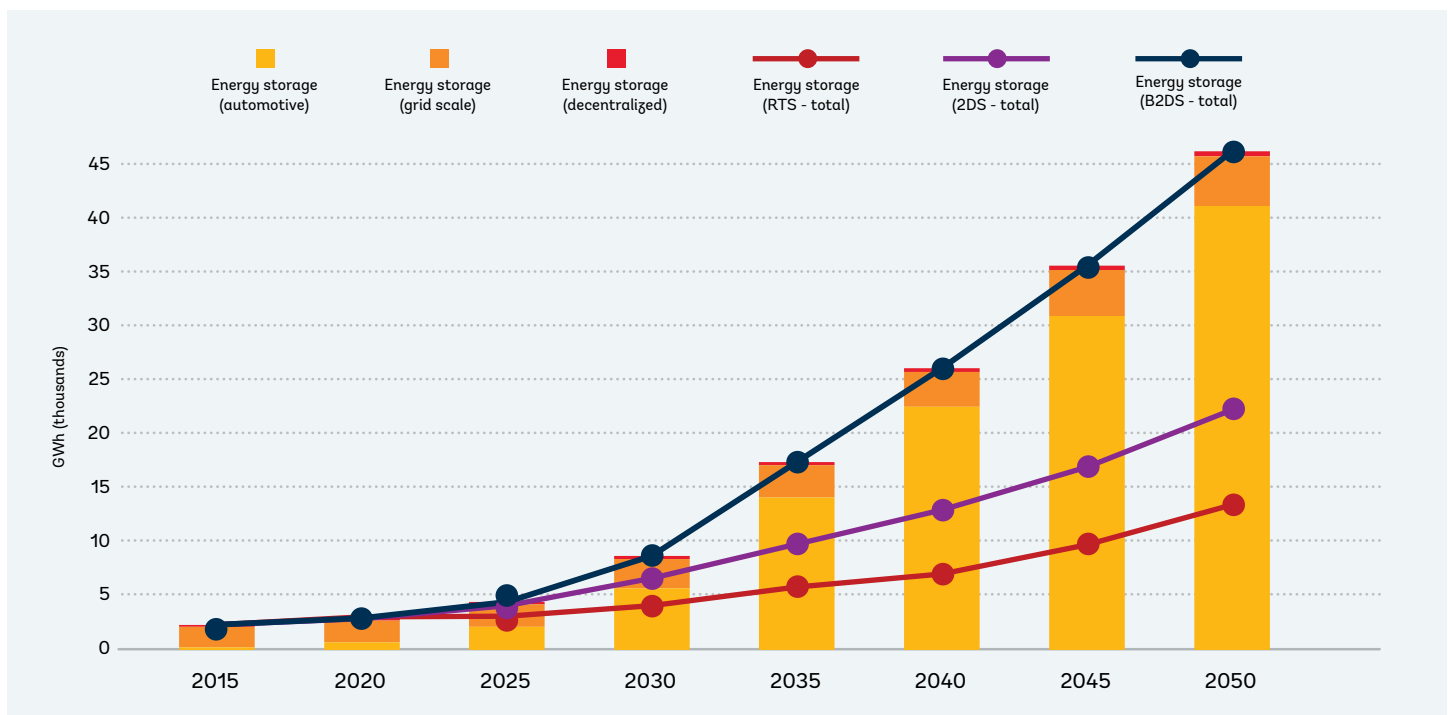
Unlike electricity generation, mineral demand estimates for energy storage technology were solely derived from the IEA,¹⁴ as data on energy storage under the IRENA scenarios were not available. The IEA 4DS (base scenario) also does not include the penetration of energy storage in the electricity mix. Energy storage predictions up to 2050 were extrapolated from data provided by the IEA on energy storage requirements for automotive and nontransportation-related energy storage up to 2040 and 2060. The average of the storage requirements from 2040 and 2060 was taken to give an estimate of the required storage in 2050, and then combined with data from a wide variety of sources on other key aspects of the storage sector.

As seen in figure 2.2, all three IEA scenarios demonstrate that the relative demand for energy storage, particularly with respect

to energy storage for transportation, is expected to rise dramatically by 2050. In the 2DS, for example, demand for storage rises from 4,108 gigawatt-hours (GWh) in 2025 to 22,270 GWh in 2050. The demand for energy storage technology rises exponentially as each scenario increases in climate ambition, with a difference of 32,792 GWh from the RTS (in light red) to B2DS (in dark blue) in 2050.

The energy storage market penetration is split between transportation (covering electric and hybrid vehicles) and nontransportation (covering storage from electricity generation), with the latter again split between grid scale (for regulation of grid voltage and storage from intermittent electricity generation, such as renewables) and decentralized (storage from individual, small-scale renewable energy installations). Redox-flow batteries are only used in grid-scale applications.

Figure 2.2 Expected Growth in Energy Storage Through 2050



Source: Based on IEA ETP 2017.

Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, GWh = gigawatt-hours, RTS = reference technology scenario.

14 IRENA's scenarios only provide data for electricity generation and not energy storage.



Mineral Intensity of Clean Energy Technologies

The clean energy transition is expected to be much more mineral intensive than fossil-fuel-based electricity generation. It is important to understand the extent to which mineral demand will grow globally to supply renewable energy and storage technologies. Table 3.1 provides an overview of the minerals covered in this analysis and their relevance to each technology identified in the technology-based mitigation scenarios.

Copper, aluminum, chromium, manganese, molybdenum, and nickel are required for a range of low-carbon technologies, making them critical elements for realizing a low-carbon future. The mapping of relevant minerals to energy technologies found in the technology-based mitigation scenarios is by no means an exhaustive list, as it focuses exclusively on certain electricity generation and energy storage technologies—and a range of other minerals are also needed, but they have not been included in the model owing to data constraints.

These minerals include, but are not limited to, dysprosium for direct-drive wind turbines; cadmium, tellurium, selenium, and gallium for various types of solar PV panels; and platinum in other forms of energy storage (such as fuel cells, discussed in the Emerging Energy Technologies section in chapter 3). The exclusion of these minerals from this analysis should not, however, be interpreted as a commentary on their lack of criticality for individual technologies, or the low-carbon transition. Some technologies may also use small amounts of minerals in components, such as the use of carbon brushes in the motors of wind turbines; however, no data were available on such use and thus they were excluded from the model.

As mentioned in chapter 1, the new infrastructure required to support a low-carbon transition has not been addressed, nor have other clean energy options, such as hydrogen-based vehicles, where platinum would play a key role. The need to connect some 840 million people without electricity access today as well as build the motors and chassis to electrify 135 million electric vehicles that are expected to come online in the next 10 years to

decarbonize the transportation sector (IEA 2019b) are examples of new energy infrastructure that also have not been captured in this analysis. Additionally, the materials needed to install these low-carbon technologies, such as cement to stabilize wind turbines' installation, have not been addressed in this analysis.

Table 3.1 Mapping Minerals with Relevant Low-Carbon Technologies

	Wind	Solar photovoltaic	Concentrated solar power	Hydro	Geothermal	Energy Storage	Nuclear	Coal	Gas	Carbon capture and storage
Aluminum										
Chromium										
Cobalt										
Copper										
Graphite										
Indium										
Iron										
Lead										
Lithium										
Manganese										
Molybdenum										
Neodymium										
Nickel										
Silver										
Titanium										
Vanadium										
Zinc										
Total	10	8	2	8	6	11	11	9	8	6

Solar Photovoltaic

Solar photovoltaic (PV) has been the most rapidly deployed renewable energy technology globally, with installed capacity reaching 485 GW in 2018 (IRENA 2019b), outpacing all other technologies in growth between 2017 and 2018, growing by 24 percent. The high learning rate¹⁵ of solar PV (22–40 percent) has resulted in dramatic cost reductions, with the global-weighted average levelized cost of energy (LCOE) falling by 77 percent between 2010 and 2018 (IRENA 2019c), making it one of the most attractive technologies for renewable energy investors worldwide.

This trend can be reflected with installed capacity of solar PV expected to reach up to 8,519 GW (IRENA 2019c) by 2050 in Africa, Asia, and Europe owing to continued cost decreases, where the technology is expected to reach price parity with fossil fuel technologies. Solar PV's relative growth in Africa, for example, is likely to be huge, with the IEA's *World Energy Outlook 2019* projecting solar PV deployments in the region to grow by more than 3,000 percent between 2018 and 2040. By 2050, most solar PV deployments are expected to take place in non-OECD countries, especially in China and India.

Four widely used solar PV subtechnologies are represented in this analysis:

1. **Crystalline silicon (crystal Si)** cells make up about 85 percent of the current market. They can either be manufactured as single crystalline, polycrystalline, or amorphous silicon.
2. **Copper indium gallium selenide (CIGS)** is a “thin film” solar technology. It can be made into thinner cells than crystal Si, which may reduce material and manufacturing costs while allowing for flexible cells.
3. **Cadmium telluride (CdTe)** is another thin film technology. It is cost competitive with crystal Si and has good efficiency. However, the toxicity of cadmium and the future supply of tellurium make the future of this technology uncertain.
4. **Amorphous silicon (amorphous Si)** solar cells are the final thin film technology. They suffer from lower performance than crystal Si but are able to be printed on flexible materials.



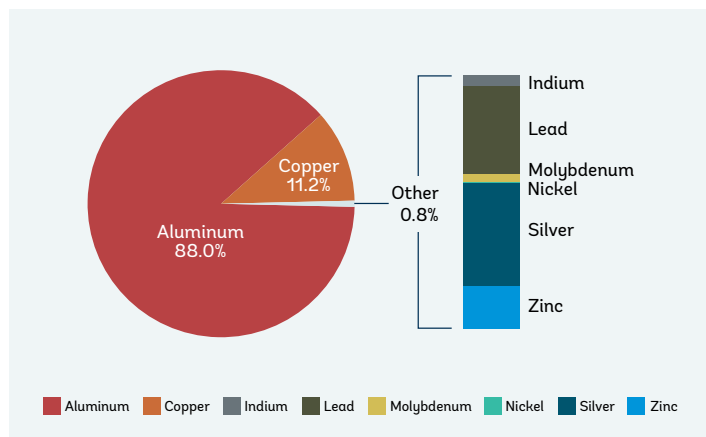
¹⁵ The learning rate is defined as the fractional reduction in cost for each doubling of cumulative production.





Solar PV technologies are primarily made up of aluminum, copper, and silver—with various minerals also playing a role in each of the different technologies, some of which are included in this analysis, such as indium in CIGS, and some that are not, such as cadmium for CdTe. Figure 3.1 shows the major mineral demand used to supply solar PV through 2050. Aluminum accounts for more than 85 percent of most solar PV components, being used for the frames of the panels, and copper following suit at about 11 percent. While silver accounts for a smaller share of mineral composition in a 2DS, less than 0.05 percent, it accounted for nearly 7 percent of total silver demand in 2015 owing to the rapid deployment of solar PV worldwide (Sanderson 2016).

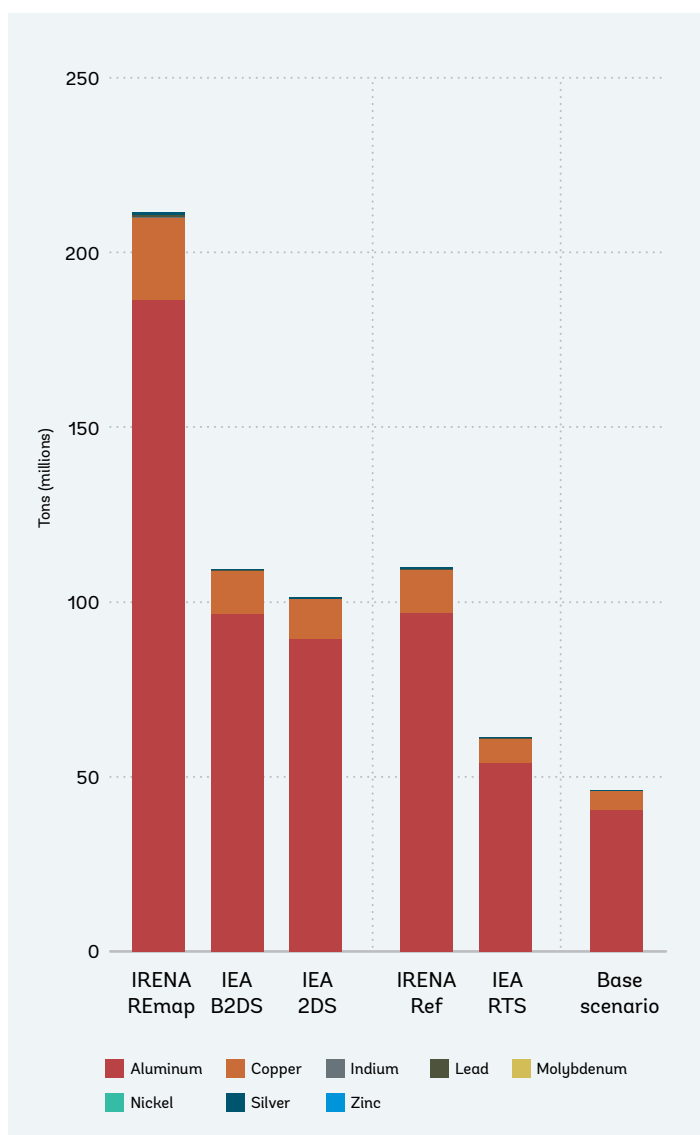
Figure 3.1 Share of Mineral Demand from Solar Photovoltaic Under the IEA 2DS Through 2050



Note: 2DS = 2-degree scenario, IEA = International Energy Agency.

Between the scenarios, IRENA's REmap scenario is by far the most materially intensive, owing to its higher installed capacity of solar PV, with 160 million tons of aluminum and 20 million tons of copper required by 2050 (figure 3.2). Compared with the base scenario, the demand for both minerals grow by more than 350 percent.

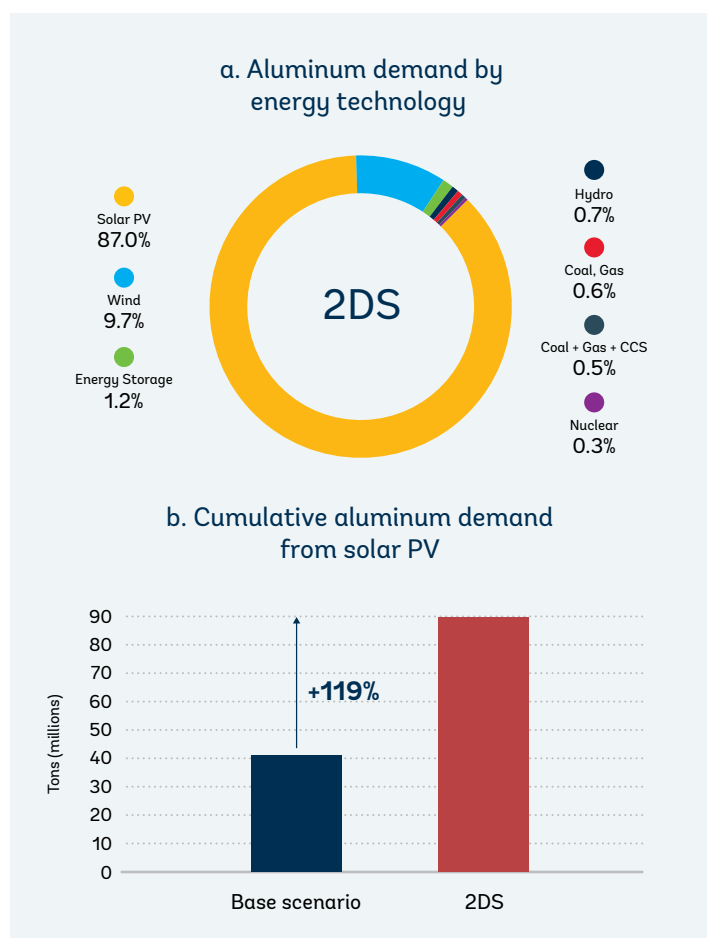
Figure 3.2 Cumulative Demand for Minerals Needed for Solar Photovoltaic Through 2050



Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap = renewable energy roadmap scenario, RTS = reference technology scenario.

While aluminum is a major contributor to solar PV technologies, it is also used in most other low-carbon technologies, such as wind, energy storage, and hydroelectricity. Figure 3.3 shows that the vast majority of growth in demand for aluminum is tied to solar PV used both in the cells themselves and in the frame and attachments. Its greatest use is with crystal-Si cells as these are still assumed to represent the greatest share of the solar market by 2050. Greater ambition to combat climate change is associated with greater penetration of solar PV and therefore greater demand for aluminum—cumulative demand for aluminum is 119 percent greater in the 2DS than in the base scenario.

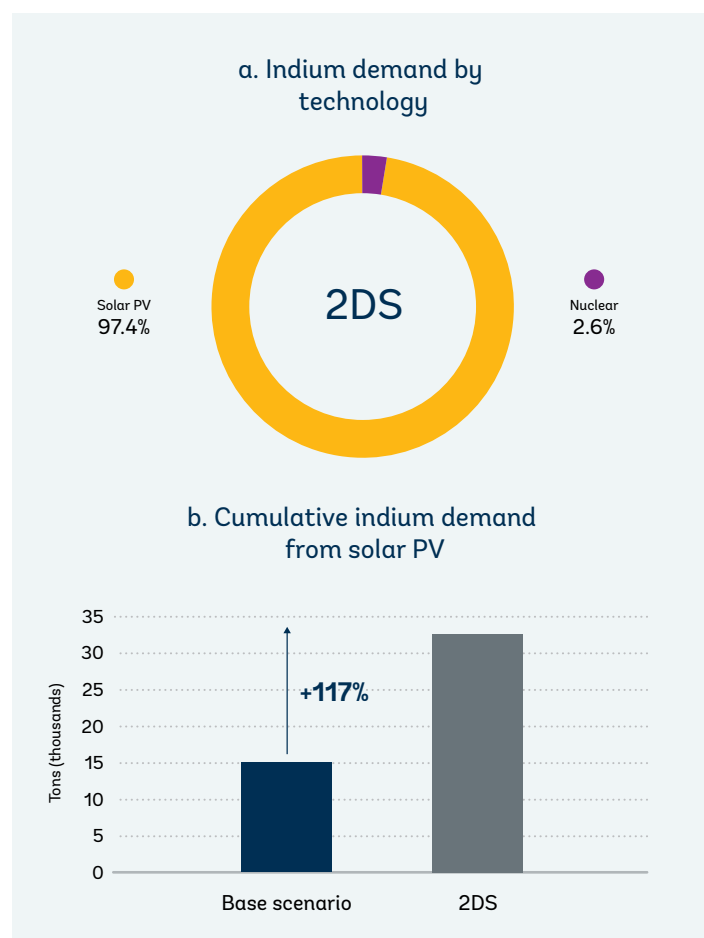
Figure 3.3 Total Aluminum Demand by Energy Technology Through 2050 (2DS, Base Scenario)



Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, PV = photovoltaic.

Indium is another critical element that is used almost exclusively for solar PV. Figure 3.4 shows the cumulative demand for indium by technology. The vast majority of indium (97 percent) is used in solar PV, predominantly in CIGS solar cells, with the remaining 3 percent used in nuclear power. The relative share in a solar PV is small but critical to a key type of solar PV subtechnology: thin film. The current literature expects this subtechnology to grow, and in the model, the three thin film subtechnologies—CIGS, CdTe, and amorphous silicon—are assumed to grow from 20 percent to 50 percent of solar panels.

Figure 3.4 Total Indium Demand by Energy Technology Through 2050 (2DS, Base Scenario)



Note: 2DS = 2-degree scenario, PV = photovoltaic.

Trade-Offs in Solar PV Subtechnologies

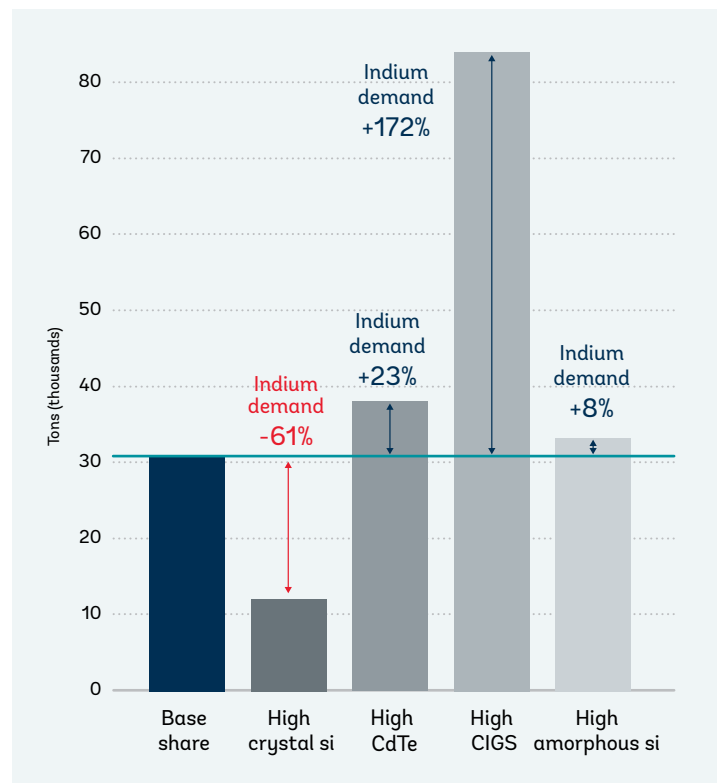
There are trade-offs in mineral demand from solar PV technology, depending on which subtechnologies end up being deployed most through 2050. Each technology for constructing solar PV cells has distinct advantages and disadvantages, as well as differing mineral content.

Since indium is the most affected by potential changes in the subtechnologies solar PV market share, figure 3.5 presents how indium demand could increase or decrease, depending on various outcomes. Table 3.2 breaks down the penetration of different subtechnologies relative to the base share to demonstrate how the demand for indium would change.

In the base share scenario, the share of crystal Si declines in use with gradual increases in share from the other three emerging technologies. The high crystal Si scenario keeps the subtechnology's share at 2017 levels, with static shares for the other three subtechnologies. The high CdTe, CIGS, and amorphous Si scenarios have the relevant technologies growing to half the market by 2050, with crystal Si declining in importance and small increases for the other two subtechnologies.

Indium is the key mineral affected by changes in subtechnology market share in solar PV; minerals such as silicon, gallium, and tellurium would also be affected, but these are not included in the model. Demand for indium is greatest in the high CIGS scenario, and smallest in the high crystal Si scenario, as seen in figure 3.5. These changes are potentially significant, with indium demand increasing by more than 170 percent, compared to the base share, when penetration of CIGS is highest. In contrast, if crystal Si remains the dominant subtechnology, then indium demand would be more than 60 percent lower than in the base share scenario.

Figure 3.5 Cumulative Demand for Indium from Solar PV Subtechnologies Compared to Base Share Under 2DS Through 2050



Note: 2DS = 2-degree scenario, amorphous Si = amorphous silicon, CdTe = cadmium telluride, CIGS = copper indium gallium selenide, crystal Si = crystalline silicon, PV = photovoltaic.

Table 3.2 Share of Subtechnology Penetration in Solar PV Market Compared with Base Share Under 2DS

2050 share	Crystal Si	CdTe	CIGS	Amorphous Si
Base share (2DS)	50%	16.7%	16.7%	16.7%
High share: Crystal Si	80%	6.7%	6.7%	6.7%
High share: CdTe	16.7%	50%	16.7%	16.7%
High share: CIGS	16.7%	16.7%	50%	16.7%
High share: Amorphous Si	16.7%	16.7%	16.7%	50%

Note: 2DS = 2-degree scenario, amorphous Si = amorphous silicon, CdTe = cadmium telluride, CIGS = copper indium gallium selenide, crystal Si = crystalline silicon, PV = photovoltaic.





Wind

Similar to solar PV, wind energy has also been one of the fastest growing renewables, with installed capacity reaching 566 GW in 2018 (IEA 2019c). Increases in wind turbine size, higher efficiency, lower cost of capital, and economies of scale have lowered wind electricity generation prices to the point where it is competitive with fossil fuel generation in many areas, and, according to Citibank, is even “approaching the average wholesale electricity price in a number of large markets—including Italy, Spain, the United Kingdom, and China—and has already attained and surpassed parity in Brazil” (Savvantidou et al. 2013). Onshore wind costs are frequently below \$40 per megawatt-hour in developed markets. Offshore wind has seen even more dramatic cost reductions, falling from a range of \$150–\$200 per megawatt-hour in 2015 to under \$50 per megawatt-hour in the United Kingdom in late 2019 (ESMAP 2019).

Under the IEA and IRENA scenarios, the bulk of onshore wind growth is expected to take place in emerging markets with strong wind resources and consistent policy support. Offshore wind is expected to expand its current footprint in Europe and China before moving into emerging markets over the next few years. A recent study by the World Bank found over 3.1 terawatts of offshore wind technical potential in only eight emerging markets.

Simply put, wind turbines convert the kinetic energy of wind into electricity. The largest onshore wind turbines now exceed 6 MW of peak generation capacity, enough to power more than 5,000 homes in the United States. The largest offshore wind turbines are twice that size (12 MW) and have blades as long as 107 meters (indeed, they are the largest pieces of rotating machinery that humans have ever invented). The next generation of wind turbines are expected to reach generation capacity up to 15 MW or even 20 MW soon (AIP 2019).

Figure 3.6 Evolution of the Wind Turbine

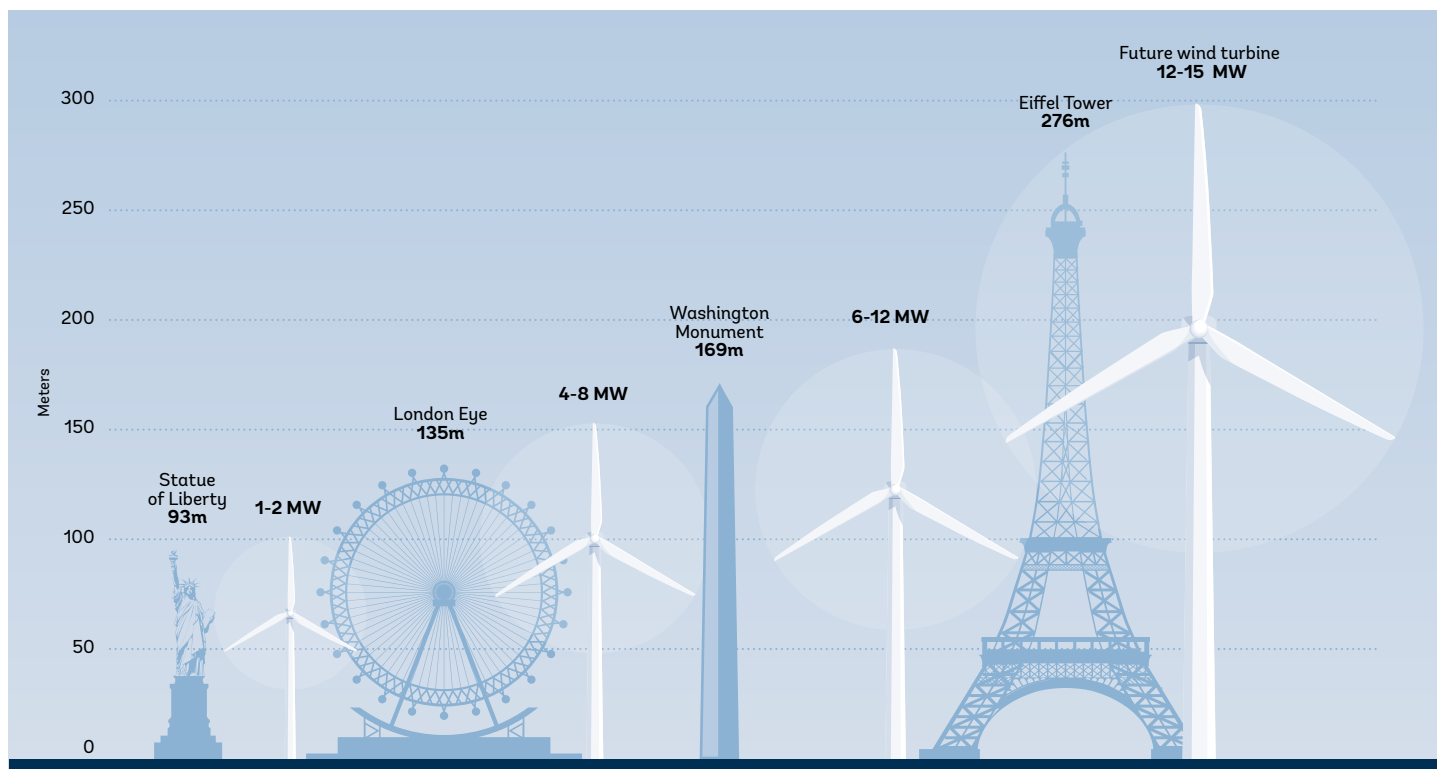


Illustration adapted from various sources (for example, https://www.researchgate.net/figure/Evolution-of-wind-turbine-size-and-output-Liebreich-2017_fig3_331249559; Power Technology, <https://www.power-technology.com/features/haliade-x-look-ges-supersized-new-wind-turbine/attachment/ge-infographic-1-haliade-x/>).

Onshore and offshore wind turbines share many commonalities, but they also have significant differences in design, technology, and required materials, both in the turbines themselves and in the balance of plant. Offshore wind turbines encounter harsher conditions than their onshore counterparts and thus need to be more resistant to corrosion, higher winds, and extreme weather.

Offshore wind farms also require greater material inputs in their foundations (mainly steel) and in the cabling required to transmit the electricity onshore (for example, copper). Offshore wind farms do, however, offer greater capacity factors than their onshore counterparts (ESMAP 2019).

Modern utility-scale wind turbines can be divided into two categories: geared or direct drive.

1. **Geared turbines** make up roughly 80 percent of global installed capacity. These “Danish design” machines use a gearbox to convert the relatively low rotational speed of the turbine rotor (12–18 rpm) to a much higher speed (1,500 rpm) for input to a generator. The vast majority of these generators are double-fed induction generators, which use significant amounts of copper and iron. Geared turbines have achieved a very low cost with a high level of reliability, although they generally require more frequent maintenance because of the higher number of moving parts relative to their direct-drive counterparts.
2. **Direct drive wind turbines** feature generators that are fixed directly to the rotor and therefore turn at the same speed. Certain models (for example, those produced by Goldwind) employ a generator with permanent magnets consisting of rare earth minerals such as neodymium and dysprosium. Other models (for example, those produced by Enercon) use an electrically excited rotor utilizing significant amounts of copper. Direct-drive turbines tend to be initially more expensive per megawatt, although this can be offset by lower maintenance during the turbine’s operation.

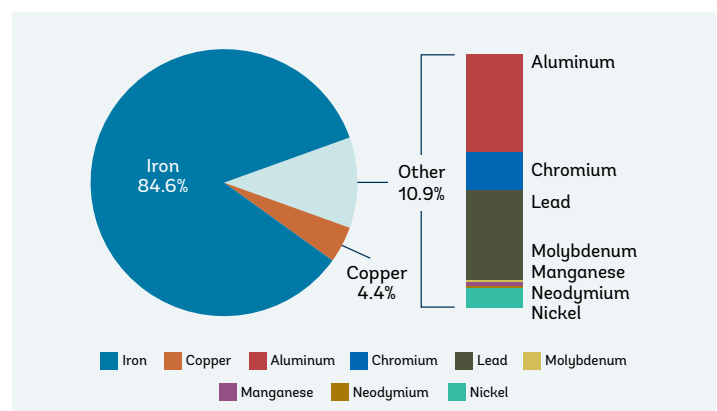
In general terms, geared turbines tend to dominate onshore installations, where maintenance is relatively straightforward. Conversely, direct-drive turbines are preferred in offshore wind applications, where maintenance is much more challenging. The difference in how these subtechnologies are deployed between

onshore and offshore wind has implications in how the model derives mineral demand from wind technologies.

The main components of turbines (towers, castings, nacelle, shafts, and so on) are primarily made up of steel. The blades are a composite of fiberglass, resins, balsa wood, and adhesives (some use carbon fiber, although this increases the cost significantly). Modern wind turbines can be anywhere from 150 to 250 meters in height from base to blade tip, nearly the height of the Eiffel Tower. Steel figures have been excluded from the analysis because of potential double counting issues, with minerals included in the analysis such as chromium being used in the steel needed for wind turbines. Steel is primarily manufactured using a mix of iron ore, carbon, and other elements. Other elements also could be used for steel production, including nickel, molybdenum, titanium, manganese, vanadium, or cobalt, depending on the type and quality of steel required for industrial applications.

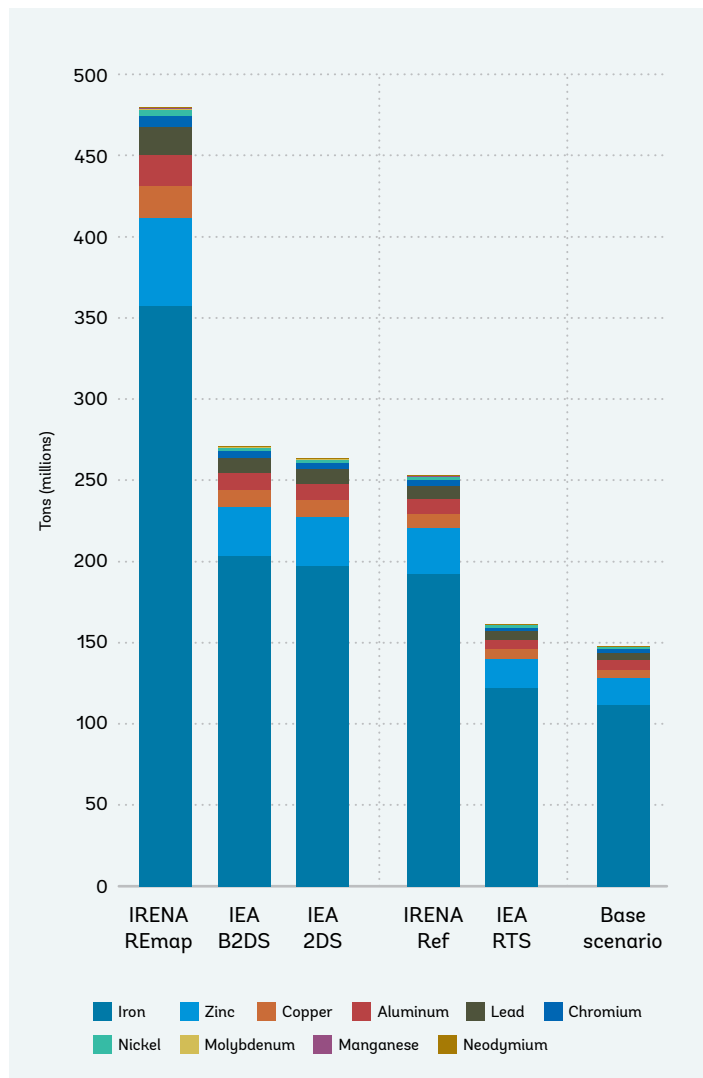
Figure 3.7 shows the major minerals used to supply wind installations through 2050, with iron accounting for 84.6 percent of demand and copper 4.4 percent. Note, the iron reported here is that which is used directly in the turbine, in either the generator core, the mainframe, or the rotor hubs; it does not include the iron needed for the steel components. All other minerals combined represent nearly 11 percent of demand, primarily for the permanent magnets (neodymium), gearboxes (nickel), or cabling (aluminum). Minerals not included in this analysis include dysprosium, which is used in permanent magnet direct-drive turbines.

Figure 3.7 Share of Mineral Demand from Wind Under IEA 2DS Through 2050



Note: 2DS = 2-degree scenario, IEA = International Energy Agency.

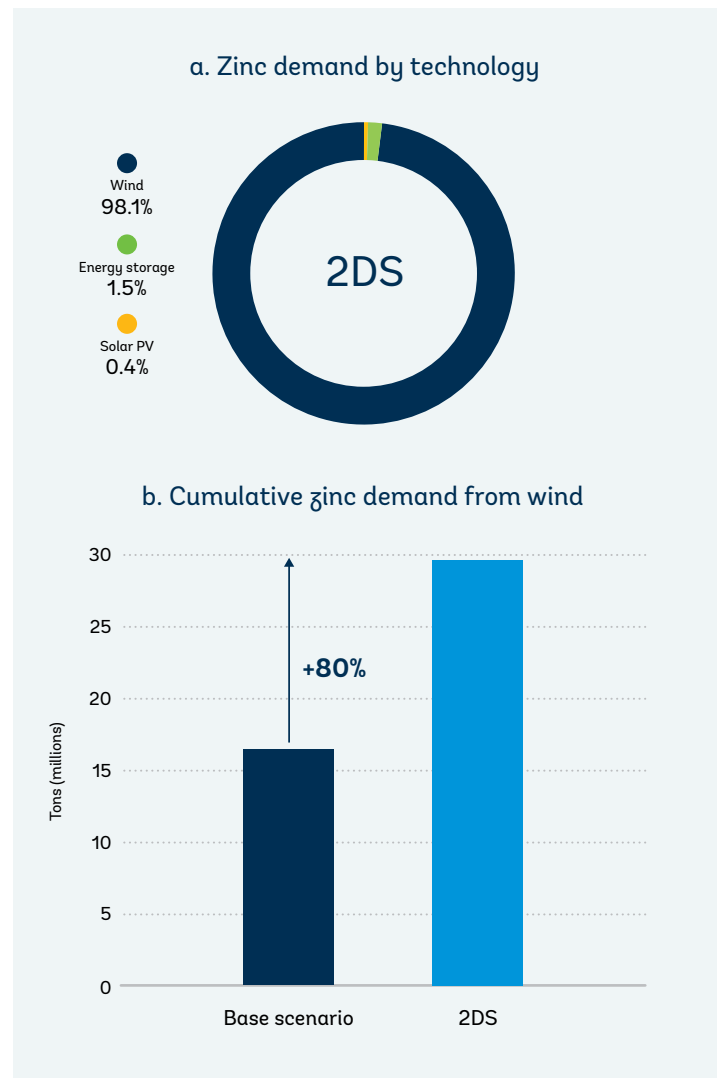
Figure 3.8 Cumulative Demand for Minerals Needed for Wind Through 2050



Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap = renewable energy roadmap scenario, RTS = reference technology scenario.

As seen in figure 3.8, the strongest demand for these minerals comes from the IRENA REmap scenario, representing a 78 percent increase from the IEA B2DS, as there is a higher installed capacity of wind in comparison to the IEA scenarios. The slight variations across the minerals across the technology-based mitigation scenarios are due to slightly differing mixes of offshore and onshore wind that have different mineral compositions.

Figure 3.9 Total Zinc Demand by Energy Technology Through 2050 (2DS, Base Scenario)



Note: 2DS = 2-degree scenario, PV = photovoltaic.

With the exception of zinc, all the minerals used to construct wind turbines are also needed to build other clean energy technologies. As seen in figure 3.9, 98.1 percent of zinc demand from energy technologies comes from the wind industry, as the mineral is predominantly used for protecting wind turbines from corrosion.

Trade-Offs in Wind Subtechnologies

Similar to solar PV, there are trade-offs in mineral demand for wind depending on which subtechnology—geared or direct drive—ends up being the most widely deployed. Currently, the most widely deployed wind technology is geared, as it is often used for onshore wind applications; direct drive is primarily targeted for the deployment of offshore wind, given its lower maintenance requirements. While onshore wind makes up the majority of wind energy deployment across all scenarios, the share of offshore wind is expected to increase with technology improvements and expected falling costs (LCOE).

Neodymium, which is only used in permanent magnet direct-drive turbines, is a key mineral affected by the balance between these technologies. Two alternative scenarios are constructed to highlight how shifts in the balance between geared and direct-drive turbines may affect the demand for neodymium.

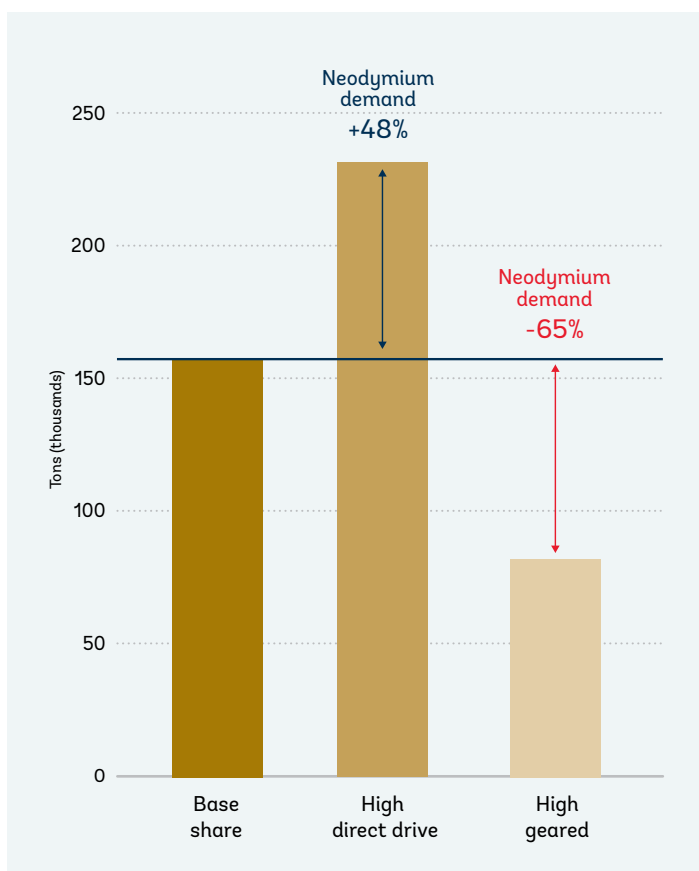
The first scenario has a higher share of direct-drive turbines,¹⁶ rising to 40 percent of onshore turbines and 90 percent of offshore turbines by 2050, compared with 25 percent and 75 percent in the mixed base scenario. The second scenario has higher shares of geared turbines, accounting for 90 percent of onshore turbines and 40 percent of offshore (table 3.3).

The greatest demand for neodymium comes in the high share direct drive scenario (see figure 3.10), with cumulative demand almost 50 percent higher than the base share scenario. In contrast, demand for neodymium in the high share geared scenario is 65 percent lower than the base share scenario.

Table 3.3 Share of Subtechnology Penetration in Wind Market Compared with Base Share

2050 share	Onshore Geared	Onshore Direct drive	Offshore Geared	Offshore Direct drive
Base share (2DS)	75%	25%	25%	75%
High share: Geared	90%	10%	40%	60%
High share: Direct drive	60%	40%	10%	90%

Figure 3.10 Cumulative Demand for Neodymium from Wind Subtechnologies Compared to Base Share Under 2DS Through 2050



Note: 2DS = 2-degree scenario.

¹⁶ It should be noted that not all direct-drive turbines use permanent magnets and thus demand neodymium. Data on the neodymium concentration in direct-drive turbines are drawn from a number of sources in the literature and a central point was used. The substitution between different direct-drive turbines is a scale of resolution beyond the scope of the model.

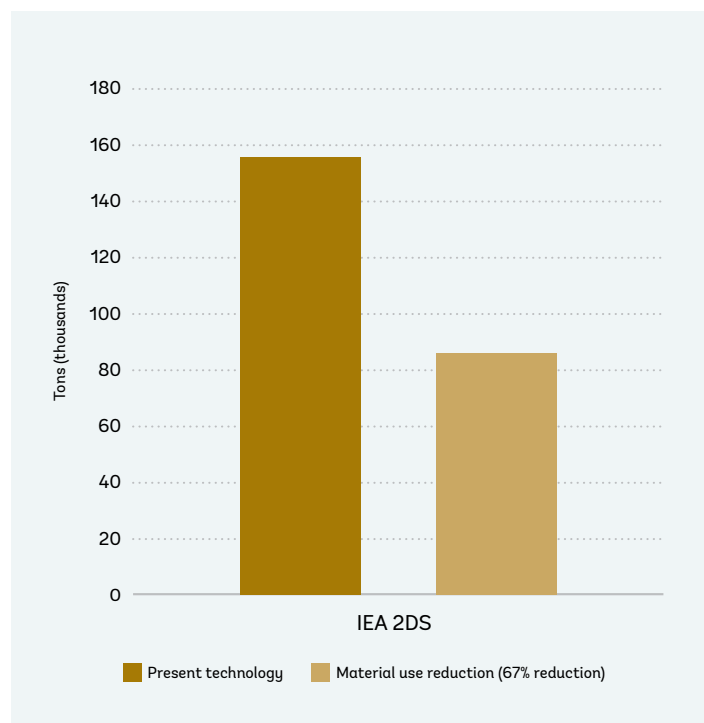


Material Use Improvements in Wind Turbines

Material improvements in direct-drive onshore and offshore wind turbines could lead to potential efficiency gains in the use of neodymium in the turbines. Such improvements could include (1) the decreased use of permanent magnets through alternative designs (for example, air core axial flux), and/or (2) the increased use of hybrid turbines using a medium-speed gearbox and permanent magnet generator.

To estimate the efficiency gains from the reduction of materials in wind turbines, a 67 percent mineral reduction is assumed through 2050 under a 2DS, a figure derived from the lowest figure for neodymium use in direct-drive turbines in the literature. As noted in figure 3.11, if material improvements were to take place, cumulative demand of neodymium would fall by 45 percent, compared with the present mineral composition of current wind technology.

Figure 3.11 Cumulative Demand for Neodymium from Wind Technologies Under Present Technology and Material Use Reduction Under 2DS Through 2050



Note: 2DS = 2-degree scenario, IEA = International Energy Agency.



Geothermal

Geothermal energy currently accounts for less than 1 percent of global electricity generation capacity (IEA 2019c) and is actively being used in more than 20 countries;¹⁷ the United States is the world's largest producer, at about 2.5 GW in 2018.¹⁸ Geothermal energy can be used for electricity generation, direct or indirect use, or co-generation. There are limitations with the use of geothermal energy since electricity can only be generated in locations with high or medium temperatures, typically close to tectonically active regions.¹⁹ Countries such as Indonesia, Iceland, the Philippines, and New Zealand—countries in tectonically active regions—actively use geothermal to meet their electricity needs. Indonesia recently announced a plan to build 7.2 GW of geothermal by 2025 given its comparative advantage in this resource to meet its growing energy demand.²⁰

Geothermal generates electricity from thermal energy located below the earth's surface, whether in liquid, trapped steam, or rock. Therefore, geothermal requires a very high level of quality steel to be able to carry reservoirs of steam and hot water for electricity generation. Corrosion-resistant alloys, for example, are needed in the geothermal plants, requiring minerals such as titanium and molybdenum. The demand for these minerals from specific geothermal plants will vary from location to location based on the number and depth of wells needed to access the thermal energy.²¹

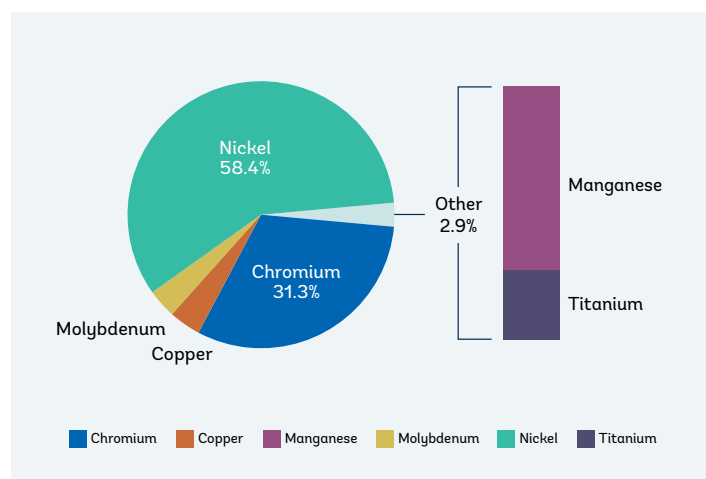
Geothermal uses relatively more steel than wind, approximately 6–10 times as much per megawatt of capacity. Unlike wind—which also requires a large amount of steel, primarily manufactured from a mix of nickel and iron ore—geothermal requires steel alloys with a large quantity of titanium to cope with the high heat and pressure in geothermal power generation. Literature on geothermal production is more limited than for wind and solar PV, and given that a large share of mineral demand for

the technology comes from the use of elements to create various alloys of steel, steel has, again, been excluded from this analysis to avoid double-counting.

Figure 3.12 shows the major minerals required for supplying geothermal through 2050. In addition to being used in wind, chromium represents a key mineral for geothermal technologies, with 36 percent of its demand from all energy technologies going toward geothermal.

The highest capacity of geothermal is found in the REmap and B2DS scenarios, with overall mineral demand of relevant minerals increasing by 78 percent and 71 percent from the Ref and RTS scenarios, respectively (figure 3.13).

Figure 3.12 Share of Mineral Demand from Geothermal Under 2DS Through 2050



Note: 2DS = 2-degree scenario.

¹⁷ "Geothermal Energy," National Geographic, <https://www.nationalgeographic.com/environment/global-warming/geothermal-energy/>.

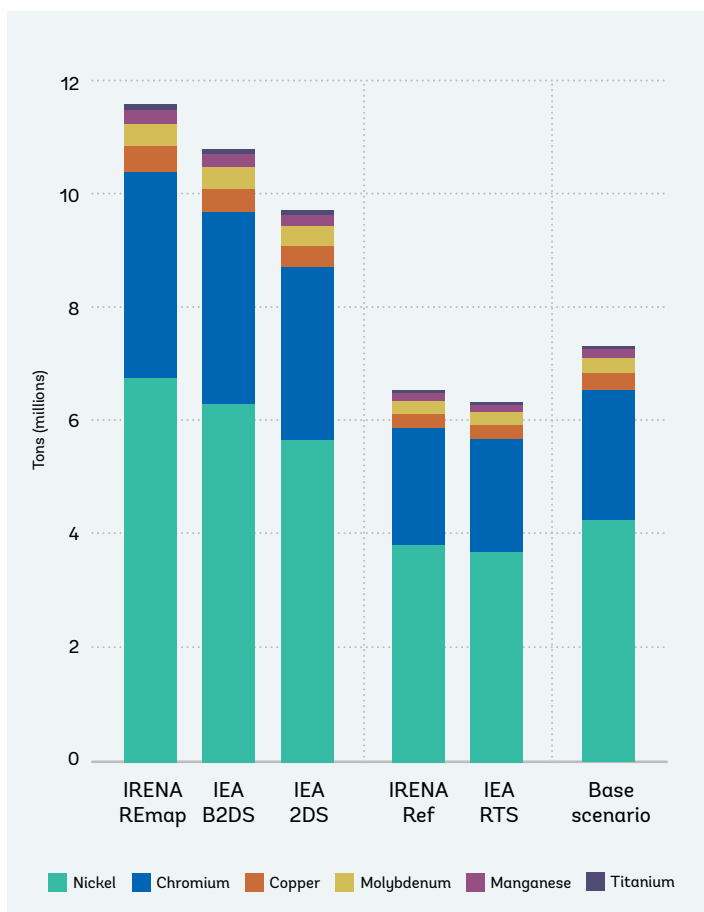
¹⁸ "Geothermal Energy," International Renewable Energy Agency, <https://www.irena.org/geothermal>.

¹⁹ *Ibid.*

²⁰ "Indonesia Needs \$15 Billion Investment to Meet Geothermal Target by 2025," Reuters, August 13, 2019, <https://www.reuters.com/article/us-indonesia-geothermal/indonesia-needs-15-billion-investment-to-meet-geothermal-target-by-2025-idUSKCN1V30R0>.

²¹ Data used in the model is an average of three plants—a 50 MW facility with 25 wells at depth of 5 kilometers; a 10 MW facility with 5 wells 1.5 kilometers deep, and 48.4 MW facility with 22 wells 2.5 kilometers deep—and covers both plant facilities and well pipes (Moss et al. 2013).

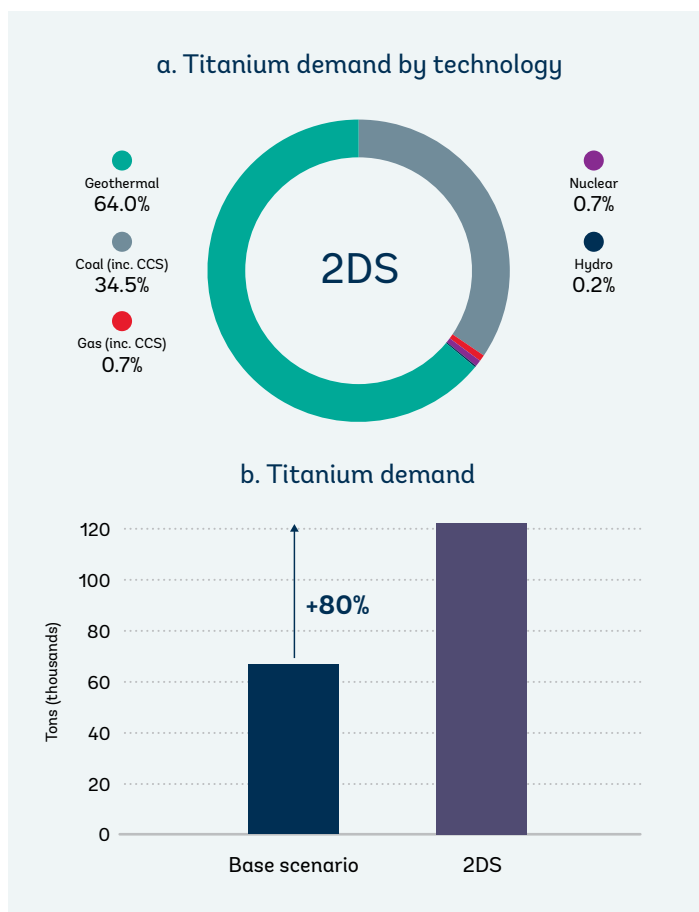
Figure 3.13 Cumulative Demand for Minerals Needed for Geothermal Through 2050



Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap =renewable energy roadmap scenario, RTS = reference technology scenario.

Contrary to solar PV and wind mineral demand trends, figure 3.13 illustrates that the overall demand for geothermal minerals in the base scenario is slightly higher than in both the RTS and Ref scenarios because of different assumptions around geothermal deployment up to 2050. In the base scenario, a higher share of geothermal capacity is expected. This reflects changes in assumptions about the projected costs of geothermal energy over time, relative to other renewable technologies. Because the costs of solar PV and wind have plummeted in recent years, these technologies are now seen as more attractive over other renewable technologies. Therefore, the most up-to-date projections from IRENA

Figure 3.14 Total Titanium Demand by Energy Technology Through 2050 (2DS, Base Scenario)



Note: 2DS = 2-degree scenario, CCS = carbon capture and storage.

and the IEA now project lower levels of geothermal capacity than the slightly older IEA data from which the base scenario is drawn.

Titanium is one of the relevant minerals that are affected by the assumptions around both geothermal and coal and CCS deployment. As seen in figure 3.14, under a 2DS, geothermal accounts for 64 percent of titanium demand, while coal and CCS account for 34.5 percent. With titanium being heavily used in both technologies, its demand will grow regardless of whether the world moves toward a more fossil fuel intensive or lower-carbon energy pathway.





Concentrated Solar Power

Concentrated solar power (CSP) produces electricity by concentrating the sun's heat using mirrors to heat water and drive steam turbines. A variety of CSP plant sizes exist, ranging from 1 MW to 400 MW. One of the main advantages of CSP, compared with solar PV, is that it can be equipped with molten salts to store heat, which can then be released in the evening, making it an ideal renewable energy source for large-scale applications. Despite its advantages, CSP only accounted for 5.5 GW of installed capacity globally in 2018, compared with 480 GW of solar PV,²² because of its high costs relative to other renewables and geographic constraints. CSP can only be deployed in locations with excellent direct normal irradiation, which is typically found in desert regions, so currently CSP is most found in countries such as Chile, Spain, and the United States.

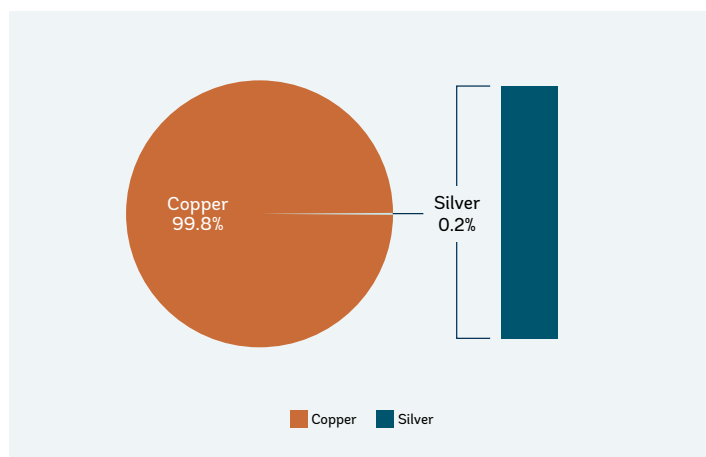
Regions such as North Africa and the Middle East are expected to take the lead in developing their CSP capacity, even though CSP deployment will remain small relative to solar PV and wind. There is potential for the technology to be further scaled up given continued falling prices and technological improvements. Growth rates may still be large; the IEA's *World Energy Outlook 2019* projects growth in Africa-deployed CSP at more than 900 percent by 2040. This growth is most likely to occur in developing countries, with the IEA projecting that, under the 2DS, almost 80 percent of all CSP installed capacity will be in non-OECD countries by 2050. CSP's storage capacity also makes it an attractive renewable source for developing countries endowed with high direct normal irradiation.

Given the niche aspect of the technology, there are considerable fewer studies on the material inputs required for CSP systems. Bulk materials such as glass, steel, and aluminum are needed for the support structures for the mirrors, but no data were available in the literature for these materials, or the minerals identified were outside the model. Data were available, however, for the use of copper (for wiring, pumps, electric motors, and the generator) and silver (used for coating the glass for the mirrors). Various types of CSP plants are emerging—including parabolic trough systems,

linear fresnel systems, and central receivers—with each using varying amounts of silver. There was insufficient data on both installed capacity and material composition to model these types separately, but the model does capture variations in silver demand from the various types.

Figure 3.15 shows the balance between copper and silver for which data were available under a 2DS, with copper representing a much greater share of modeled demand because of its wider spread use across CSP facilities.

Figure 3.15 Share of Mineral Demand from Concentrated Solar Power Under IEA 2DS Through 2050



Note: 2DS = 2-degree scenario, IEA = International Energy Agency.

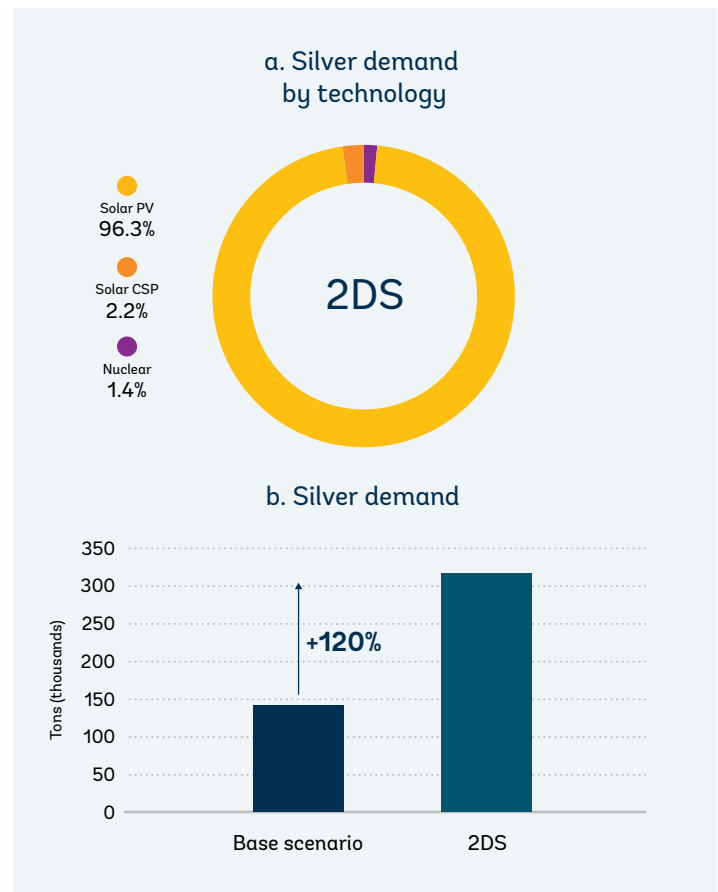
Figure 3.16 Cumulative Demand for Minerals Needed for Concentrated Solar Power Through 2050



Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap = renewable energy roadmap scenario, RTS = reference technology scenario.

Mineral demand is strongest in the B2DS, as seen in figure 3.16, where it is expected that CSP capacity will be the highest. Both of the IRENA scenarios, Ref and REmap, are bearish on CSP's share in the global electricity mix through 2050, explaining the lower demand for copper and silver. This reflects different assumptions on the projected costs of the technology against other renewable technologies, such as solar PV. The base scenario also projects a higher share of CSP than the later RTS one, reflecting changing beliefs on the balance between CSP and solar PV, with cost reductions in the latter causing it to be projected as an even greater share of renewable capacity compared with CSP in the more recent IEA projections.

Figure 3.17 Total Silver Demand by Technology Through 2050 (2DS, Base Scenario)



Note: 2DS = 2-degree scenario, CSP = concentrated solar power, PV = photovoltaic.

While the projected figures for both copper and silver appear to grow dramatically in the more ambitious scenarios, they pale in comparison to the minerals' use in solar PV. For example, figure 3.17 shows the demand for silver by technology through 2050 under a 2DS. The vast majority of demand for silver, at 96.3 percent, is linked to solar PV growth, predominantly from solar PV's subtechnology, crystal Si, with only 2.2 percent of silver demand linked to CSP and 1.4 percent to nuclear. Under a 2DS, demand for silver is expected to double, growing from 1.4 thousand tons in 2017 to nearly 3.2 thousand tons in 2050.





Energy Storage

Energy storage technology stores electricity when it is generated and can then later dispatch it as needed.²³ It is a very important technology for renewable energy, particularly for variable ones such as solar PV and wind, which are nondispatchable, as electricity is only generated when the sun is shining or when the wind is blowing. Energy storage can provide a solution and act as an ancillary service for these specific technologies by storing electricity in a battery and then releasing it during peak hours, usually in the evening. Given this high potential, the World Bank launched the Energy Storage Program to scale up 17.5 GWh of battery storage by 2025 in developing countries.²⁴

While energy storage can play a major role in stabilizing the grid from variable renewable energy, its costs are still too high for it to be deployed more widely. Relative to solar PV and wind technologies that have an average LCOE of 0.05/kWh, battery storage has LCOE costs averaging 250/kWh, making it too expensive for most applications today. Despite the high costs, the increased use of batteries in electric vehicles has been the primary reason why battery costs have fallen quickly, from 288/kWh in 2016 to 157/kWh today, representing a 46 percent decrease in price.

Energy storage is crucial for the low-carbon transition for two main reasons: (1) It is used to power electric vehicles, and (2) it is needed to store power from intermittent electricity generation from solar PV and wind farms, including grid and decentralized operations. Both applications of energy storage are included in the model from the IEA's technology-based mitigation scenarios since data on energy storage were not available for the IRENA and base scenarios. Battery electric vehicles are expected to account for approximately 90 percent of deployments in the IEA scenarios, with stationary and decentralized applications making up the other 10 percent; the mineral demand follows this sectorial split.

Mobile Energy Storage

The energy storage landscape for automobiles (and other wheeled ground vehicles, including buses, vans, and trucks) is changing very rapidly. All vehicles today have some battery energy storage, almost always a lead-acid battery, to help start the engine and to power vehicle electronics. There are two primary batteries used in the automotive sector and covered in this analysis:

- **Lead-acid batteries** have dominated the early stages of electric vehicle operation because they are a mature technology and are inexpensive, but they are limited by their weight and their range. They are being gradually replaced by Li-ion batteries, initially developed for use in laptops and other electronics.
- **Li-ion batteries** offer a much higher energy density than previous generations of batteries, meaning more energy can be stored for the weight of battery. They also require less maintenance and offer a range of flexibility since they can be manufactured with a variety of different minerals, and are tailored for different functions. They do, however, come at a higher cost, require protective circuits, and are a potential fire risk.

The model assumes that initially a mix of lead-acid and Li-ion batteries are used in electric vehicles, with Li-ion quickly taking over the entire market.

Stationary Energy Storage

Stationary energy storage has different desirable features from the use of batteries in electric vehicles. Weight, for example, is less of a concern, and different applications of stationary storage have different needs. Some batteries need a lot of power to be stored for short durations, whereas others need less power but a longer storage time. Different batteries may therefore play a role in mineral demand:

- **Li-ion batteries** are the dominant technology at the moment in stationary energy storage, although lead-acid batteries still play a small role in some applications.

²³ In this section, energy storage refers to battery technologies specifically, not other forms of energy storage, such as pumped hydroelectricity, nor thermal storage (such as the molten salts used in CSP). Batteries are also a crucial component of electric vehicles, vital for storing and carrying the electricity needed to run the motors of these vehicles.

²⁴ For more information, see the World Bank's Energy Sector Management Assistance Program's "Energy Storage Program" webpage: <https://www.esmap.org/energystorage>.

- **Redox flow batteries** are an emerging technology in stationary energy storage. They are heavy and large, and thus unsuitable for vehicles, but they can be built with extremely large capacities (up to 200 MW, compared with 100 MW for Li-ion) and have a long life span.

In the model, Li-ion batteries provide the largest amount of stationary storage, with a declining role for lead-acid batteries and an emerging role for vanadium-based redox flow batteries.

Battery Technology Post-2030

The battery space is emerging rapidly, and many new options are under development. This uncertainty is much greater post-2030 owing to the huge scale of innovation and experimentation occurring in the sector. The assumption that Li-ion batteries dominate both the mobile and stationary market for the next decade is conservative. Post-2030, the scale of uncertainty is much greater, with a wide range of options in both markets.

Within mobile storage, options such as solid-state Li-ion batteries could enter the market. However, the automotive market itself could pivot, with hydrogen fuel cell vehicles entering the market at scale. Within the stationary space, there will be increasing demand for longer-duration batteries. Some of this demand could be met by vanadium redox flow batteries, but other options are also emerging rapidly, including iron-based flow batteries, thermal-electric options that involve storing energy as heat in a variety of different media from molten salts (also used in CSP to store energy) or rocks. There is even concrete and mechanical storage, which stores energy as mechanical energy and discharges it by dropping weights.²⁵

Predicting which, if any, of these technologies emerges to commercial scale is impossible, but each could affect the demand for minerals generally, and especially the minerals used heavily in the types of stationary storage assumed in the model, such as lithium, cobalt, nickel, manganese, and vanadium. The impacts of some of these technologies are discussed in the Emerging Energy Technologies section later in this chapter.

Battery Composition

Batteries generally have three main elements: a cathode, an anode, and an electrolyte that sits between the two materials to enable electricity to be collected and discharged at different times. The minerals used for these elements differs between and within battery technologies.

Redox flow batteries differ in that they operate by pumping a liquid electrolyte (usually sulfuric acid, mixed with vanadium salts—in vanadium redox flow batteries), through a core consisting of a positive and negative electrode, separated by a membrane.²⁶

Examples of the different types of batteries covered in the model are given in table 3.4.

As the climate scenarios become more ambitious, 12 of the 17 minerals in this analysis show much larger increases in demand because of their use in energy storage, particularly those minerals used in Li-ion batteries (figure 3.19). Lead, vanadium, and iron show smaller increases: They are not used in Li-ion batteries, but rather in lead-acid or redox flow batteries, whose deployment do not vary as significantly across the 2DS and B2DS.

Figure 3.18 Li-ion Battery

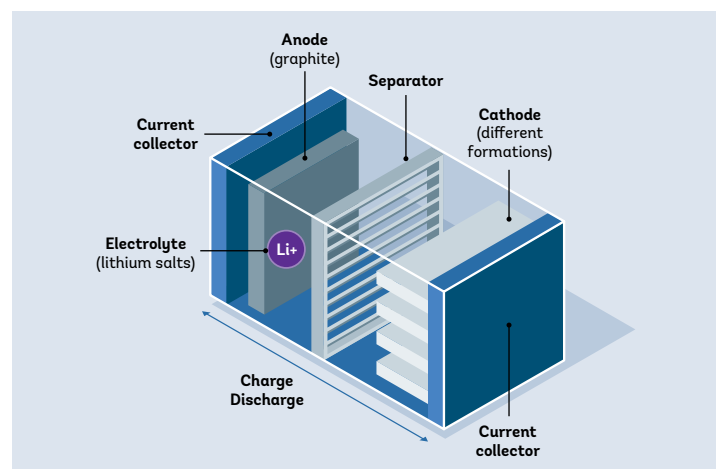


Illustration adapted from the World Bank's Minerals for Climate Action Infographic, <https://www.worldbank.org/en/news/infographic/2019/02/26/climate-smart-mining>.

²⁵ One example of mechanical storage includes a technology that uses abandoned mine shafts. Energy is stored by lifting weights to the top of the shaft and discharged by dropping the weights to the bottom of the shaft.
²⁶ A number of different chemistries are possible, but batteries using vanadium are the most mature and thus are the main type of redox flow battery included in the model.

Table 3.4 Batteries and Their Subtechnologies Covered in the Ref, 2DS, and B2DS

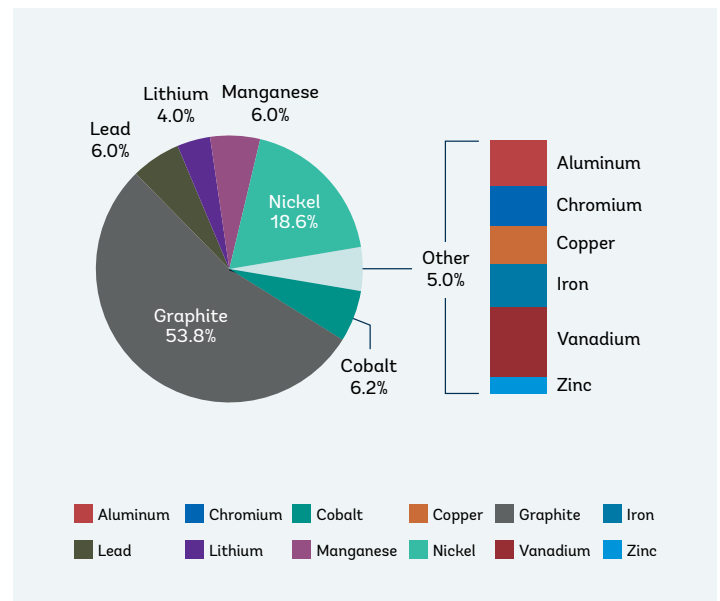
	Cathode	Anode	Electrolyte	Uses
Lithium-ion	Various: • Nickel manganese cobalt (NMC) oxide • Nickel manganese cobalt (NMC) oxide • Nickel cobalt aluminum (NCA) oxide • Lithium cobalt oxide (LCO) • Lithium manganese oxide (LMO) • Lithium iron phosphate (LFP)	Graphite	Lithium salt	• Electric vehicles, stationary storage, medical devices, e-bikes • Electric vehicles, stationary storage, medical devices, e-bikes • Portable electronics • Power tools, medical devices • Electric vehicles, electric buses, stationary storage
Lead-acid	Lead-dioxide	Lead	Sulfuric acid	Vehicles, backup power systems, stationary storage
Redox flow	n.a.	n.a.	Vanadium-based	Stationary storage

Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, n.a. = not applicable, Ref = reference scenario.

While cobalt and lithium are probably best known for being used in energy storage, batteries generally use a wide variety of minerals for the cathode, as covered in figure 3.19, including aluminum, lead, and manganese. Graphite, used for the anode, accounts for nearly 53.8 percent of mineral demand. Nickel, needed for cathode production in NMC (nickel manganese cobalt oxide) and NCA (nickel cobalt aluminum oxide) batteries, accounts for the second highest level of demand, at 18.6 percent. Cobalt, another battery mineral, is expected to account for 6.2 percent of total demand up to 2050 under a 2DS. Lithium, accounting for 4 percent of total demand, is used across all Li-ion batteries, regardless of the cathode composition.

It should be noted that this analysis does not take into account the implications of mineral supply to achieve a low-carbon future, but for demand for energy storage minerals specifically. Supply has been minimally highlighted owing to the fact that some battery minerals, namely cobalt and graphite, are primarily (more than 50 percent) produced in one country, albeit not the same one.²⁷

Figure 3.19 Share of Mineral Demand from Energy Storage Under IEA 2DS Through 2050



Note: 2DS = 2-degree scenario, IEA = International Energy Agency.

27 China produces nearly 70 percent of the world's natural graphite, while the Democratic Republic of Congo produces more than 60 percent of the world's cobalt (EC 2018)

Compared to the IEA RTS, mineral demand increases by 107 percent in the B2DS because of the large-scale deployment of battery electric vehicles (figure 3.20). The uncertainty regarding battery storage deployment is high, particularly as battery storage technologies are expected to be in greatest demand post-2030. Still, the storyline remains the same as that for energy generation technologies: Greater climate ambition leads to greater overall mineral demand. However, as demand levels grow, the types of technology that might meet that demand become uncertain, as more space is available for new battery technologies, with different mineral requirements, to enter the market.

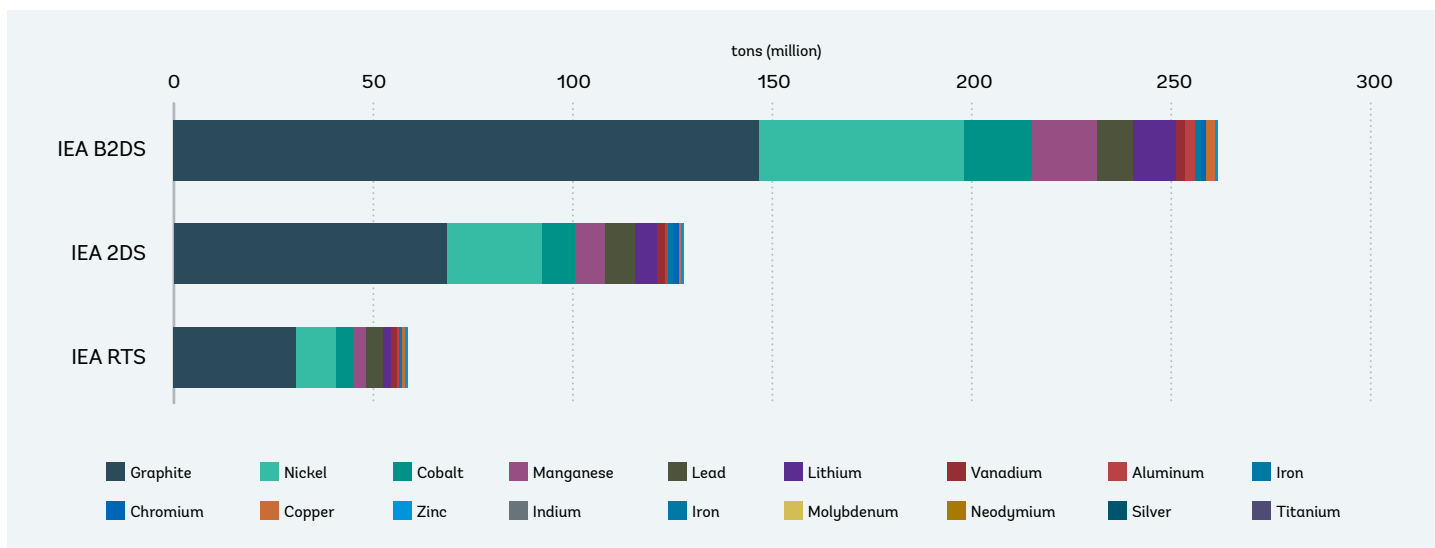
The only use of both graphite and lithium in energy technologies included in the model is linked to energy storage in Li-ion batteries for the anode and electrolyte, respectively.²⁸ As these two minerals are not used in other energy technologies, their overall demand cannot be compared to other technologies.

Trade-Offs in Battery Subtechnologies

Within some battery technologies, trade-offs exist between component minerals, and thus the choice of subtechnology or even specific types of subtechnology can have implications for the demand for not just one mineral, but a grouping of minerals. With battery manufacturers concerned about mineral supply chains, especially for cobalt, the battery industry has been spearheading efforts to reduce the amount of cobalt needed in batteries, to reduce supply chain risks, while maintaining the efficiency level in battery technology. Mainstream media and nongovernment organizations reporting on the labor and environmental issues surrounding cobalt extraction have put pressure on downstream companies to become more responsible in where and how they source cobalt for battery technologies.

With the battery sector changing the most rapidly among all technologies, being able to forecast which subtechnology will be the most used up to 2050 is nearly impossible. The scarcity of available data on, for example, the different shares of the different battery chemistries in the Li-ion market, both now and in the

Figure 3.20 Cumulative Demand for Minerals Needed for Energy Storage Through 2050



Note: Demand in the 4DS scenario is not presented because energy storage is not modeled in that scenario. 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, RTS = reference technology scenario.

28 Graphite has some niche uses in other energy technologies, such as the use of carbon brushes in the motors of wind turbines, but no data were available for these uses and their scale is likely to be very small compared with the use of graphite in battery technologies.

future, has been a challenge. In the model, data have been drawn from across the various chemistries, and, using the methodology described above, have modeled the “average” Li-ion battery. However, to illustrate how changes in the types of Li-ion battery that may dominate the future market may impact mineral demand, two illustrative scenarios have been developed.

In the battery sector, the Li-ion battery compositions are described by their mineral content ratio. In a NMC811 design, for example, the 8, 1, and 1 represent the nickel (80 percent), manganese (10 percent), and cobalt (10 percent), respectively, used in the cathode, while in the NMC111 design, nickel, manganese, and cobalt are used in equal proportions. The latter has been the main chemistry used in NMC batteries to date, but there is increasing interest in the new NMC811 design, which is potentially cheaper, lighter, and offers longer range to electric vehicles—along with reducing the amount of cobalt required.

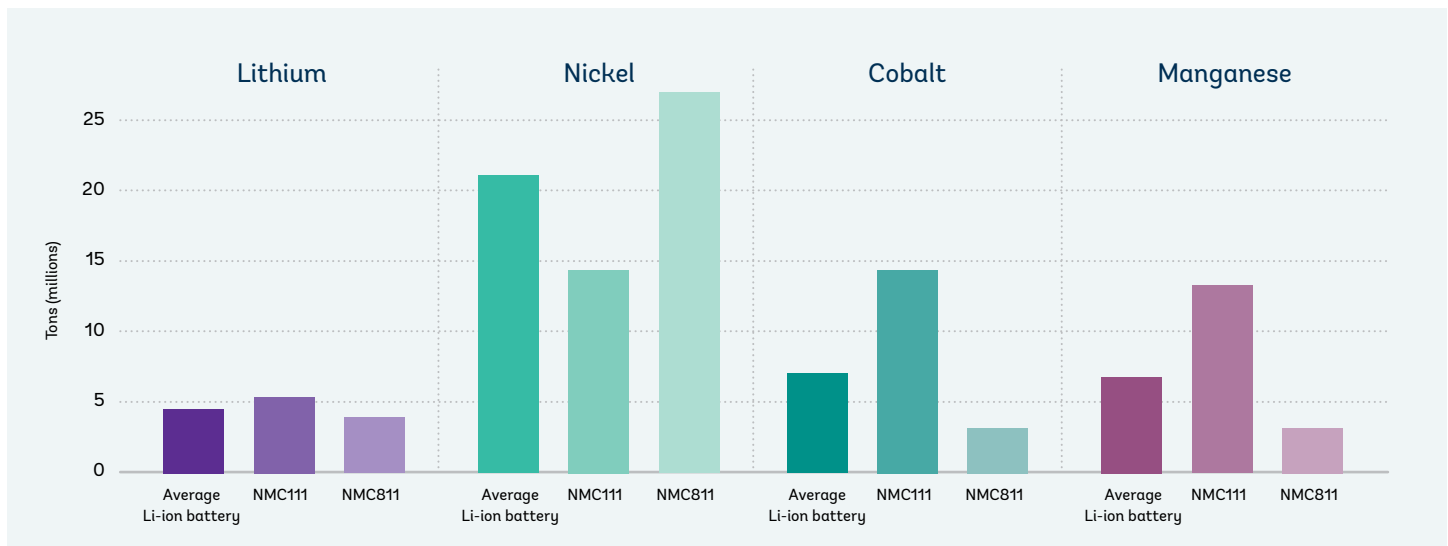
To demonstrate the impact of shifts in demand within the Li-ion battery market, two alternative scenarios are compared to the “average” Li-ion battery, which is the base in the model

(see figure 3.21). In the first scenario, every Li-ion battery is assumed to be an NMC811, while in the second one, all batteries are assumed to be an NMC111.²⁹

Lithium demand varies by almost 20 percent from the base share depending on the battery choice. Figure 3.21 shows that the higher levels of lithium demand with NMC111 are also associated with much greater levels of cobalt and manganese demand, approximately 100 percent more than the base share. However, with NMC111, nickel demand is much lower, over 35 percent lower.

There a clear trade-off between nickel, cobalt, and manganese (and to a lesser extent lithium), depending on which battery subtechnology emerges. Shortages (and thus higher prices) of minerals such as cobalt could incentivize shifts to different Li-ion battery types—either NMC811 or non-cobalt types like lithium-iron phosphate. On the other hand, shortages in lithium could shift battery types to NMC811, increasing the demand for nickel.

Figure 3.21 Cumulative Demand for Minerals from Li-ion Battery Scenarios Under 2DS Through 2050



Note: 2DS = 2-degree scenario, Li-ion = lithium-ion.

29 These are extreme scenarios, but they demonstrate potential directions and scales of impact on demand for particular minerals.

Material Use Improvements in Li-ion Batteries

Many of the technologies needed for a low-carbon future are being deployed rapidly while cost-reductions are occurring.³⁰ These cost reductions stem from many sources, including decreasing concentration of minerals such as cobalt. In 2018, the minerals needed to build cathodes and anodes (battery cell) accounted for approximately 70 percent of the total cost of a battery (Goldie-Scot 2019).

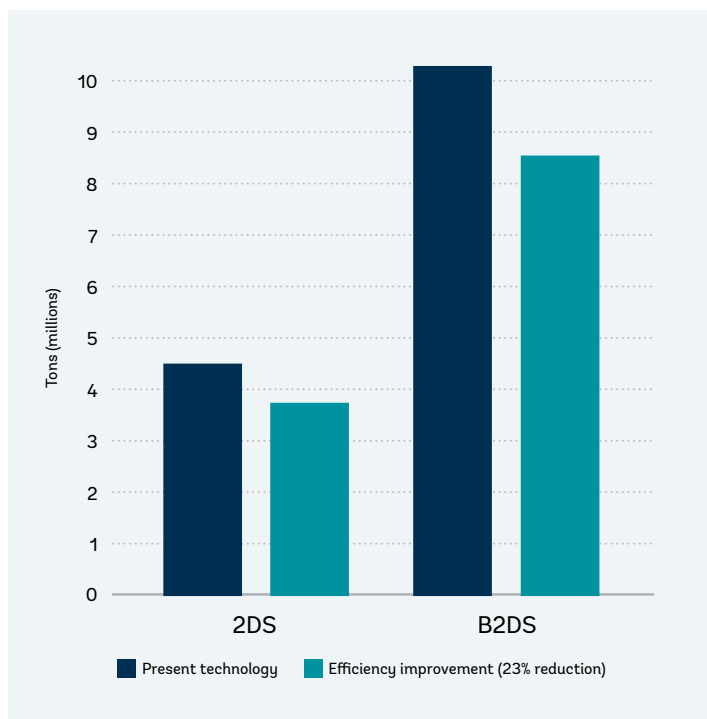
Although not all technologies show a clear pattern of reduction (depending on how subtechnology choice is assumed to occur), there are patterns of change. For example, various sources in the literature show a reduction in the estimated composition of lithium in Li-ion batteries over recent years.³¹ In 2016 Teske et al. estimated a composition of 0.24 tons per megawatt-hour for a Li-ion (NCA) battery. By 2018, the IEA estimated a composition of 0.1 tons per megawatt-hour for a similar battery (IEA 2018).

To capture this effect, the model was extended using the assumption that all Li-ion batteries would keep improving their use of lithium, with all batteries moving to the most efficient type seen in the literature today. This shift led to a 23 percent reduction in the use of lithium in Li-ion batteries by 2050. Figure 3.22 shows the effect of these material improvements in Li-ion batteries on the demand for lithium under a 2DS and B2DS. The impact of this result would reduce the demand for lithium by between 16 and 17 percent, with the largest absolute difference seen under a B2DS.

Improvements in the energy density of Li-ion batteries, such as the amount of energy batteries can store per kilogram, as well as their cycle life, how many times a battery can be charged and discharged before its capacity starts to fall below 80 percent of its original capacity, will also have important implications for demand for minerals such as lithium, graphite, and cobalt. Should density and cycle life increase sharply, then the demand for new batteries and the minerals they require will fall.



Figure 3.22 Cumulative Demand for Lithium from Energy Storage Under Present Technology and Material Use Reduction Through 2050 Under 2DS, B2DS



Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario.

³⁰ See, for example, figure 5.1 of IEA's 2018 report *Global Electric Vehicle Outlook*.
³¹ See, for example, Teske et al. (2016) and IEA (2018).

Emerging Energy Technologies

This section discusses the various emerging technologies that are considered potential game changers in the transformation of the energy system globally. Other than carbon capture and storage, these specific technologies have not been included in the model to estimate demand across the 17 minerals analyzed in the model, but they are included here because their potential commercialization in the near term could have implications on overall mineral demand. This analysis remains technology agnostic with regard to which energy technology could become more prominent to achieve a low-carbon future, but as the emerging technologies are also mineral intensive, they are addressed in the report.

Carbon Capture Storage

Carbon capture and storage (CCS) is one of the key technologies that is expected to be deployed under the IEA scenarios, albeit with great uncertainty, and it has been partially captured in the model. However, it has been included in the Emerging Energy Technologies section because the technology is still at relatively early stages of development compared to solar PV, wind, geothermal, CSP, and energy storage.

CCS involves the capture of CO₂ from three sources:

- Combustion of coal and gas
- Transportation of the CO₂ from source site to long-term storage
- Long-term storage of the CO₂

Figure 3.23 Carbon Capture Storage

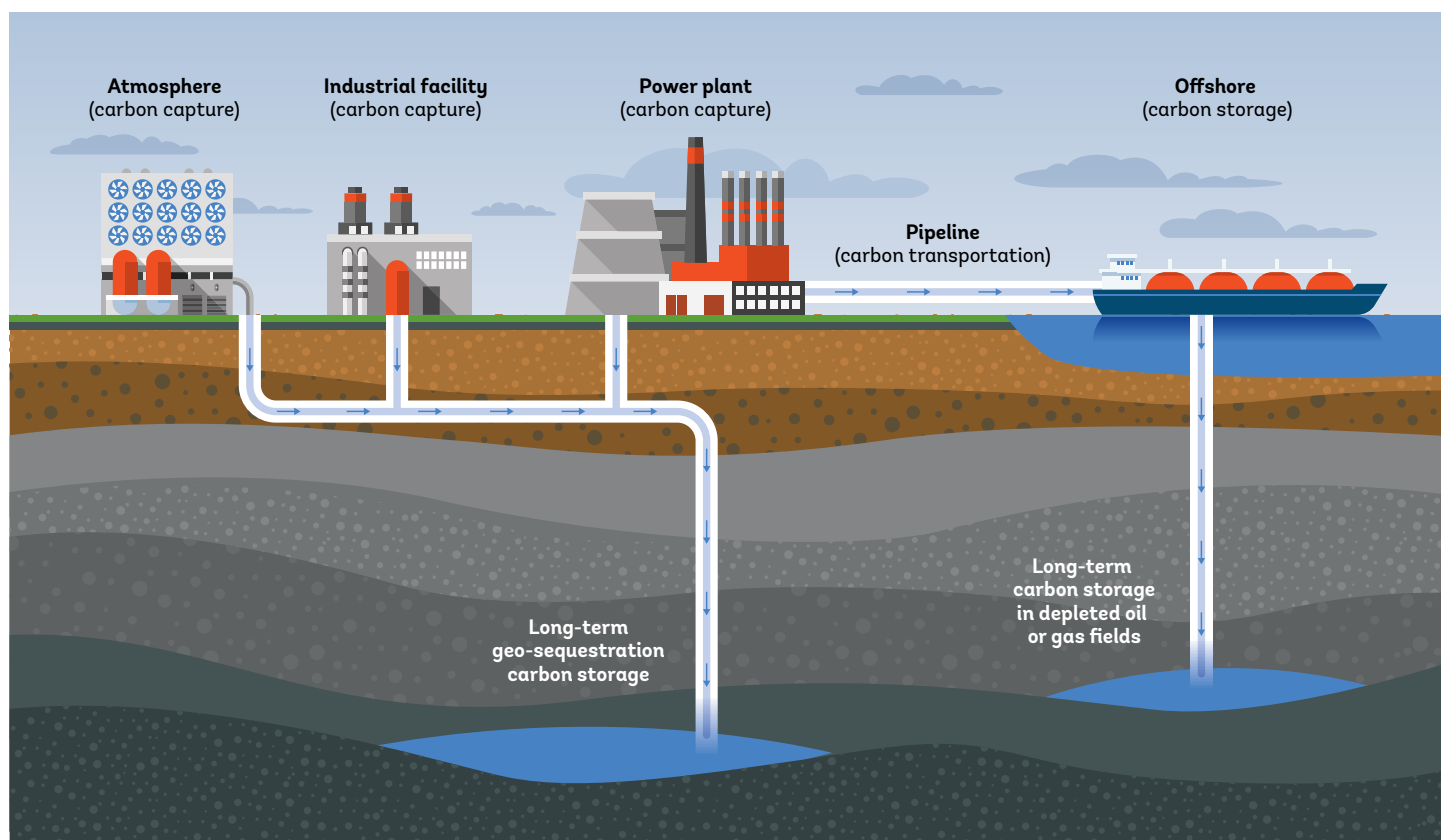


Illustration adapted from various sources (for example, Shell Sustainability Report 2016, <https://reports.shell.com/sustainability-report/2016/energy-transition/our-work-to-address-climate-change/carbon-capture-and-storage.html>; Carbon Capture and Storage Association, <http://www.ccsassociation.org/what-is-ccs/>).

Widespread commercial-scale CCS has yet to emerge and there is great uncertainty over how large a role it will play in the future. CCS's role in technology-based mitigation scenarios varies widely. The IEA sees an increasing role for the technology in the 2DS and B2DS scenarios; it projects that under the 2DS, 350 GW of coal plants with CCS attached will be in operation, representing 74 percent of all coal facilities. IRENA, on the other hand, sees the technology differently and does not include CCS in their scenarios.

Crucial to the scale at which CCS may be deployed are costs, including the size of a carbon price, which is vital for ensuring that CCS is commercially viable; regulatory and legal factors relating to the storage of carbon, and any liabilities that may result from this process; and availability of suitable geological formations to store the CO₂ underground.

These factors have limited the widespread adoption of CCS, resulting in its slow acceptance. In 2018, there were 43 large-scale facilities at various stages of operation, with 20 operating commercially (GCCSI 2019). The technology itself, however, is not entirely new—capturing CO₂ and injecting it into oil wells to improve recovery has been going on for over 45 years. Projects are emerging that involve capturing CO₂ from electricity plants, as well as from iron and steel facilities.

The sparsity of large-scale operating CCS plants makes projecting the mineral composition of the technology in the future challenging. Work in this area has identified chromium, cobalt, copper, manganese, molybdenum, and nickel as the key minerals involved in the technology. These minerals are used in a variety of ways in CCS, either in capturing the CO₂ (such as manganese and nickel) or in the steel alloys needed for the CCS plant, transportation pipes, and other changes needed for the generation plant. A critical factor is the length of the pipelines needed to transport the CO₂ to the storage sites; this will vary between facilities and would alter the overall scale of demand for minerals from the technology.

Batteries: Next Generation

Among many battery experts, the view is that Li-ion batteries will dominate the battery sector in the next decade,³² similar to projections made under the model used in this analysis. However, a number of rapidly emerging new battery technologies could potentially challenge the proposed future dominance of Li-ion batteries. Great uncertainty exists about when, or if, these new batteries will reach widespread market deployment. However, many of these new technologies offer substantial benefits over Li-ion batteries should they become viable; thus, they could play a large role in providing energy storage options, both mobile and stationary, post-2030. Two groups of these technologies, solid-state Li-ion batteries and zinc-air batteries, are examined to give understanding on the potential impact of such breakthrough technologies on demand for minerals.

Figure 3.24 Solid-State Battery

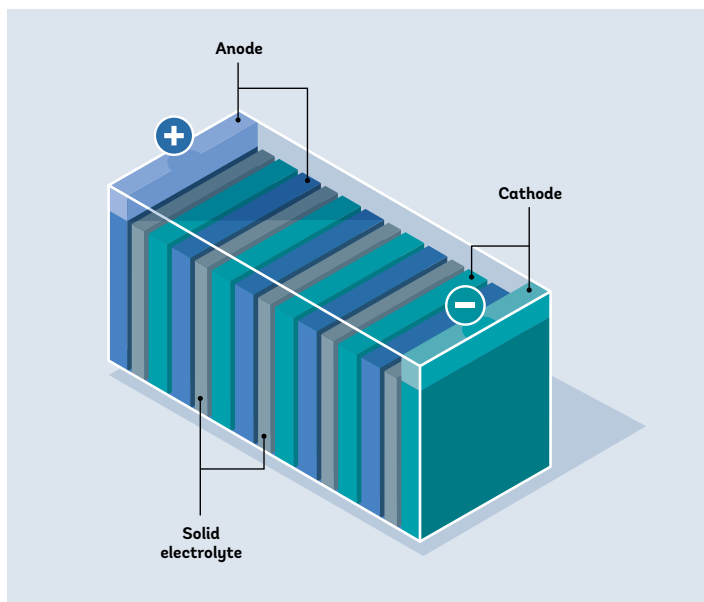


Illustration adapted from various sources (for example, Electronics-Lab.com, <https://www.electronics-lab.com/solid-state-li-ion-batteries-high-energy-dense-batteries-closer/>).

32 See, for example, Tsiropoulos, Tarvydas, and Lebedeva (2018).

Solid-State Batteries

Solid-state batteries differ from their more common liquid counterparts by replacing the liquid electrolyte in conventional Li-ion batteries with a solid alternative such as a polymer or ceramic. This structure enables engineers to replace the graphite anode with a lithium mineral anode, which greatly increases the storage potential of the battery. Solid-state batteries, theoretically, offer greater storage, faster charging, improved safety, and a reduced fire risk because they use nonflammable ceramic electrodes. This structure also reduces the need for cooling systems, allowing space for larger batteries in applications such as electric vehicles. The batteries are, however, hindered by costs, design safety, and production techniques. They have been proposed for use in electric vehicles—especially because of their fast charging, higher storage, and reduced fire risk—and stationary storage applications. Projections, however, place them 5 to 10 years away from market deployment.³³

Should solid-state batteries play a major role from 2030 onward, there may be implications for the demand of some minerals used in energy storage applications. Lithium demand would likely remain strong, as the mineral would still be required for the anode. Graphite demand could fall as the graphite anode is replaced by lithium.³⁴ The greatest uncertainty lies in the composition of the solid electrolyte; the wide variety of different options being proposed use a range of additional minerals, including tin, aluminum, silver, and boron (Vargi et al. 2016). Therefore, great uncertainty exists not only on the potential scale of future market deployment of solid-state batteries, but also on the implications of such deployment on demand for minerals.

Zinc-Air Batteries

Zinc-air batteries have become more prominent in the emerging storage sector because of their high specific energy density compared to other storage options, such as Li-ion batteries. Zinc-air batteries have emerged as the leading mineral-air battery type because they are safe, environmentally friendly, and potentially cheap and simple. The potential advantages of the technology can be seen in a comparison of the practical energy density of different battery technologies. Lithium-air batteries are possible and have even higher energy densities, but zinc is more attractive for a number of reasons, including safety, ease of recyclability, and greater global availability. Zinc-air batteries could potentially be used in both electric vehicles—either solely or, potentially more practically, as a range extender in combination with a Li-ion battery—and stationary storage (Sherman et al. 2018). For example, New York Urban Electric Power is working with a number of public sector partners to deploy a 1 MWh grid-connected zinc-air battery for demand response and peak shaving.

Should zinc-air batteries reach large-scale deployment in electric vehicles, or in stationary storage, they could dampen the demand for the minerals used in Li-ion batteries (for example, lithium, graphite, nickel, manganese, and cobalt). Demand could then shift to nickel, manganese, and zinc itself, but also potentially to lanthanum or silver as well. Large-scale deployment, however, is only likely to be post-2030, with the timing, the scale, and the composition of the batteries highly uncertain.

33 See, for example, Meeus (2018).

34 Lead-acid batteries offer 40 watt-hours (Wh)/kg; Li-ion batteries, 160 Wh/kg; and zinc-air batteries, approximately 350 Wh/kg (Caramia and Boggini 2014).

Floating Offshore Wind

Offshore wind has experienced rapid growth in recent years, especially in the North Sea and China. The vast majority of projects are installed on fixed foundations (usually monopiles) in water less than 60 meters deep. For deeper waters (up to 1,000 meters), floating foundations may be used. Although the floating wind technology is still at a nascent stage, it offers great future potential to rapidly increase the scale and the geographic scope of offshore wind. At the same time, it could also increase the mineral demand for steel because floating platforms tend to be much heavier than their fixed counterparts. An October 2019 report by ESMAP estimated that eight developing countries—Brazil, India, Morocco, the Philippines, South Africa, Sri Lanka, Turkey, and Vietnam—have the technical potential for more than 3,000 GW of offshore wind, two-thirds of which would require floating turbines (ESMAP 2019).

Floating turbines are just starting to enter commercialization. A 30 MW demonstration project, Hywind, has been operating

in the United Kingdom since 2017. And a number of pilot projects have begun elsewhere, with different models of floating foundations emerging, such as spar-buoy, spar-submersible, and tension-leg platform. Many of these models draw on existing applications of floating foundations within the offshore oil industry. Each model has different advantages and disadvantages and varying implications for mineral demand. Costs are also falling rapidly, declining 86 percent since 2009 (ESMAP 2019).

Beyond steel, demand for other minerals from floating offshore wind turbines could be similar or different from other wind options. The biggest difference in mineral demand relates to the length of transmission cabling required. Where floating offshore turbines will be deployed is not just a function of distance from the shore but also depth to the seabed. In areas where floating turbines are deployed a relatively short distance from the shore, then cabling will not necessarily be longer, and demand for copper may not be greater. Should floating offshore turbines be deployed at greater distances, however, then demand for copper could rise.³⁵

Figure 3.25 Floating Offshore Wind

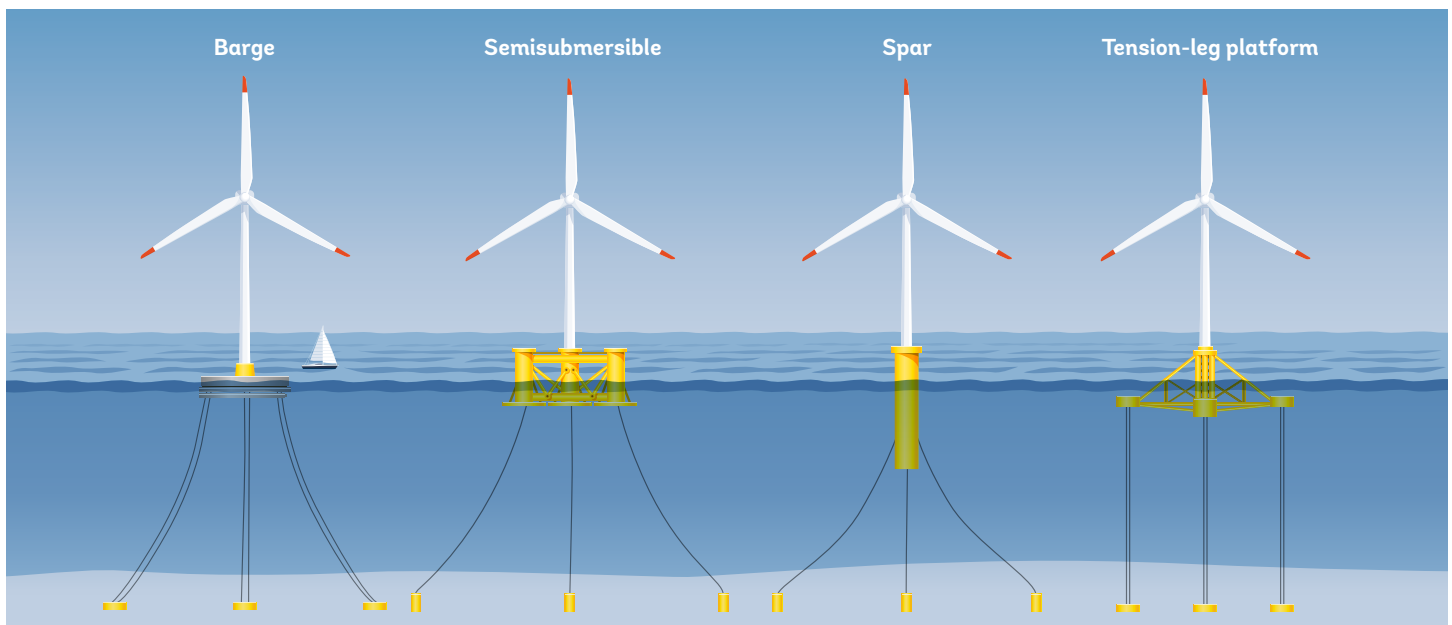


Illustration adapted from ESMAP (2019) and various other sources.

35 These factors are discussed in more depth in life-cycle assessments of floating turbines, such as in Tsai et al. (2016) and Chipindula et al. (2018).

Fuel Cells and Hydrogen

A key potential low-carbon technology not included in this analysis is the use of fuel cells and hydrogen in the clean energy transition, for providing space heating and powering various industrial processes as well as transportation. The use of fuel cells and hydrogen to provide a power source for low-carbon transportation has been explored for some time now because of its potential to lower carbon emissions (assuming green hydrogen is used) and the potential for hydrogen to be used as an energy carrier. Despite this promise, hydrogen deployment has been limited by high costs barriers in providing the fuel cells and the required hydrogen needed to power those cells, along with infrastructure constraints.

Figure 3.26 Hydrogen Fuel Cell

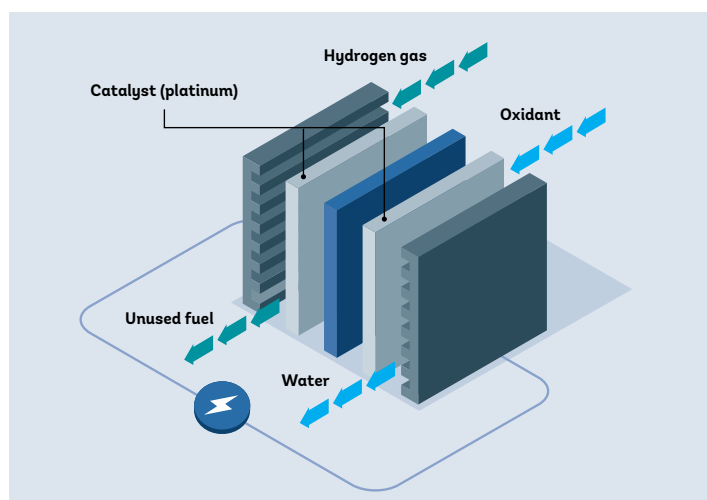


Illustration adapted from various sources (for example, Setra, <https://www.setra.com/blog/what-is-a-hydrogen-fuel-cell-and-how-does-it-work>).

Fuel cell transportation has specific features that give it a comparative advantage over batteries and other low-carbon technologies. Fuel cells offer a higher energy density per weight than batteries, allowing for longer distance travel and improved performance in vehicles, such as buses and heavy freight. The point-to-point nature of this form of transportation also helps overcome some of the infrastructure constraints associated with needing to electrify all electric vehicles with transmission

infrastructure. All these features combined explain why fuel cells have been emerging predominantly in buses, and medium to heavy freight transportation.

Fuel cells have various subtechnologies, including ones that use a catalyst prominently made out of platinum or ruthenium, but there are two main subtechnologies:

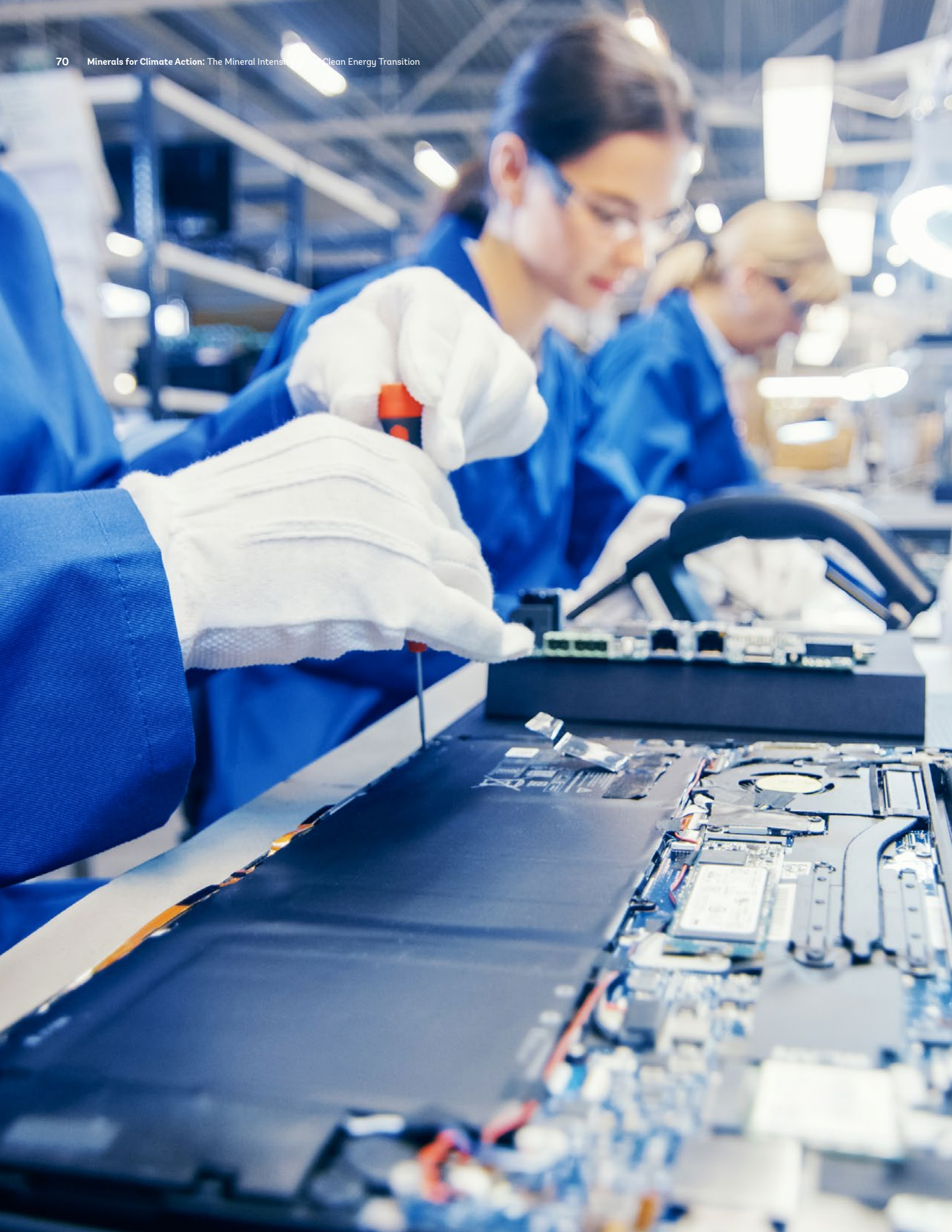
- **Proton exchange membrane fuel cells** are the most commonly used hydrogen subtechnology because of their low weight. These fuel cells operate at low temperatures and require a catalyst usually made out of platinum to split the hydrogen and oxygen molecules. This subtechnology also utilizes chromium steel, composed of 18 percent chromium and 8 percent nickel.³⁶
- **Solid oxide fuel cells** do not require a catalyst. These fuel cells operate at very high temperatures and are thus not suitable for transportation; they are predominantly used for stationary power generation. Although the solid oxide fuel cell does not need platinum as a catalyst, it uses other minerals such as yttrium, zirconium, lanthanum, and samarium in the anodes, cathodes, and electrolytes.

The platinum market as a whole showed a surplus in 2018, in part attributable to a decline in consumption of diesel cars, in which platinum is used in the catalytic converter (Johnson Matthey 2019). This trend is likely to continue, and whether it will be offset by sufficient demand from fuel cells depends on their speed and scale of deployment. Platinum may also play further roles in future energy systems, as it is important component not just of the fuel cells but also in the electrolysis production of hydrogen. Should hydrogen grow as an energy carrier for uses beyond fuel cells, such as space heating, platinum demand could rise strongly.

Recycling will also play an important role in platinum demand from hydrogen. Platinum group minerals are highly recyclable, with potential recovery rates of 95 percent possible (Hagelüken 2012). The scale at which platinum group minerals could be recycled from fuel cell applications, especially within transportation, remains to be seen, but it could have a large impact on overall demand for primary platinum.³⁷

³⁶ Estimates have highlighted potential future efficiency gains, reducing the share of steel to 0.02 kg/KW by 2025—down from 0.1 kg/KW in 2008 (Moss et al. 2013).

³⁷ The current use of six platinum group metals as catalysts in fine chemical production demonstrates recycling rates of 80–90 percent. Recycling rates in automotive applications are lower, but still around 50–60 percent. Recycling from electrical applications have proved trickier, with rates below 10 percent.



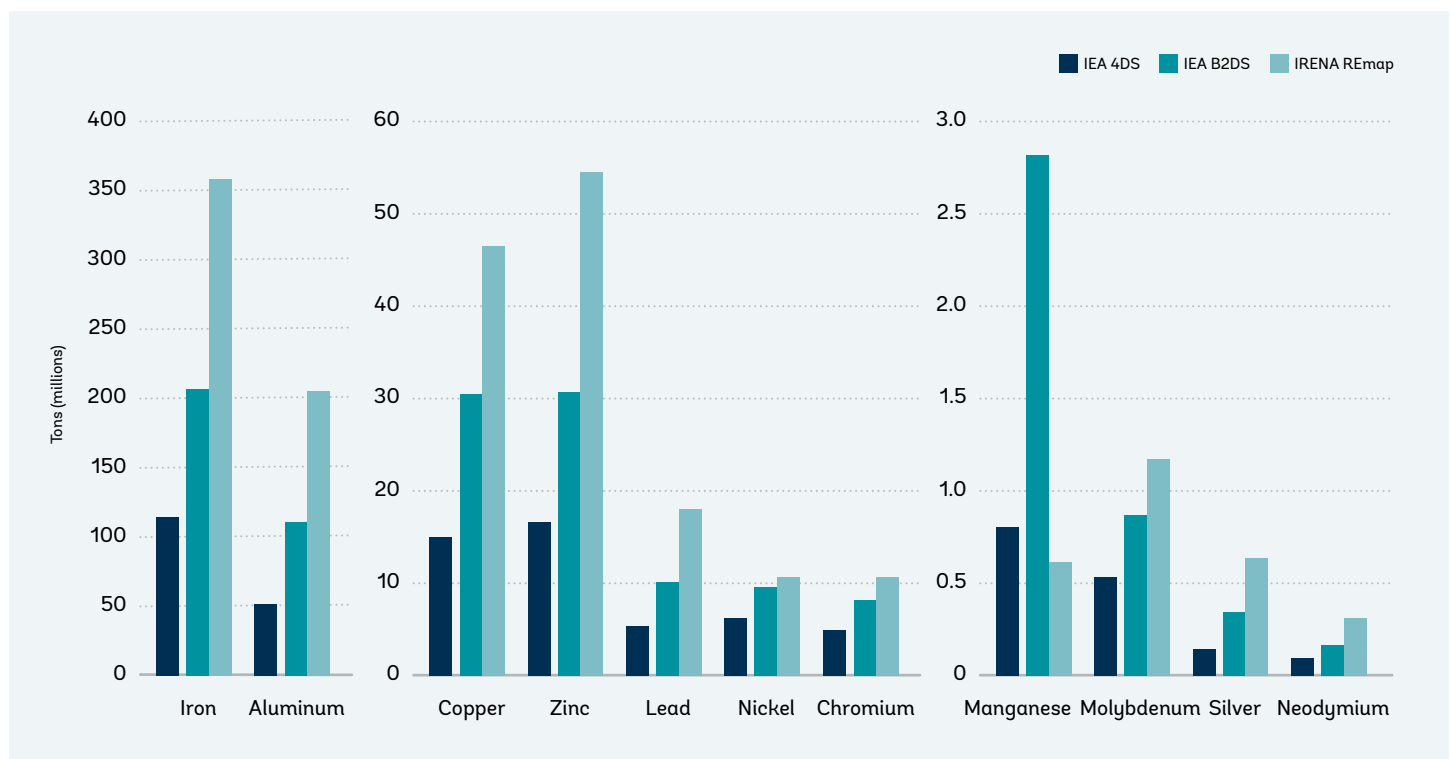
Overall Mineral Demand up to 2050

This chapter illustrates the overall demand across all 17 minerals from the six technology-based mitigation scenarios to show the impact that the clean energy transition will have on minerals in comparison with the base scenario. Figure 4.1 shows the total cumulative demand for minerals through 2050 from **electricity generation** technologies only under IRENA's REmap and the IEA's base scenario (4DS) and B2DS (again, energy storage figures are not provided because the data were unavailable for the base and IRENA scenarios).

The figures demonstrate an overall increase in demand for as many as 11 minerals used across a variety of energy technologies, with iron and aluminum showing the highest absolute increase, followed by copper and zinc. These trends indicate a relative increase in mineral demand with the relative ambitiousness of each technology-based mitigation scenario. This confirms one of the critical conclusions of previous findings: Not only is low-carbon energy transition materially intensive, but that intensity increases with the level of decarbonization.

Most minerals show the highest levels of demand under the IRENA scenario, when compared with their IEA counterparts, owing to the IRENA scenario's greater reliance on wind and solar PV technologies. The key exception is manganese, which shows much higher levels of demand under the 4DS and B2DS scenarios because of its use in CCS, which the IEA considers more likely than IRENA.

Figure 4.1 Cumulative Demand for Minerals for Energy Technologies (Without Storage) Through 2050 Only Under 4DS, B2DS, and REmap



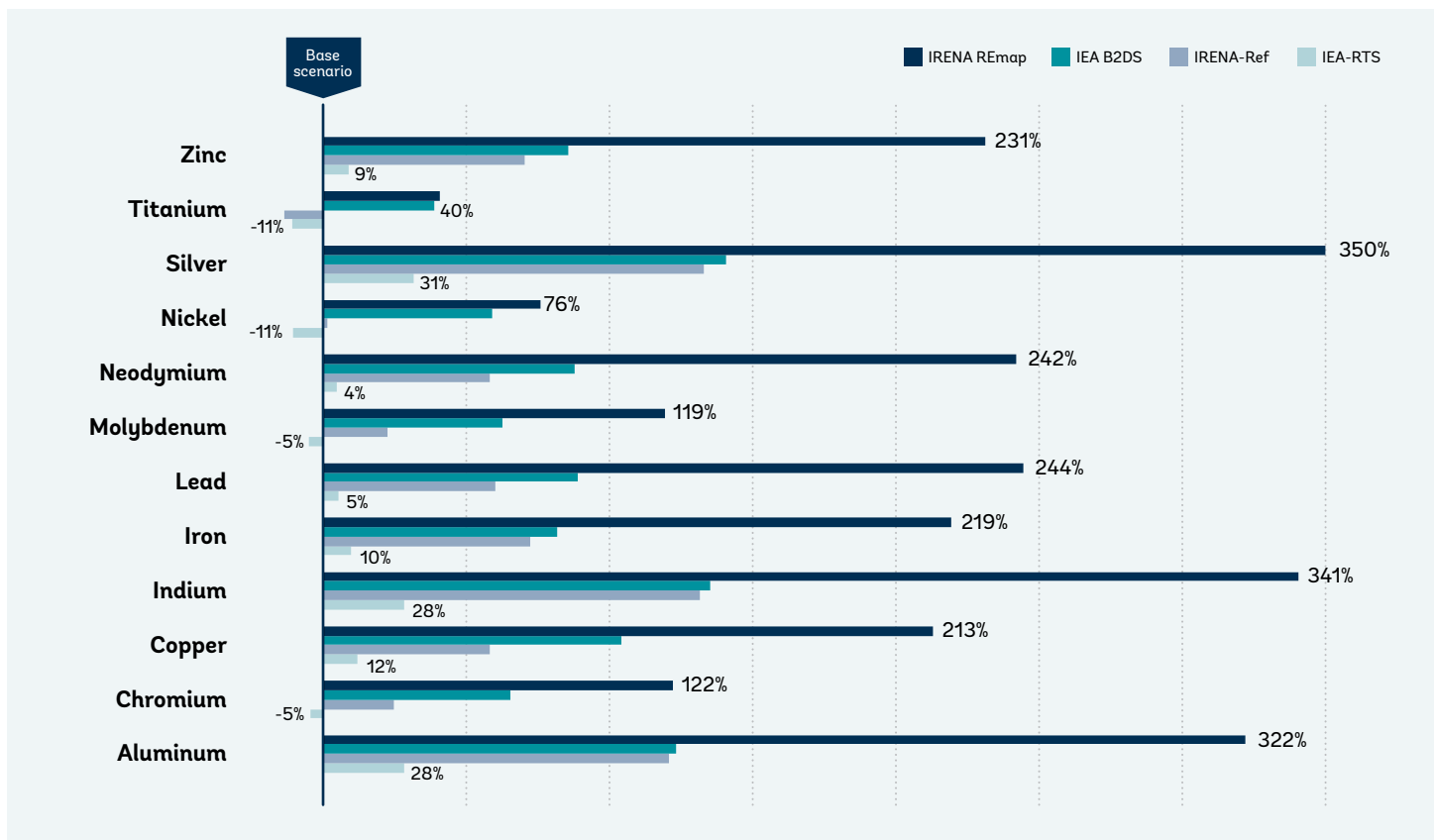
Note: Base scenario = 4-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, REmap = renewable energy roadmap scenario.

Figure 4.2 provides another way of looking at the scenarios and implications for minerals demand: the percentage of expected change from the base scenario in supplying electricity generation technologies only. In the REmap scenario, demand for aluminum, indium, and silver are expected to increase by more than 300 percent by 2050 from the base scenario, while the demand for copper, iron, lead, neodymium, and zinc is expected to increase by more than 200 percent. In comparison, in the most ambitious scenario under the IEA (B2DS), the demand for more than five minerals is expected to double by 2050, from the base scenario.

Annual Demand

The results presented to date have highlighted the cumulative scale of minerals needed to meet the challenge of the low-carbon transition. However, it is important to note the annual pathway that is needed to meet this cumulative scale. It is not simply a one-off investment in a stock of minerals that are needed for the low-carbon transition. Instead, it is a steadily increasing annual requirement that is needed to meet a higher future projected demand for electricity. This evolution can be seen in figure ES.1, which highlights that annual rates of demand are increasing up to 2050. The rate of increase tails off slowly to 2050, but it still reveals a picture whereby annual demand in 2050 is much greater than that in 2020.

Figure 4.2 Relative Change in Demand for Minerals from Energy Technologies (Without Storage) Through 2050 Under RTS, Ref, B2DS, and REmap, Compared to Base Scenario

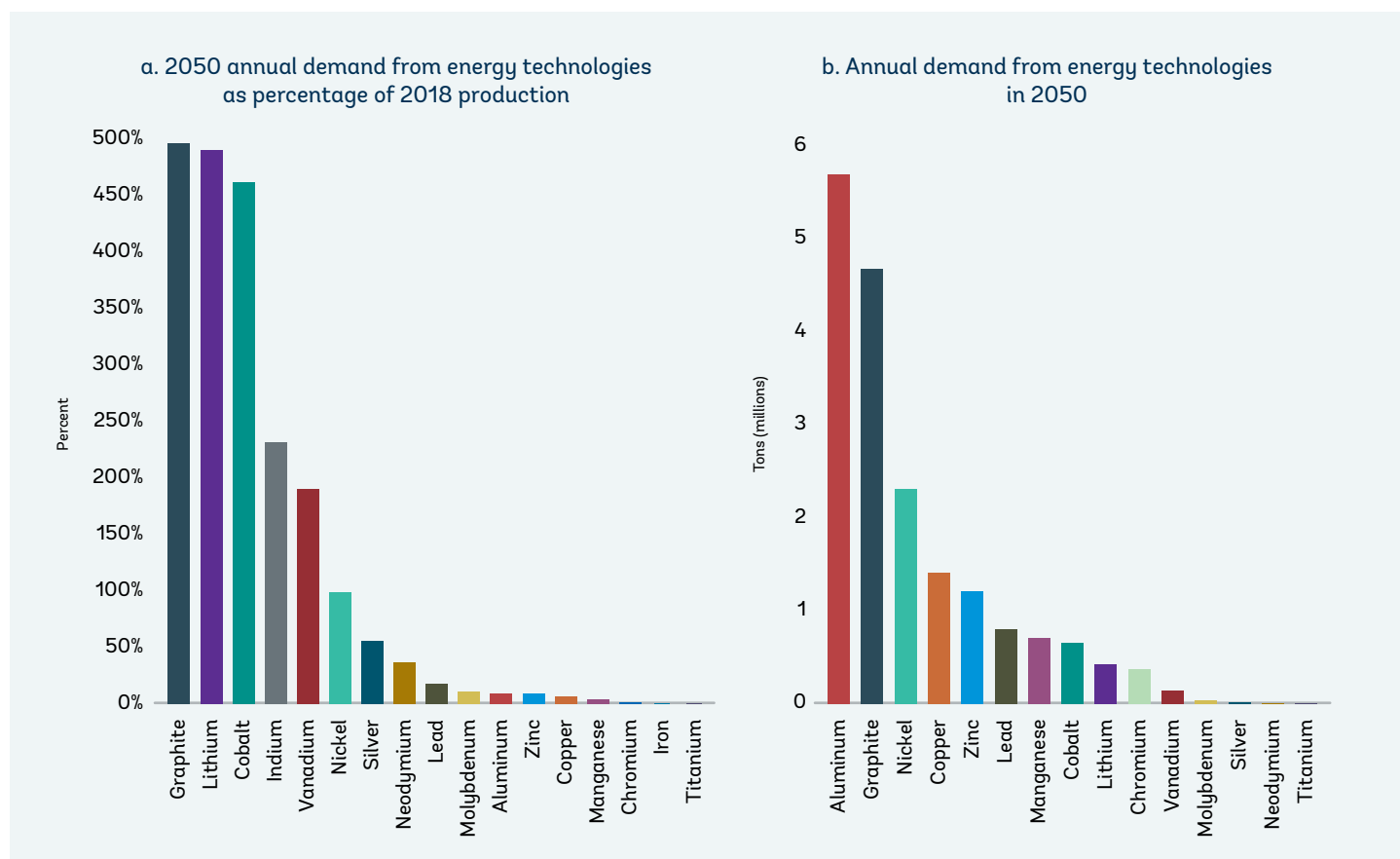


Note: Base scenario = 4-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap = renewable energy roadmap scenario; RTS = reference technology scenario.

As all 17 minerals covered in the model are used for different applications outside the energy sector, this analysis compares the mineral demand coming from the 10 energy technologies under the 2DS and compares it with 2018 production figures. Figure 4.3, panel a, provides the percentage increase in mineral demand based on 2018 production figures, with the majority of demand coming from battery minerals, namely graphite, lithium, and cobalt. These minerals will be needed at scales significantly beyond current production levels, by up to as much as five times. Figure 4.3, panel b, illustrates the annual absolute increase in mineral production up to 2050, with production figures being the highest for aluminum, graphite, and nickel.

Graphite demand increases in both absolute and percentage terms since graphite is needed to build the anodes found in the most commonly deployed automotive, grid, and decentralized batteries. About 4.5 million tons of graphite is needed to be produced annually by 2050, or a cumulative of 68 million tons, while graphite demand increases by nearly 500 percent from 2018 production figures, demonstrating the critical role graphite plays in the clean energy transition, being used in Li-ion batteries, the most widely projected deployed battery technology.

Figure 4.3 Projected Annual Mineral Demand Under 2DS Only from Energy Technologies in 2050, Compared to 2018 Production Levels



Note: 2DS = 2-degree scenario.

Market Dynamics and Mineral Demand

The demand estimates produced in this analysis are the demand that would occur assuming that supply can fully adjust to meet that demand and that no substitution or efficiency improvements occur. Higher levels of demand would lead to higher prices, causing increases in supply but also substitution of other minerals, where technically possible, as well as innovation in efficiency improvements. The outlook presented in this section should be seen as the first pillar in understanding the full impact that a low-carbon transition will have on the markets for minerals. These results should be combined with further research on the supply aspects as well as the substitution and technical efficiency possibilities.

Even where future demand from energy technologies does not exceed current production, the share of demand from energy technology in total demand for virtually all these minerals is likely to rise, which carries implications for their relative accessibility over the next few decades.³⁸ For example, the percent share of aluminum appears to be relatively small, but the mineral's absolute numbers are much greater than lithium (the highest percentage increase)—at about 5.6 million tons in 2050, compared with 0.4 million tons for lithium that same year. Absolute demand may be so high that it could bring pressure on the aluminum industry's capacity to meet the expected demand in servicing the low-carbon future.

Cross-Cutting Minerals

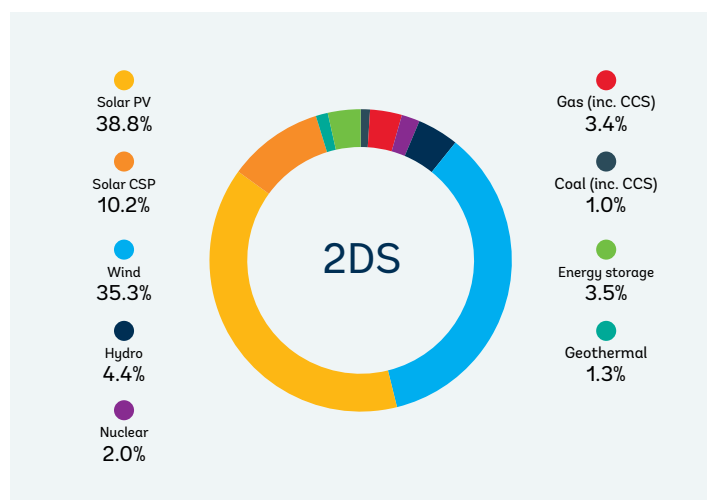
Cross-cutting minerals refer to minerals that are used across a wide variety of energy generation and storage technologies. Earlier in this report, the demand for minerals such as lithium, graphite, silver, and aluminum was identified as being concentrated in one or two specific energy technologies up to 2050. This section also focuses on the minerals that are used throughout a broader spectrum of energy technologies, as this has implications for the overall demand of minerals regardless of which technology or subtechnology ends up being deployed the most under each technology-based mitigation scenario.

Copper, chromium, and molybdenum are examples of minerals that are used across eight or more technologies, with copper being used in all energy generation and storage technologies covered in the model. It is important to pay attention to cross-cutting minerals since these are a subset of minerals that are not dependent on the deployment of one specific energy technology for the demand to be affected. In other words, changes in technology or subtechnology deployment will most likely have a minimal impact on the overall demand of cross-cutting minerals.



38 As market dynamics were not considered in this analysis, further information on how market dynamics could potentially impact this report's mineral projections, which are based on the IEA and IRENA scenarios, can be found in annex B.

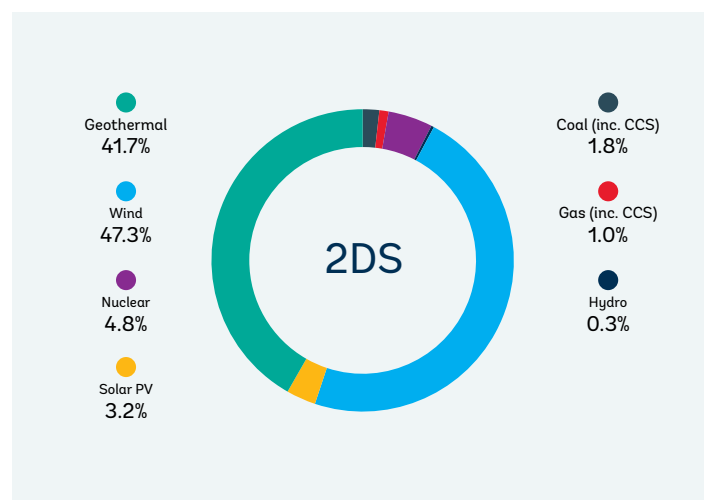
Figure 4.4 Total Copper Demand by Energy Technology Through 2050 Under 2DS



Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, PV = photovoltaic.

Figure 4.4 shows the total cumulative demand for copper from electricity generation and energy storage technologies through 2050. The greatest share of demand comes from solar PV (39 percent) and wind (35 percent), particularly for offshore wind. Together, solar PV and wind represent 74 percent of total copper demand in a 2DS. This is likely a significant underestimation of the demand for copper in servicing the clean energy future since it does not include infrastructure requirements, such as transmission systems. The International Copper Association estimates that more than 60 percent of refined copper is used for supporting electricity and heating systems.³⁹

Figure 4.5 Total Molybdenum Demand by Energy Technology Through 2050 Under 2DS

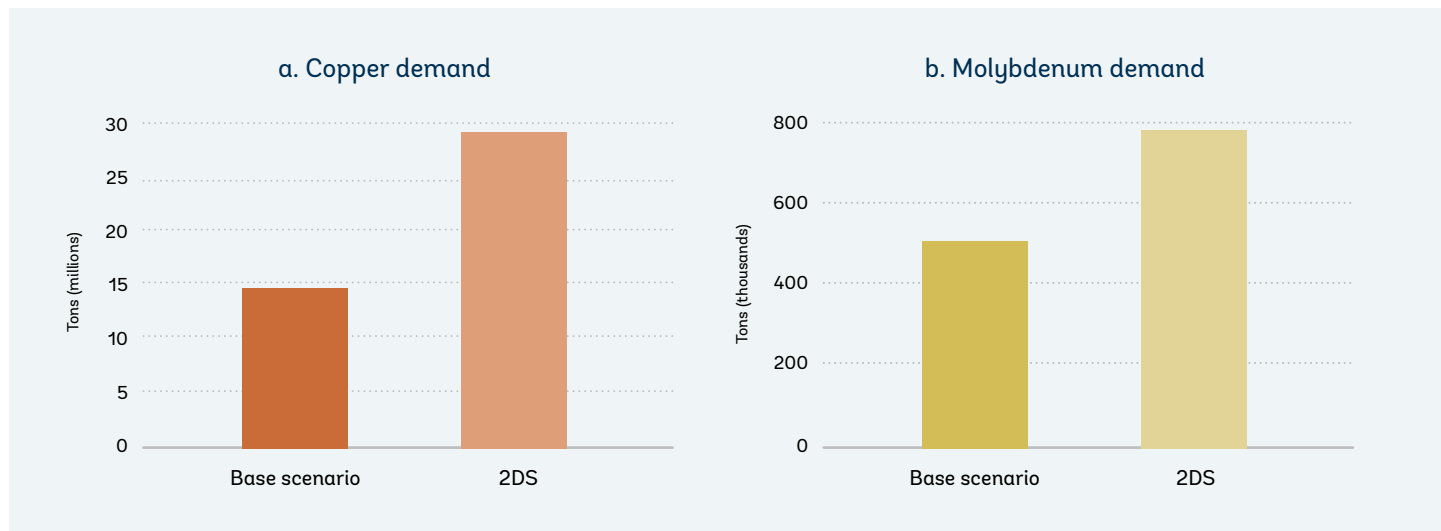


Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, PV = photovoltaic.

Molybdenum is another critical mineral required for a range of low-carbon technologies, especially wind and geothermal. The greatest share of demand for molybdenum from electricity generation and energy storage technologies comes from wind (47.3 percent) and geothermal (41.7 percent), with all the other generation and energy storage technologies together accounting for only a small share (11 percent) (figure 4.5). This is despite the fact that molybdenum typically only makes up 0.15 percent of the mineral composition of a wind turbine. Together, wind and geothermal account for 89 percent of molybdenum demand under a 2DS. There is a lack of clear data allowing for determination of which subtechnology of wind accounts for the greatest demand.

39 For further information, see "Energy and Renewables," Applications, Copper Development Association: <https://copperalliance.org.uk/about-copper/applications/energy-and-renewables/>.

Figure 4.6 Cumulative Copper and Molybdenum Demand Through 2050 (2DS, Base Scenario)



Note: 2DS = 2-degree scenario.

While copper and molybdenum are both cross-cutting minerals, there is a significant difference between the two: Copper is a base metal that is used across a wide variety of industries,⁴⁰ while molybdenum is considered to be a niche mineral that is usually recovered as a byproduct or co-product of copper (figure 4.6).⁴¹ The difference can also be seen in production figures. In 2018, 21 million tons of copper was produced, whereas only 0.3 million tons of molybdenum was extracted—a 20.7-million-ton difference between the two minerals. In other words, 7,000 percent more copper was produced in 2018 relative to molybdenum, even though both minerals are used across a wide variety of energy technologies and will both contribute to a low-carbon future pathway given their importance in solar PV, wind, and geothermal technologies.

As mentioned earlier, the copper figures are most likely vastly underestimated, with copper's demand likely to increase significantly from new transmission infrastructure needed for new transportation infrastructure and energy systems, as well as for a growing global population.

⁴⁰ In this case, copper is referred to as a base metal since it is commonly used and inexpensive. It is not considered a precious metal such as silver or gold. However, for consistency, all minerals and metals in this report are referred to as minerals.

⁴¹ "Molybdenum," Minerals Database, Minerals Education Coalition, accessed 2019, <https://mineralseducationcoalition.org/minerals-database/molybdenum/>.

Demand Risk Matrix

A key element of this analysis is to understand how overall mineral demand could be affected by the technology concentration of each mineral or the increase in growth from energy technologies compared to current production figures. The relative importance of mineral demand is even more important for minerals that are *cross-cutting*, meaning they do not depend on the deployment of one or two specific technologies to be relevant.

A **demand risk matrix** has been developed under a 2DS to provide an overview of these trends based on technology concentration levels per each mineral relative to 2018 production figures (in absolute and percentage figures). Two indexes, which make up the matrix, have been created, to ease comparisons between minerals:

- **Weighted coverage-concentration index** (technology concentration index): This index captures how cross-cutting or concentrated in a few technologies the minerals are in the model. A value for 1 is given for the most cross-cutting mineral, namely copper, with the scores for all other minerals relative to copper. The index is calculated on an equal weighting of two items: (1) the number of technologies that require one mineral, and (2) the share of demand for minerals that comes from a single technology. The assumptions are described in further detail in annex B.
- **2018-2050 production-demand index** (demand index): This index captures the scale to which production must scale up to meet demand from energy technologies. The index consists of two parts:
 - *Relative demand* is captured by comparing 2050 demand from energy technologies to 2018 total production of the mineral. An index between 0 and 1 is then computed, with the mineral with highest relative demand, graphite, given a score of 1 and each other mineral given a score relative to graphite.
 - *Absolute demand* is captured through the absolute level of demand in 2050 from energy technologies for each mineral. The mineral with the highest level (aluminum) is given a score of 1 and every other mineral is given a score between 0 and 1 relative to aluminum.

The two parts of the index are given an equal weight to compute an overall production-demand index. The two indexes are then plotted together to give four categories, or quadrants. A breakdown of the quadrants and the possible interpretation on mineral demand from **energy technologies** is below, as seen in figure 4.7 and annex B.



Figure 4.7 Demand Risk Matrix Under 2DS



1 Quadrant 1 Medium-Impact Minerals:

Minerals that fall in quadrant 1 are the least impacted minerals from demand. These minerals feature in only a small range of energy technologies and the anticipated increases in demand are a small percentage of 2018 production levels. It is important to stress that this matrix only compares minerals demand from energy technologies only and does not consider supply risks, nor the demand from other industries outside the energy sector.

- This is not to say that these minerals are not important to the deployment of particular subtechnologies. Neodymium is a rare earth that is critical for the deployment of offshore wind.

2 Quadrant 2 High-Impact Minerals:

Minerals that fall in quadrant 2 are important because, although they only feature in a small number of technologies, their level of future demand is much greater than 2018 production levels. Changes to the technologies or subtechnologies used may have big implications for overall levels of demand. They are predominantly (but not exclusively) minerals used in energy storage technologies.

- Lithium, which is only used in energy storage under this analysis, is projected to need 488 percent of 2018 production levels to meet its 2050 demand under a 2DS.⁴²

3 Quadrant 3 High-Impact, Cross-Cutting Minerals:

Minerals that fall in quadrant 3 are critical because the demand from 2018 production levels increases significantly, yet their use is also widespread across a variety of technologies.

- Aluminum is used widely for both energy generation and storage technologies. The demand for aluminum is therefore expected to be critical regardless of which technology-based mitigation scenario is achieved. While aluminum's overall level of demand from energy technologies is less than 10 percent of its 2018 production levels, it has the highest production levels compared to all other 16 minerals, with cumulative production reaching 102 million tons by 2050 to primarily supply solar PV and then other energy technologies.

4 Quadrant 4 Cross-Cutting Minerals:

The minerals in quadrant 4 are important because while their overall demand from energy technologies relative to production (in percentage) is not as dramatic as that for minerals in quadrants 2 or 3, they are used across a wide variety of technologies and are not dependent on one specific technology. Therefore, the demand for these minerals will exist no matter which technologies or subtechnologies are deployed.

- Copper, for example, represented as an index of 1, is used across all 10 energy technologies covered in the model and therefore is the mineral for which the demand will be the least impacted by significant changes in the technology-based mitigation scenarios.

42 While this report does not address supply, about 71 percent of all rare earths, including neodymium, are produced in China.



Mineral Recycling, Reuse

Recycling could play an increased role in meeting demand for minerals to supply a low-carbon transition. As of today, the most recycled minerals are iron and steel (AGI 2017). Minerals mapped under the demand risk matrix in the previous section could, in theory, shift into different quadrants, depending on whether some of these minerals are partially recycled once energy technologies reach end of life, reducing the amount of minerals that need to be extracted. The opportunities for mineral recycling are important to explore, particularly as mineral demand increases under the most ambitious climate pathways.

Primary minerals refer to minerals that are extracted and processed into a final mineral product before being used to manufacture products, including energy technologies, while secondary minerals refer to minerals that have been recycled from a variety of products. The model's estimated projections for the potential role of recycling do not consider the economics of mineral recycling, nor the technical limitations of recycling. The cost of recycling is a crucial factor in determining how much recycling takes place. If the primary mineral is available much

more cheaply than recycled material, then very little recycling will occur. Policy support and technological improvements will play a critical role in how the mineral recycling industry develops to bring down costs and encourage innovation to meet demand from low-carbon technologies.

Recycling

Only five minerals have been selected to analyze the potential impact of recycling on mineral demand, given the limitations of available data on mineral recycling, as well as to provide consistency with other sections. Aluminum is specifically highlighted because it is used across almost all energy generation technologies and storage and has significant demand implications relative to its 2018 production levels (quadrant 3 – high-impact, cross-cutting minerals). Lithium and cobalt are relevant because the demand for these minerals increase by 488 percent and 460 percent, respectively, relative to 2018 production (quadrant 2 – high-impact minerals). Nickel and copper are showcased because both minerals are cross-cutting minerals (quadrant 4 – cross-cutting minerals) and their increase in demand in either absolute or relative numbers is significant, relative to niche minerals, under a 2DS.

As discussed in the Recycling, Reuse section of chapter 1, two recycling rates are important for the analysis:

- **End of life (EOL):** The percentage of material that is recovered at the end of a product's life and recycled into new material
- **Recycled content (RC):** The percentage of a new product that is made using secondary (recycled) material

The implications of recycling under a 2DS can be seen in figures 4.8–4.10. In these charts, the end-use demand for the relevant minerals is illustrated, chiefly the amount of minerals that is actually required to go into a wind turbine or solar panels. The figures show the amount of primary mineral that is required if current RC rates remain the same until 2050,⁴³ along with the situation if EOL rates increase to 100 percent by 2050 (lithium rates are estimated differently, as explained in the Recycling, Reuse section in chapter 1).

Figure 4.8 presents the impacts for aluminum and copper recycling. Approximately 102.8 million tons of aluminum is required to meet demand from the energy technologies under a 2DS. Should RC rates remain constant at today's levels of 35 percent, then 42.3 million tons would be met by secondary or recycled production, with the remaining 60.5 million tons coming from primary production, from bauxite extraction.

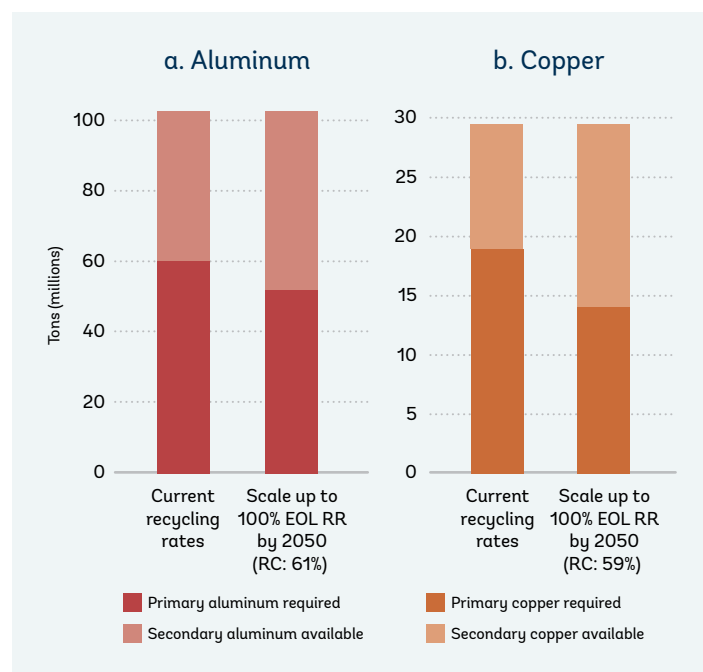
If EOL rates increase to 100 percent by 2050—implying that all aluminum available is recycled—then RC rates rise to 61 percent. The final amount of aluminum needed to supply technologies doesn't change, but the amount met by secondary production rises to 57 million tons, with 24 percent less primary production required.⁴⁴ The demand for primary production does not disappear completely even with a 100 percent EOL rate, as the production of secondary aluminum is limited by the supply of scrap available.

Should structural changes to the nature of the economy take place, which means that the ratio of scrap availability to overall mineral demand changes, then the potential to increase RC rates from 100 percent EOL rates exist, reducing primary mineral

demand further. Examples of such changes that could increase scrap availability include changes to the design of products to enable better mineral recovery, and large falls in demand for the mineral from other sectors, outside the energy industry.

For copper specifically, current RC rates are assumed to be 28.5 percent (figure 4.8) and an increase to 100 percent EOL by 2050 increases RC rates to 59 percent, reducing the overall cumulative demand for primary copper from energy technologies by 26 percent. While increasing EOL rates to 100 percent has a similar impact on both minerals, primary demand for aluminum still outweighs primary copper demand by more than three times, at over 46 million tons for aluminum and over 14 million tons for copper through 2050. Again, the copper figures may be underestimated given that transmission figures are not included in this analysis.

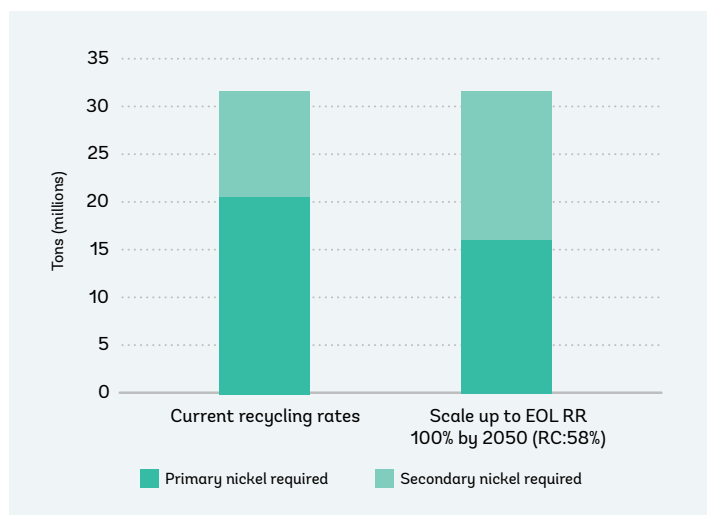
Figure 4.8 Impact of Recycling on Cumulative Demand for Aluminum and Copper Under 2DS Through 2050



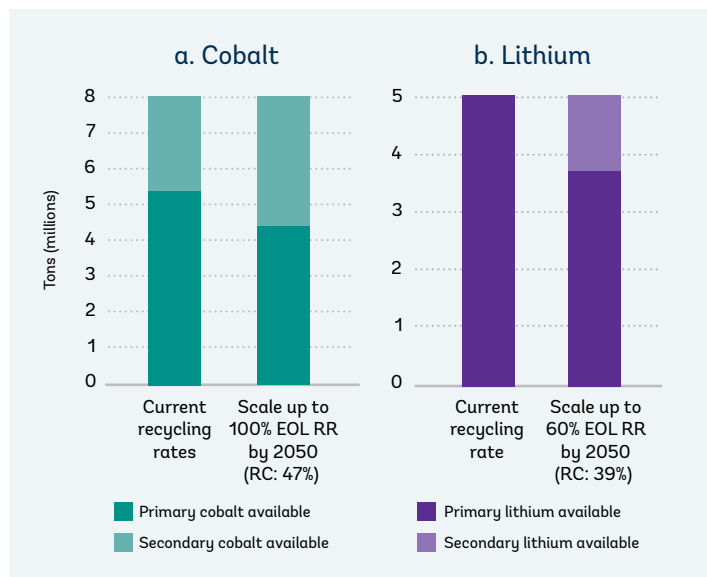
Note: 2DS = 2-degree scenario.

⁴³ Data on global recycling rates for different minerals are patchy and a review of the literature shows a wide range of estimates.

⁴⁴ The change in primary demand is a function of two factors: the time path of end-use aluminum demand and the time path of recycling rates. Although the results seem trite, they are in fact contingent on how fast recycling rates increase and when the majority of end-use demand occurs. Given that the larger share of end-use demand occurs closer to 2050, should recycling rates scale up more quickly than the linear trend assumed here, then overall primary demand would decrease. Similarly, a slower transition to higher recycling rates will require higher levels of primary aluminum to be supplied.

Figure 4.9 Impact of Recycling on Cumulative Demand for Nickel Under 2DS Through 2050

Note: 2DS = 2-degree scenario, EOL = end of life, RC = recycled content, RR = recycling rate.

Figure 4.10 Impact of Recycling on Cumulative Demand for Cobalt and Lithium Under 2DS Through 2050

Note: 2DS = 2-degree scenario.

Nickel is a crucial metal for the move to a green energy future as it is needed in energy storage, for use in Li-ion batteries, and is also used in a wide range of generation technologies, often being used as a component of the steel required. Rates on the RC of nickel, or scrap nickel, vary, but they center on 35 percent. Should RC rates stay at this level, then primary demand for nickel through 2050 would stand at just over 20 million tons (figure 4.9). Following similar assumptions for copper and aluminum, as well as assuming that EOL rates increase to 100 percent by 2050, then RC rates increase to 58 percent and primary demand for nickel would fall by 23 percent compared to today's RC rates.

The battery minerals cobalt and lithium have very different recycling trajectories. Cobalt currently has an RC of 32 percent, with primary cobalt accounting for 5.4 million tons of demand up to 2050 (figure 4.10). An increase to 100 percent EOL by 2050 increases RC to 47 percent, reducing the overall cumulative demand for primary cobalt from energy technologies by 15 percent, following a similar trajectory as aluminum and copper with regard to decreased demand from primary production. However, the technical challenges of extracting cobalt for use in batteries may make these assumptions less robust than for aluminum and copper, which are easier to recycle.

Lithium, on the other hand, is very different because current lithium recycling rates (both EOL and RC) are close to zero according to a variety of sources.⁴⁵ However, some sources have highlighted the high future potential for recycling to grow in this area.⁴⁶ For example, they project medium and high recycling scenarios of EOL rates of 40 percent and 80 percent, respectively. In this analysis, a midpoint has been selected, with EOL rising to 60 percent by 2050 implying an estimated 39 percent RC rate.⁴⁷ The impact of such recycling is to reduce cumulative demand for lithium by 26 percent.

⁴⁵ It should be noted that there is a large amount of research and activity investigating the potential to recycle lithium from Li-ion batteries. However, to date little available public data show this is yet happening commercially at any scale. In fact, where there are recent studies, they have highlighted the low cost of lithium and the relatively high cost of recycling as a key barrier to scaling up lithium recycling. See, for example, Ziemann et al. (2018) and Church and Wuennenberg (2019).
⁴⁶ This is drawn from the analysis in Ziemann et al. (2018).
⁴⁷

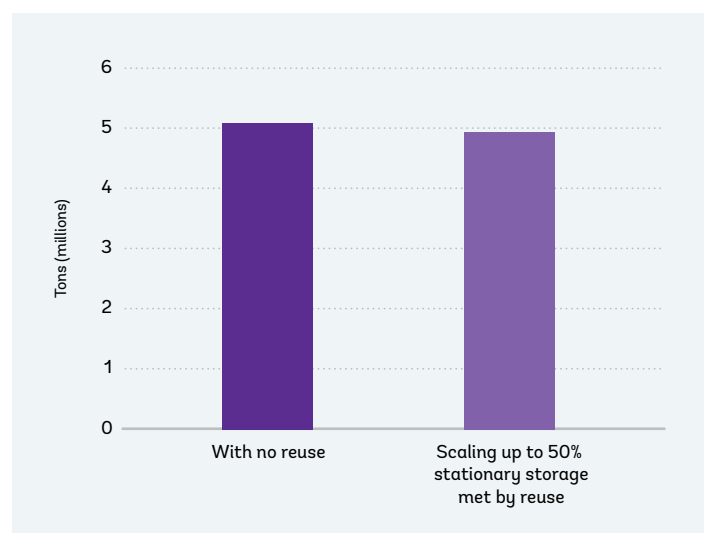
Reuse

Reuse differs from recycling in that recycling involves the breaking down of the material and re-forming it for an alternative use. The term “reuse” in this context is used to mean the reusing of the original component, such as a battery, for another use beyond what was original intended. For example, Li-ion batteries that are used in electric vehicles could potentially be used in other types of energy storage applications.⁴⁸ While reuse of batteries could provide opportunities for stationary storage applications, this potential solution to reducing overall mineral demand should be carefully approached from waste and safety perspectives.

This could be the case if, once clean energy technologies reach end of life and can be to some degree repurposed, they do not end up being used as an excuse to dispose these technologies under the guise of a “repurposed” product; this is especially true for developing countries or underserved communities that may end up becoming recipients of these technologies once they reach end of life, resulting in an increased amount of waste.

In this context, reuse has also been termed as repurposing. Conservative assumptions have been applied to the rate of reused Li-ion batteries with the assumption that reused batteries meet 50 percent of the demand for Li-ion batteries in stationary storage by 2050. This reduces the total cumulative demand for lithium by 3 percent (figure 4.11). Should there be a reuse of Li-ion batteries in transport, either between cars or between trucks and buses and cars—through remanufacturing processes—then this could reduce primary demand for lithium substantially.⁴⁹ There is, however, little current evidence of these processes occurring at a commercial level, despite much research and interest in the area.

Figure 4.11 Impact of Reuse on Cumulative Demand for Lithium Under 2DS Through 2050



Note: 2DS = 2-degree scenario

Otherwise, with lithium demand only coming from energy storage under the Ref, 2DS, and B2DS, particularly in the automotive sector, the only way to significantly reduce lithium’s demand would be by finding ways to reuse Li-ion batteries in the electric vehicle sector, as stationary storage applications only account for a small share of energy storage deployments up to 2050. However, this trend is unlikely as electric vehicles require batteries with the capacity to undertake a large amount of cycling (charging and discharging) and to hold a charge and recharge quickly—features associated with new batteries.

⁴⁸ See the discussion in Ahmadi et al. (2017).

⁴⁹ See Strandridge and Hasan (2015) for further details.

Opportunities and Challenges

While the opportunities for recycling minerals could help address demand risks associated with the low-carbon transition, some recyclable minerals may not be suitable for the production of certain energy technologies, as some technologies may require a very high grade of a specific mineral for their application (for example, steel). Moreover, the energy intensiveness of some recycling processes could pose the same issues that have been identified in steel and aluminum production.

Recycling rates vary massively between minerals because of cost and technical issues. Rates for recycling of steel are especially high, with over an estimated 85 percent of it being recycled EOL. Even within minerals, rates vary across products. For example, 95 percent of steel from automobiles is recycled, compared with 70 percent from steel packaging. Recycling rates, however, can be deceptive. Despite 85 percent of steel being recycled, about one-third of steel comes from primary production, as the majority of steel is locked up in long-term, durable structures, limiting the amount of steel that is available for recycling, especially when demand is increasing.

Recycling brings environmental benefits in a number of areas, especially in GHG emissions, with the carbon footprint from the secondary production of minerals, such as aluminum, being a fraction that of primary production. For other minerals, however, recycling comes with additional environmental challenges, such as energy use and water footprints, that need to be weighed against the environmental benefits.

Overall, recycling could present interesting opportunities for countries with advanced recycling technology with reliable low-carbon, electricity production to potentially reduce the pressure of increasing demand for certain minerals, but policy coherence among countries will be needed so that future international recycling practices take into account the environmental, safety, and high costs of mineral recycling.



Refurbishment of structures and equipment to prolong their life spans has not been covered by this analysis, but it is another crucial feature phenomenon that could affect the demand for primary minerals. Recycling of many components of energy technologies may prove to be technically difficult or costly. Refurbishing parts of energy technologies can prolong life spans dramatically, reducing the mineral footprint. For example, old wind turbines at the end of their life span can be refurbished by retaining the tower but replacing some or all of the other components, increasing the capacity of the turbine or retrofitting it with more efficient components such as gearboxes or generators. Estimating the scale of such effects is difficult, but increasing refurbishment would reduce the overall scale of mineral demand, and may impact minerals used in frames and structures more than those minerals used in specific components such as motors or magnets.





Global Warming Potential of Energy Technologies, Minerals

GWP of Energy Technologies

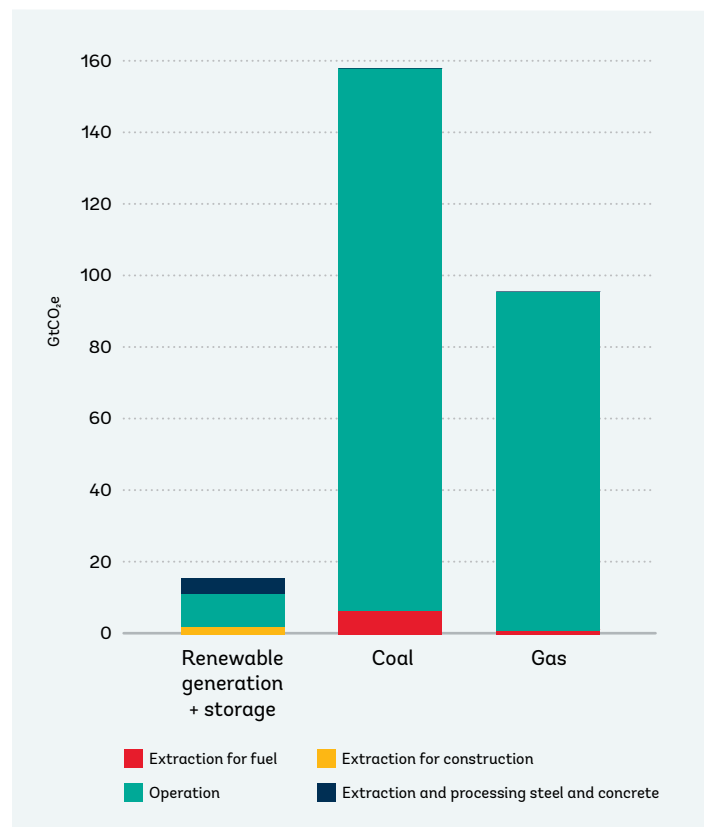
The importance in calculating the GWP of energy technologies is to compare the carbon footprint associated with extracting and recycling more minerals to supply a low-carbon future. The aim is to understand the carbon footprint implications of the clean energy transition, particularly as the previous sections of the analysis have demonstrated that low-carbon technologies, including generation and storage, are extremely mineral intensive. With the Paris Agreement calling for increasing global temperature to not exceed a 2°C scenario, the GWP analysis provides the approximate calculation of the carbon footprint of clean energy technologies compared with fossil fuel ones under the IEA 2DS, mirroring the approach taken in the demand risk matrix to meet mineral demand.

As seen in figure 5.1, there are emissions associated with minerals required for a low-carbon future up to 2050, but clean energy technologies provide a substantially smaller overall GHG footprint than either coal or gas—with renewable energy and storage contributing approximately 16 GtCO₂e through 2050 in the 2DS, compared with almost 160 GtCO₂e from coal and approximately 96 GtCO₂e from gas. In the base scenario, where substantially more electricity is generated from these latter sources, the emissions from coal and gas are much greater, at more than 470 GtCO₂e and 130 GtCO₂e, respectively.

The primary difference between clean and conventional energy has to do with the operation of each of those technologies. While the GHG footprint in the extraction and processing of minerals required for the construction of renewable energy technologies is likely to be higher than that for fossil fuel generation, once the emissions that result from extracting coal and gas, and crucially in burning it to generate electricity, are taken into account, fossil fuel generation has a significantly greater footprint. In other words, the relative GWP of “cradle to gate” of renewable energy technologies compared with the GWP of fossil fuel combustion under a 2DS are considerably smaller.

Although steel and cement were not included in the analysis, they have been included in figure 5.1 because of their high contribution to emissions from the construction of both renewable and fossil fuel energy technologies. Steel is currently estimated to account for 7–9 percent of total GHG emissions. Cement accounts for approximately 8 percent (Timperley 2018). Data on the steel and cement needed to build the technologies, and the carbon footprint for steel and cement, were drawn from the literature, with high, median, and low values used to capture the range of estimates in a similar manner as other aspects of the model.

Figure 5.1 Cumulative GWP Through 2050 from “Cradle to Gate” Mineral Extraction and Processing, Operations of Renewable Electricity Generation, and Energy Storage Technologies Compared to Fossil Fuel Technologies Under 2DS



Note: Extraction for construction includes the cradle-to-gate emissions from the 17 minerals included in the analysis. Extraction and processing steel and concrete includes cradle-to-gate emissions for steel and concrete and are included because of the scale of emissions from these two minerals compared to the 17 minerals included in the analysis. GtCO₂ = gigatons of carbon dioxide, GWP = global warming potential.

GHG emissions from just the operation of coal and gas facilities alone are comparable to 2017 GHG emissions⁵⁰ of more than 60 years of European Union emissions, at an annual basis. This finding is consistent with the wider literature that have examined the life-cycle footprint of the different energy technologies. It also falls in line with the IEA's estimation of coal combustion contributing to the 0.3°C of the 1°C increase in global average temperature above preindustrial levels, representing about 30 percent of total GHG emissions globally.⁵¹

The National Renewable Energy Laboratory (NREL) conducted an exercise attempting to harmonize the various life-cycle estimates of different energy technologies. The NREL's scope differs from the GWP estimated above, as this analysis focuses solely on the GWP relating to the mineral extraction and processing, as well as the operation of energy technologies, without considering the end of life of these technologies, but the findings from their work are similar.⁵²

The takeaway from this GWP analysis is that, while a more ambitious climate scenario leads to a higher demand for number of minerals, the GWP of clean energy technologies, using a cradle-to-gate approach, is significantly smaller than coal and gas; therefore, the clean energy transition is the preferred means to achieve a 2°C or below pathway that is in line with the Paris Agreement and the Sustainable Development Goals.

GWP of Minerals

Given the material intensity of low-carbon technologies, as well as the implications associated with their disposal, particularly for battery technologies, current and future renewable energy policy should also take into account the emissions associated with these technologies' increased deployment. It should also be noted that the GWP analysis does not consider the environmental and social risks (for example, water, ecosystems, and so on) associated with increased extractive and processing activities, particularly **cross-cutting minerals** (quadrant 4) and **high-impact, cross-cutting minerals** (quadrant 3).

The GWP can also be used to look at the carbon intensiveness for each mineral, relative to the 2DS, to understand which mineral has the lowest and highest carbon footprint. Figure 5.2 shows the balance between the emissions impact of these minerals and their demand importance in the transition to a low-carbon energy system, with circle size representing a mineral's cumulative emissions up to 2050.

Aluminum has the highest cumulative carbon footprint under a 2DS, at 840 MtCO₂e, as solar PV is expected to be the most widely deployed renewable energy technology under that scenario, accounting for 87 percent of total aluminum demand; it is also used across a range of other energy technologies. Additionally, aluminum demand is expected to grow by 111 percent, from 48.8 million tons under the base scenario to 102.8 million tons in a 2DS. Aluminum is the highest ranked mineral on the demand index as it is a **high-impact, cross-cutting mineral**; it is used across a wide range of technologies and has the highest annual production levels, reaching 5.6 million tons per year by 2050.

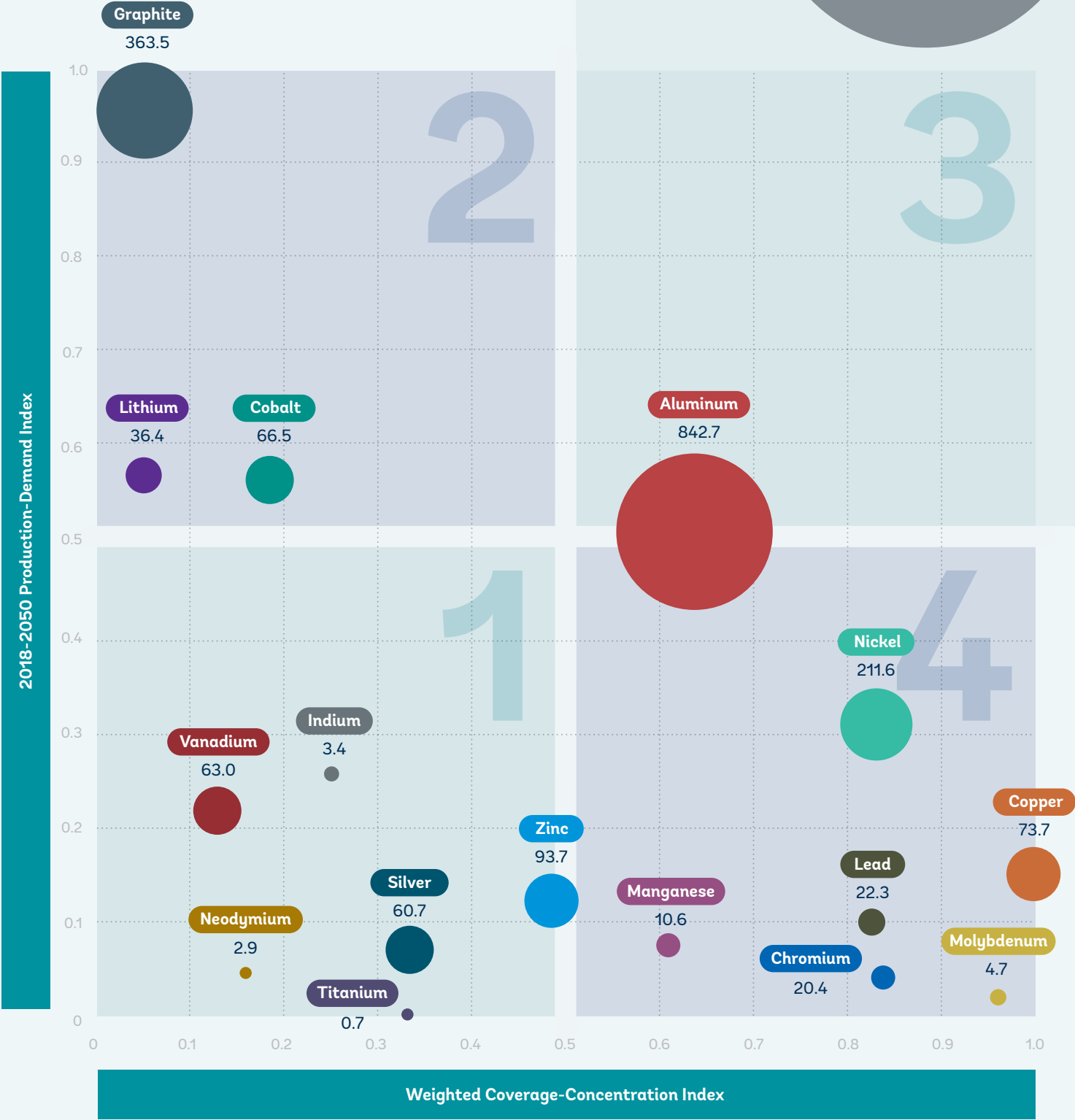
50 Data sourced from Union of Concerned Scientists, "Each Country's Share of CO2 Emissions," published July 16, 2008, updated October 10, 2019, <https://www.ucsusa.org/resources/each-country-share-co2-emissions>.

51 Data available from the IEA Data and Statistics database: <https://www.iea.org/data-and-statistics?country=WORLD&fuel=CO2%20emissions&indicator=CO2%20emissions%20by%20energy%20source>.

52 The NREL finds that the mean carbon emissions per kilowatt-hour from solar PV is just 6 percent of the same kilowatt-hour produced by a coal plant, and 12 percent of a kilowatt-hour from a gas plant. More information on the project is available at "Life Cycle Assessment Harmonization," NREL: <https://www.nrel.gov/analysis/life-cycle-assessment.html>.

Figure 5.2 Total Cumulative Emissions from Cradle to Gate for Energy Technologies Through 2050 Under 2DS Compared to the Demand Index (MtCO₂e)

Emissions values are MtCO₂e.



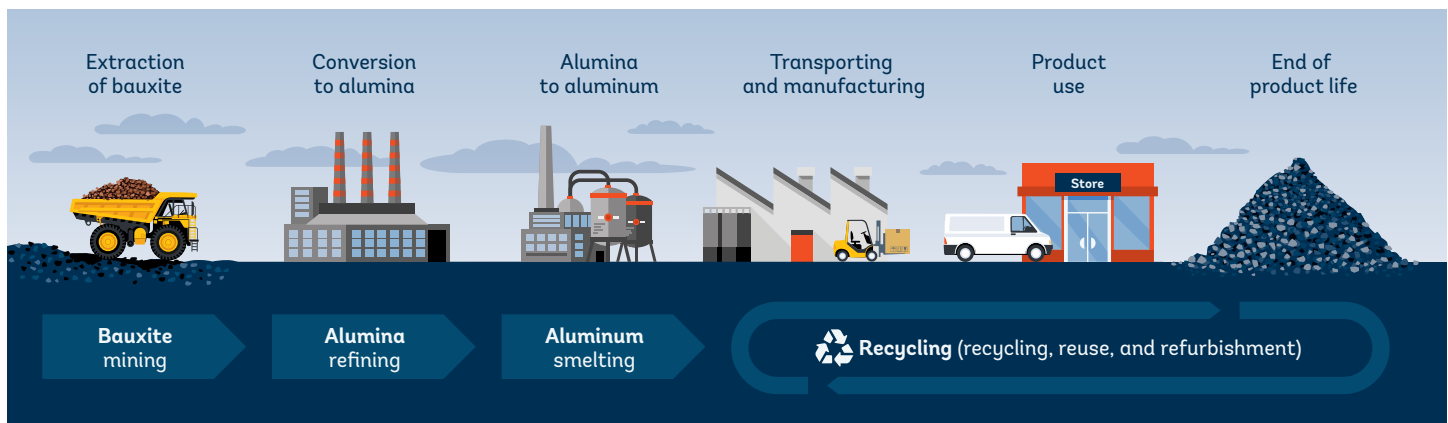
Graphite follows suit as a **high-impact mineral**, accounting for about 360 MtCO₂e up to 2050 because it is exclusively used to manufacture anodes used in most battery technologies. Nickel has the third highest GWP and falls into the **cross-cutting mineral** category; it both has high levels of future demand, nearly doubling production from 2018 levels, and is used across a wide range of technologies.

Together, aluminum, graphite, and nickel production for energy technologies account for a cumulative 1.4 GtCO₂e up to 2050, nearly equivalent to the total 2018 CO₂ emissions from France,

Germany, and the United Kingdom combined.⁵³ Steel has not been included in the GWP analysis to avoid double-counting minerals such as nickel, titanium, iron ore, and chromium, given that these minerals are needed to produce steel. The emissions from steel would be so high, that its cumulative emissions would stand at 3.7 GtCO₂e—more than four times higher than the GWP of aluminum.

Six minerals have been selected from three of the four quadrants in the demand risk matrix to understand which energy technology has the highest GWP per mineral under a 2DS. Similar to trends above, aluminum accounts for the largest share of emissions,⁵⁴ led

Box 5.1 Reducing Emissions from Aluminum Production



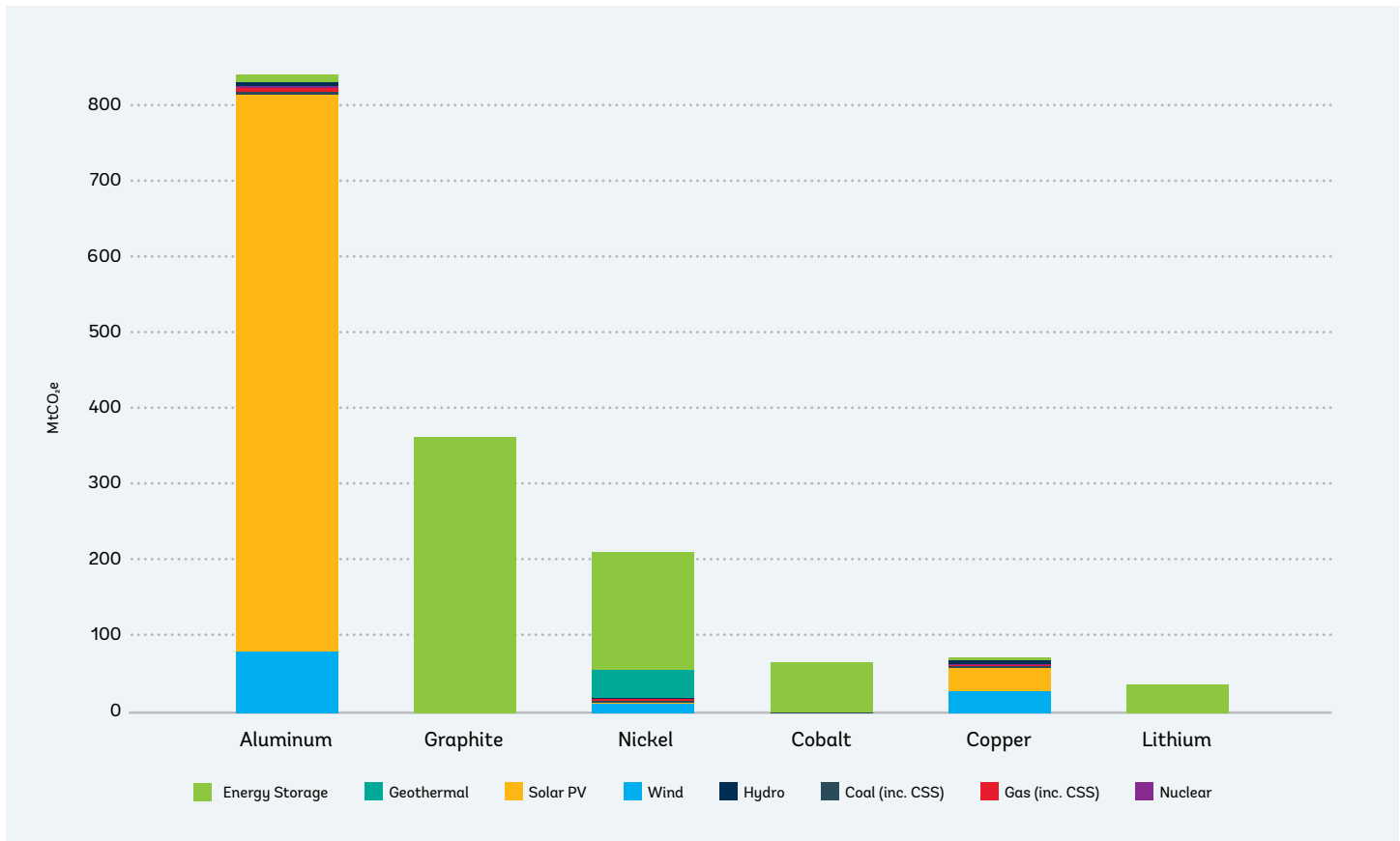
Primary aluminum production is a multistaged process that transforms bauxite that is dug out of the ground into first alumina (aluminum oxide) through crushing, washing, treating, and baking the bauxite (the Bayer process), and then into aluminum via electrolysis (Hall-Héroult process).

Emissions are produced at each stage, with the greatest proportion coming from the final stage because of the large amounts of electricity involved and the CO₂ that directly arises from the process itself. Emissions per ton of aluminum could fall dramatically in the future—especially from this final stage—as a result of the low-carbon

transition itself. Increased renewable deployment reduces the carbon intensity of electricity and therefore the emissions from the electrolysis process. Using data from the academic literature, it is estimated that cumulative emissions of 840 MtCO₂e from aluminum from energy technologies only could fall to under 500 MtCO₂e as a result of these changes, and increased recycling. However, as the process of producing aluminum produces direct CO₂ emissions from the process of breaking down aluminum oxide (alumina) into aluminum, other technological advances will be needed to reduce emissions from the electrolysis process.

⁵³ Data from “CO₂ Emissions,” Global Carbon Atlas: <http://www.globalcarbonatlas.org/en/CO2-emissions>.
⁵⁴ A full overview of the aluminum production process and its associated emissions can be found in annex B.

Figure 5.3 Cumulative GWP from Extraction and Processing of Minerals, Not Including Operations, Using Cradle-to-Gate Through 2050 Under 2DS



Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, GWP = global warming potential, MtCO₂e = million tons of carbon dioxide equivalent.

by solar PV (87 percent) and then wind (10 percent) deployments, as seen in figure 5.3. Under a B2DS, total emissions for aluminum production to supply energy technologies increases to 0.9 GtCO₂e, representing an 8 percent increase from the 2DS. GHG emissions from cobalt, graphite, lithium, and nickel production primarily come from energy storage technologies specifically, although nickel is also used across a range of other energy technologies. Still, energy storage accounts for a large share of nickel's carbon footprint—154 MtCO₂e, representing 73 percent of total nickel emissions from energy technologies—while it accounts for 100 percent of graphite's carbon footprint equivalent (363 MtCO₂e).

As a cross-cutting mineral, copper is used across all energy technologies, with a total carbon footprint of 74 MtCO₂e under a 2DS, similar to cobalt and lithium. However, the GWP copper figure may be vastly underestimated because copper is used in a wide variety of industries and crucial for the clean energy transition, from transmission infrastructure to connecting electric vehicles worldwide. Although aluminum's large carbon footprint primarily comes from solar PV, aluminum is also considered a cross-cutting mineral because it is used across six energy technologies, including electricity generation and storage.



Conclusion

Rising Overall Demand for Minerals

The demand for base and niche minerals to help build clean energy technologies are expected to rise substantially up to 2050, increasing in both absolute and percentage terms from 2018 production levels. Although clean energy technologies are distinct, they all share a common feature: Higher material intensity in comparison to fossil-fuel-based electricity generation. Regardless of which technology-based mitigation scenario is achieved to keep global warming under 2 degrees or beyond, the rapid and large-scale deployment of renewable energy will lead to significant increases in mineral demand because of how these technologies produce and store electricity.

Based on the model presented in this report, large relative increases in demand of up to nearly 500 percent are estimated for certain minerals, especially those concentrated in energy storage technologies, such as lithium, graphite, and cobalt. Even those minerals whose relative demand increases are smaller (for example, copper) still face large increases in absolute demand. Different energy technologies require different types of minerals, either to build their structures or frames, or as components in the technology used to generate electricity, such as the PV cells in solar PV and magnets or motors in wind turbines. Therefore, the technology pathway that emerges from the clean energy transition will shape the types of minerals that will experience the largest increases in demand. That said, regardless of which low-carbon technology pathway is selected, overall mineral demand will still increase.

Technologies involved in the clean energy transition are emerging, evolving, and improving rapidly through innovation and increased deployment. Thus, the way in which the low-carbon transition will emerge is very difficult to predict. This analysis relied on the IEA and IRENA scenarios to model the future energy system, but it is highly likely that a very different mix of electricity generation, and especially energy storage technologies, will emerge as a result of policy choices, technological innovation, and market forces. New technologies such as floating offshore wind or hydrogen fuel cells could emerge and dominate the

market, or their commercialization could be hindered by costs or policy barriers. The increases in demand for specific minerals from the model should be regarded as a possibility that could emerge and are subject to shifts in policy or technologies. The overarching conclusion—that mineral demand will increase—is agnostic to the exact mix of technologies and subtechnologies that may be deployed up to 2050.

Opportunities and risks are present for both the mining sector and the governments that have low-carbon minerals, particularly in mineral-rich developing countries. For the mining industry and resource-rich economies, there are environmental and social challenges that need to be addressed as a result of mining activities. The use of scarce water resources, for example, can create conflict between mining companies and the communities around which they operate. For developing countries specifically, these environmental and social issues are exacerbated by weak governance. Countries that host these minerals are likely to see an increased demand, which, if well managed, could contribute to economic growth and sustainable development. Understanding how demand patterns for these crucial minerals may shift in the face of a new energy system is crucial to long-term planning for countries that produce these minerals and deploy renewable energy technologies as part of their national climate ambitions.

Mineral Demand Vulnerability and Risks

Meeting the challenge of large-scale deployment of renewable energy requires the steady availability of a variety of key minerals as well as stable prices and minimal market disruptions. This is particularly true in developing countries that need to deliver on SDG 7, “access to affordable, reliable, sustainable and modern energy for all.” Understanding that each mineral may carry different demand risks is crucial for the mining industry and governments, both of which need to be prepared for changes in low-carbon technology deployments, potentially causing large and volatile shifts in mineral demand. Understanding that minerals can have varying demand risks can also provide insight into potential recycling opportunities and needs.

This report has gone beyond estimating mineral demand under different climate scenarios, specifically by developing a new framework to understand the demand risks that may be associated with a group of specific minerals. Some minerals will face potentially large increases related to only one technology (or subtechnology), while others will face lower but more broad-based increases in absolute demand. Understanding which minerals fall into which demand risk category is crucial for miners, renewable energy developers, and policy makers to build a comprehensive plan for the clean energy transition.

The **demand risk matrix** provides an overview of how 17 minerals identified as key to the low-carbon transition are impacted by different demand profiles.

I. Medium-Impact Minerals

- Medium-impact minerals, such as titanium and neodymium, are still affected by demand increases and may still play an important role in the clean energy transition. Even though medium-impact minerals neither have high levels of relative demand nor are cross-cutting across a range of energy technologies, the markets for these minerals could still be affected. Although their relative demand increases are small in the climate scenarios presented, future changes in technology deployment could cause significant increases in demand for these minerals.
- Medium-impact minerals are not used in a wide range of technologies but are crucial components of specific technologies, such as neodymium for offshore wind and titanium for geothermal. Issues that threaten the ability of the market to meet this demand could severely impact the deployment of these specific technologies as well as change the shape of the low-carbon transition. In some cases, substitution and efficiency may be possible, as demonstrated in the case of neodymium for wind energy, but this may be limited in many instances. While this analysis, again, does not assess mineral supply risk, neodymium is a rare earth, and more than 70 percent of rare earths are currently produced in China.

II. High-Impact Minerals

- The clean energy transition has significant implications for the production of certain minerals. High-impact minerals such as graphite, lithium, and cobalt will, under a 2DS, need to increase their production significantly, up to nearly 500 percent by 2050 from 2018 levels. Most of this demand will come specifically from energy storage technologies; it could also carry supply risks, as more than 60 percent of graphite and cobalt production are concentrated in China and the Democratic Republic of Congo, respectively.
- Demand for high-impact minerals is therefore both potentially high and uncertain, raising opportunities and risks to both the renewable energy industry and those involved in the supply chain of these minerals. Relatively small changes in the amount and type of energy storage technologies and subtechnologies deployed could have large implications for the markets of these minerals. Similarly, any potential challenges in meeting this demand could cause changes within the storage sector, causing industry to change battery chemistry or even battery type.

III. High-Impact, Cross-Cutting Minerals

- High-impact, cross-cutting minerals, such as aluminum, are critical not only because their demand does not depend on one specific technology, but also because they are needed in higher quantities across a wide variety of energy technologies. High-impact, cross-cutting minerals are less susceptible to fluctuating demand risks because the high level of demand for these minerals will always exist no matter what type of energy technology or subtechnology is deployed up to 2050. Additionally, the scale-up in demand required is significant, implying there is a greater trigger from demand to increase supply, compared to minerals that are just cross-cutting. This makes this category of minerals a high risk for both producers and consumers alike, but also a potential opportunity for producers who will supply these minerals to meet this higher demand.
- Demand for high-impact, cross-cutting minerals is likely to be high and fairly certain over time. For aluminum specifically, its future use and production may have significant implications on the clean energy transition because it is used across

most technologies and has absolute demand figures that significantly outweigh all 17 minerals except graphite. Solar PV accounts for 87 percent of total aluminum demand since it is expected to be the most widely deployed clean energy technology as climate scenarios become more ambitious. Aluminum is thus vital to the low-carbon energy future. The challenge is to provide a steady supply of high-impact, cross-cutting minerals, like aluminum, at a cost that allows the renewable energy sector to fulfill its potential.

IV. Cross-Cutting Minerals

- Even without large increases in relative demand, minerals may be greatly impacted by the low-carbon transition. For some minerals, such as copper, future demand from clean energy technologies may not represent a large portion of current production levels.⁵⁵ However, the amount of those minerals needed, in absolute terms, outweighs the production of other minerals whose relative increases are much greater; the increase in demand is still large enough to have an impact on the overall market and availability of those minerals. Again, these projected demands only account for energy technologies and do not include the transmission lines needed to integrate these technologies into electricity grids.
- Cross-cutting minerals are also used across a wide range of electricity generation and energy storage technologies, meaning that future increases in demand are less reliant on the fate of any one technology. For these minerals, where relative demand may not be high but the absolute demand may be, this projected demand has a high certainty of occurring. Meeting this demand is also crucial to the entire fate of the low-carbon transition as these minerals are vital in many energy technologies. Even without large triggers from rapidly increasing relative demand, it will be crucial that supply can meet demand.

Role of Recycling and Reuse

Recycling, reuse, and refurbishment have important roles in limiting and meeting future demand for minerals for clean energy

technologies, but extraction of mineral resources will still be needed. Recycling rates, both end of life and recycled content, vary greatly across minerals. Current recycling rates could reduce the required primary demand for minerals involved in the low-carbon transition. Future increases in recycling rates can play an important role in mitigating increases in demand for primary minerals, as can reuse of components for energy storage technologies, such as Li-ion batteries, although commercial application of such reuse is currently limited. Incentivizing recycling, reuse, and refurbishment is a vital part of the low-carbon transition. However, more policy measures are needed to scale up action in this area, all the while remaining cognizant of both economic and environmental challenges associated with the recycling processes.

Even with large increases in recycling—including a scenario where 100 percent EOL recycling is achieved—there is still likely to be strong demand for primary minerals. This is especially the case for those minerals with the highest growth in demand, which lack existing material to recycle and reuse. Even if large increases in the mineral recycling sector can be achieved, there will still be a need to meet remaining primary demand. Further work will be needed in this area to ensure that recycling processes are carried out in a responsible way. Policy measures are needed that encourage energy efficiency, environmentally and socially sound practices, and innovation to ensure that clean energy technologies can be safely and efficiently disassembled and recycled.

Emissions Mitigation and Reduction Opportunities

While deploying renewable energy is one of the most effective ways to decarbonize the electricity sector, the mineral intensity of clean energy technologies must be addressed. Even if the emissions from the mineral production and operation of clean energy technologies are just 6 percent that of coal and gas generation, the emissions are not insignificant. Greening the electricity sector will require that upstream- and downstream-related emissions are addressed. Policy and innovation will be needed to “take urgent action to combat climate change and its

55 Current production refers to minerals produced in 2018, based on the Mineral Commodity Summaries, U.S. Geological Survey.

impacts” (SDG 13) while integrating these emissions reductions into countries’ Nationally Determined Contributions (NDCs).

Deploying renewable energy technologies globally without taking into account the mineral demand risks and the additional carbon emissions from upstream and EOL activities may hinder rather than accelerate progress on SDG 7 and SDG 13. The emission intensity of each mineral has been captured within the **demand risk matrix** to offer insight on potential avenues to maximize emissions reduction and mitigation efforts from clean energy technology production and end use. While providing a steady and cost-effective supply of minerals is vital to enable the global deployment of clean electricity generation and storage, the various demand risk profiles also mean that different mitigation strategies need to be employed to decarbonize the various areas of the clean energy mineral supply chain.

Understanding and analyzing the full mineral supply chain for low-carbon technologies are critical to effectively realize climate ambitions. This means that the clean energy transition must take into account that (1) current and future mineral production, including recycling, meets increasing demand up to 2050; (2) emissions associated with increased mineral production are effectively mitigated or reduced while ensuring a continued, stable, and affordable supply of these minerals to support a low-carbon transition; and (3) innovation is leveraged to ensure that these technologies can be safely disposed, easily disassembled, and the mineral contents recycled, at economically reasonable levels, to partially meet this new demand.

The scale, intensity, and causes of emissions vary from mineral to mineral. Mining silver, for example, is emissions intensive, though silver is not demanded on a large scale. Silver production will rise 15 thousand tons annually by 2050, from the demand of solar PV and CSP technologies alone, compared to 27 thousand tons produced overall in 2018 (USGS 2018b). On the other hand, 5.6 million tons of aluminum, produced from bauxite ore, is needed under a 2DS by 2050 to supply just low-carbon technologies, compared to 60 million tons of total aluminum produced for all uses in 2018 (USGS 2018a). Other minerals, such as copper, have smaller GHG footprints per kilogram, but they are needed at a larger scale relative to silver. Understanding these complexities

and tailoring different policy approaches for reducing the carbon footprint of these different minerals are key.

Tailoring strategies to all the different categories of minerals is critical for both helping meet the challenge of supplying strategic minerals and minimizing emissions from the clean energy transition. Aluminum, for example, falls into the high-impact, cross-cutting minerals category and happens to have the largest cumulative emissions under a 2DS or beyond. That makes it crucial for more attention to be focused on the entire aluminum supply chain to ensure steady and affordable supply, all the while decarbonizing primary aluminum production. All stakeholders along these minerals’ supply chains should look for strategies that can help reduce emissions and not exacerbate demand risks. These strategies can include government policy support, technological innovation by industry, and end users incentivizing suppliers to reduce their GHG emissions for products they are going to buy.

Some of the interventions to scale up renewable energy may offer double wins, helping both to boost economic growth in resource-rich developing countries and to reduce climate and environmental risks. One example relates to the emissions associated with the transportation of the minerals, as well as to facilitating value-added production in countries where extraction takes place and boosting manufacturing capacity for renewable technologies in areas where demand is strong—for example, solar PV in Africa, given the region’s massive solar resources. Although this lies outside the scope of this analysis, these emission reduction and mitigation opportunities may be significant for particular minerals and technologies, depending on where renewables will be deployed and where these minerals will be produced.

GHG emissions from steel and cement production are most likely significantly higher than emissions generated by the majority of the 17 minerals identified in this analysis. Steel production currently accounts for nearly 7–9 percent of total GHG emissions worldwide (WSA 2020), while cement accounts for nearly 8 percent (Rodgers 2018). Thus, for certain clean energy technologies, estimated GHG emissions associated with their production may be vastly underestimated when these are excluded. For technologies such as wind, geothermal, and hydroelectricity, steel and cement are major inputs, but they have

been unaccounted for in this analysis because of potential double-counting issues, as a variety of minerals included in the model are needed to produce steel. Enhanced international cooperation on reducing the GHG footprint of these two industries will be crucial to effectively decarbonize the production of low-carbon technologies, from an upstream perspective.

Recycling some of these low-carbon technologies once they reach end of life could help reduce emissions associated with primary mineral production, but the emissions associated with the energy intensiveness of recycling processes also need to be considered.

Recycling alone cannot eliminate all emissions associated with supplying minerals, but it could have a dramatic effect in reducing some of these emissions. For example, secondary aluminum (for example, recycled content) could have a carbon footprint that is about 5–10 percent of that coming from primary aluminum production (Nuss and Eckelman 2014). Increasing recycling therefore can greatly assist in the transition to a cleaner energy system, but challenges relating to the availability of mineral scrap and the need for purity of materials in some applications must be faced, along with reducing the emissions intensity of recycling processes themselves.

Risks Beyond the Model

The model presented here provides key insights to potential future pathways for mineral demand under different levels of ambition on climate change; however, it provides findings on just one part of a complex system. Two crucial areas, supply and wider environmental and social risks, are not covered, but they are important in understanding the wider context of the report.

Supply Risks

Overall, demand for minerals is likely to be high, varied, and in some cases uncertain. It will fluctuate with changes in technology and subtechnology deployments, market conditions, and national and international trends. It is critical to ensure that supply can meet this demand—and in a manner that minimizes the negative consequences of primary mineral production while ensuring that

the minerals crucial to either the entire low-carbon transition or key technologies within that transition are supplied to the market consistently. Understanding the supply risk is crucial for developed and developing countries, which are consumers and producers alike, to meet SDGs 7 and 13. This analysis does not address supply, including the material impacts associated with the increased extraction and production of base, precious, and rare minerals.

While this report does not consider potential mineral supply risks, it is on the basis that resource-rich developing countries will be major contributors to the clean energy future by producing a significant part of these strategic minerals and supplying them to the global market. Based on the World Bank's *Growing Role of Minerals and Metals for a Low Carbon Future* (2017), a number of key developing countries have been identified as having a potentially consequential role in producing these strategic minerals.

Wider Environmental and Social Risks

This report will inform policy makers, private sector actors, and civil society organizations in their quest to help resource-rich developing countries sustainably and responsibly produce the minerals needed to deliver on SDGs 7 and 13. Beyond specific climate-related risks, other environmental and social risks of increased mineral extraction also need to be considered throughout the supply chain. These have not been addressed in this analysis given the focus on GHG emissions.

From a broader environmental perspective, for example, the water intensiveness of the mining sector and the impact of deforestation need to be integrated in how these minerals will need to be produced to sustainably supply clean energy technologies. From a social perspective, understanding issues such as the impact of mining upon local communities is vital to ensure that the transition to a clean energy system is beneficial for all. Given how critical minerals are to the low-carbon transition, a failure to address these wider environmental and social risks could facilitate a backlash against renewable electricity generation and energy storage technologies needed to mitigate GHG emissions.⁵⁶

⁵⁶ Recent reports such as the World Bank's *Forest-Smart Mining: Identifying Factors Associated with the Impacts of Large-Scale Mining on Forests* (2019) and *Building Resilience: A Green Growth Framework for Mobilizing Mining Investment* (2019), and the IFC and ICMM's *Shared Water, Shared Responsibility, Shared Approach: Water in the Mining Sector* (2017) have shed light on some of these challenges and offered potential solutions. More research will be needed to understand the wider environmental and social risks from increased mineral production.

Next Steps and Actions

The **World Bank Group's Climate-Smart Mining** Initiative supports the sustainable extraction and processing of minerals and metals to secure supply for clean energy technologies while minimizing the climate and material footprints throughout the value chain of those materials by scaling up technical assistance and investments in mineral-rich developing countries. Achieving these objectives would represent a key win-win for climate: It would allow the wide rollout of renewable and storage technologies, required under ambitious climate scenarios, while minimizing the emissions and material footprints associated with those technologies. Being able to understand which minerals are needed for which energy technologies and subtechnologies is crucial to help renewable energy developers, miners, and governments understand where the major risks lie along the clean energy supply chain in order to reduce mineral demand, environmental and climate-related risks.

The **Climate-Smart Mining** Initiative addresses these challenges by working together with governments, development partners, industries, and civil society. Combining climate-smart mining with an understanding of the demand risks can provide actionable insight for climate, energy, and mining stakeholders to identify opportunities to reduce the carbon and material footprints of increased climate ambition while maintaining a stable supply of minerals. Each stakeholder along the supply chain has a role to play:

- **Climate policy makers:** With minerals playing a vital role in enabling the clean energy transition, it will be crucial for members of the climate community to work closely with producers of those minerals—including resource-rich developing countries and the mining industry—to ensure that the associated emissions are effectively mitigated. Mineral-rich countries that make it a priority to reduce emissions from mineral production, through **climate-smart mining** practices, could integrate their decarbonization efforts in their NDCs under the Paris Agreement. To address some of these challenges, climate stakeholders can do the following:

- ✓ Actively support mineral-rich countries that make it a priority to reduce emissions from mineral production, through climate-smart mining practices, while helping them integrate their decarbonization efforts in their NDCs.
- ✓ Support measures that aim to decarbonize the full supply chain of low-carbon technologies, including emissions from the transportation of minerals between mines and processing facilities, as well as the emissions from manufacturing these technologies.
- ✓ Leverage new and existing frameworks, such as the demand risk matrix, to focus on minerals that require a more targeted approach for climate mitigation strategies to supply specific clean energy technologies.
- **Clean energy stakeholders:** The energy sector also has an important role to play in ensuring that the low-carbon technologies they are developing and deploying are being produced sustainably and responsibly while taking into account the waste management of these technologies once they reach end of life. The energy community can play a role in helping producers of minerals reduce their carbon footprint by engaging with countries and mining companies. With the mining sector accounting for 2–11 percent of the world's total energy consumption, it will be important for the energy sector to work closely with miners to ensure that minerals are produced using clean sources of energy and **climate-smart mining** practices. Specifically, the energy sector should do the following:
 - ✓ Focus on reducing the environmental and carbon footprints of the full supply chain of their technologies, from working with miners by helping them adopt climate-smart mining practices to working on easing decommissioning, reuse, recycling, and refurbishment to increase the lifetimes of these technologies.
 - ✓ Connect with stakeholders across the mining sector as well as those involved in the recycling industry to assist in approaching these challenges from a holistic perspective.
 - ✓ Use frameworks, such as the demand risk matrix, to understand where the greatest demand challenges may lie and where innovation may need to be focused to reduce the use of particular materials.

- **Mining Stakeholders:** The mining community should position itself as a contributor to SDG 7 by ensuring that the climate and material footprints associated with the minerals they supply are minimized. Innovation is necessary to reduce the amount of energy, water, and land needed to mine these minerals. Without putting into place measures that address these challenges, by adopting **climate-smart mining** practices, it will be difficult for the mining sector to position itself as a champion and enabler of the clean energy transition. Specific actions recommended for the sector:

- ✓ Mainstream the use of climate-smart mining practices to reduce the carbon and material footprints of supplying the critical minerals needed for the low-carbon transition.
- ✓ Build networks with those involved at all stages of low-carbon technology supply chains, to help build understanding of the opportunities, challenges, and risks in supplying the materials needed for the low-carbon transition.
- ✓ Encourage and advocate for innovation to develop and share new technological developments to green mineral supply chains. This includes developing new methods to reduce water use, increase energy efficiency, deploy clean energy trucks and processing technology, and explore mineral recycling opportunities.

- **Governments:** Policies will have a pivotal role to play in ensuring that **climate-smart mining** practices are adopted throughout the entire supply chain of low-carbon technologies, to secure the supply of these minerals through sustainable and responsible means, while integrating a circular approach to these minerals. Most notably, policy makers should consider doing the following:

- ✓ Encourage, incentivize, and remove economic and technical barriers to recycling, reuse, and refurbishment of the technologies involved in the clean energy transition.
- ✓ Work with the mining sector and renewable energy developers to understand where the greatest demand risks may occur.
- ✓ Work with the mining sector and users that produce and consume these minerals to ensure that climate-smart mining practices are encouraged and incentivized, and that economic and technical barriers are removed.



Rio Tinto, Diavik Diamond Mine, Canada



Annex A.

About Climate-Smart Mining

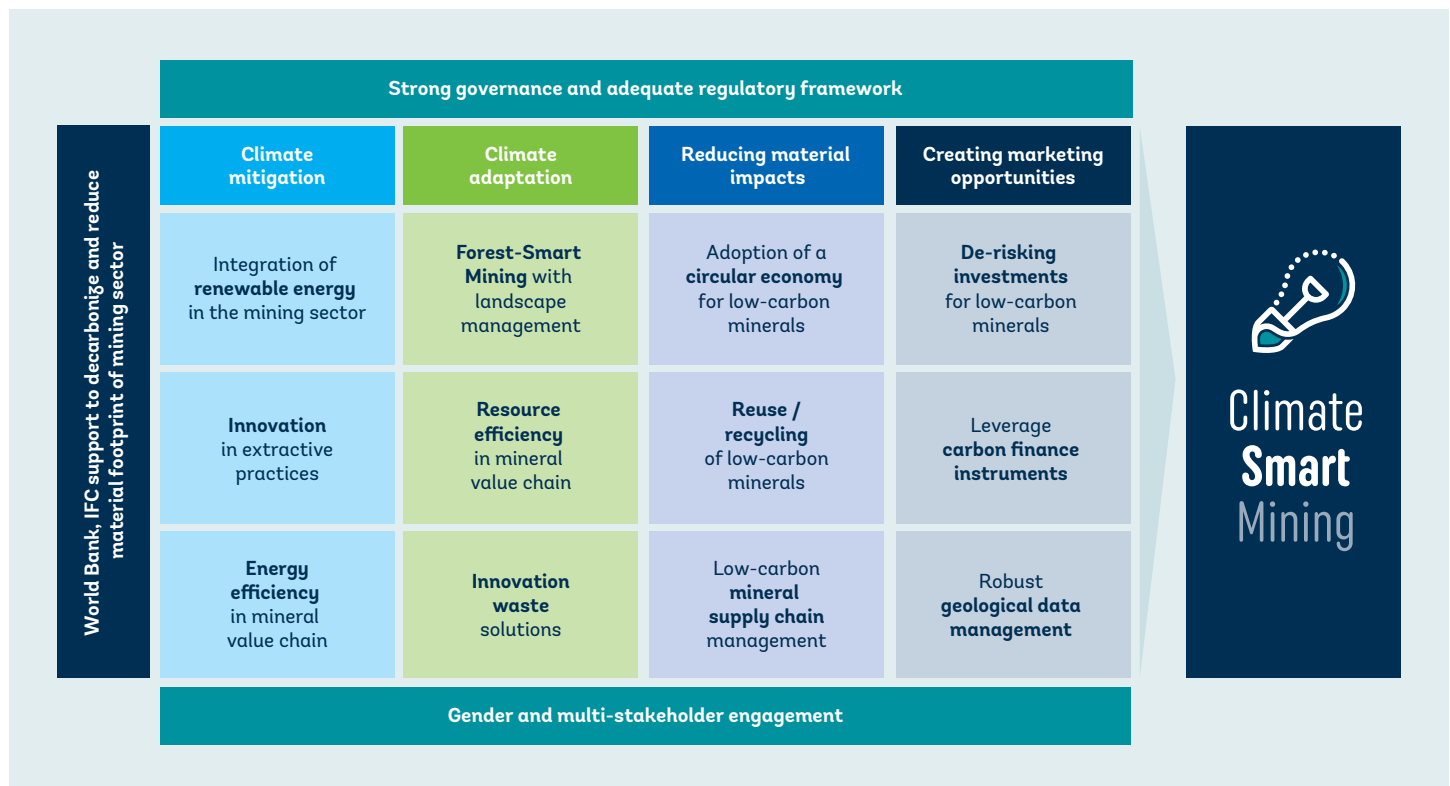
The Climate-Smart Mining Initiative will help resource-rich developing countries benefit from the increasing demand for minerals and metals, while ensuring the mining sector is managed in a way that minimizes its environmental and climate footprints.⁵⁷

The initiative supports the responsible extraction and processing of minerals and metals to secure supply for clean energy technologies by minimizing the social, environmental, and climate footprints throughout the value chain of those materials by scaling up technical assistance and investments in resource-rich developing countries.

While the growing demand for minerals and metals provides economic opportunities for resource-rich developing countries and the industry alike, significant challenges will likely emerge if the climate-driven clean energy transition is not managed responsibly and sustainably. Without climate-smart mining practices, negative impacts from mining activities will increase, affecting already vulnerable communities in developing countries, as well as the environment in which they operate.

The Climate-Smart Mining Initiative has been developed to align with the Sustainable Development Goals and the Paris Agreement to ensure that the decarbonization of the mining and electricity industries also benefits the resource-rich countries that host these strategic minerals and the communities directly impacted by their extraction, as well as the developing countries that are projected to deploy renewable energy technologies to reach their climate ambitions.

Figure A.1 Climate-Smart Mining Building Blocks



57 "Climate-Smart Mining: Minerals for Climate Action" (Brief), Extractive Industries, World Bank, <https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action>.

Annex B.

Methodology

A number of assumptions, data, and methods were utilized in the model. This annex expands on the methodology discussed in the report.

Energy Storage Assumptions

Modeling future energy storage pathways is difficult because of the rapidly emerging nature of the different technologies involved, and the relative lack of publicly available scenarios to draw on. As such, a number of assumptions were made on the basis of a broad reading of the literature and discussions with industry experts.

- **Automotive energy storage assumptions**

- By 2030, all automotive energy storage is met by li-ion batteries. Up to 2030, the use of lead-acid batteries declines linearly to zero.

- **Automotive energy storage assumptions**

- By 2030, all automotive energy storage is met by Li-ion batteries. Up to 2030, the use of lead-acid batteries declines linearly to zero.

- **Stationary energy storage assumptions**

- Energy storage requirements are met by 90 percent grid-scale energy storage and 10 percent decentralized.
- Decentralized energy storage transitions to an equal mix of lead-acid, Li-ion, and other energy storage technologies by 2050.
- Grid-scale energy storage is met by a majority of Li-ion batteries (70–84 percent of capacity, depending on scenario) and a small percentage of lead-acid (2.5–5 percent). Other technologies (mostly pumped-energy storage) decline in importance to between 17 and 25 percent, while vanadium redox flow batteries grow at a rate of 5 percent of extra additional capacity per year to account for between 2.8 and 3.7 percent of capacity by 2050, depending on the scenario.

Weighted Coverage-Concentration Index

The weighted coverage-concentration index is calculated on an equal weighting of two items: (1) the number of technologies that require one mineral, and (2) the share of demand for minerals that comes from a single technology. This index is normalized to 1 for copper, with all other minerals rated against that mineral. The two components are calculated in the following way:

- *Number of technologies that require one mineral.* This is calculated by counting how many technologies the mineral plays a role in. Any minerals used in energy storage are given a value based on the overall demand of minerals from energy storage compared to energy generation (6 percent). Those minerals also used in generation technologies are given a score based on the share of total installed capacity in 2050 in the 2DS that the technologies the minerals are used in account for, multiplied by the total amount of minerals used in generation (94 percent). For example, if a mineral was just used in wind, it would receive a score of 0.22 because wind accounts for 23 percent of installed capacity in 2050 and this would be multiplied by 94 percent. The more technologies a mineral is involved in, the higher the value.
- *Share of demand for the mineral that comes from a single technology.* This is calculated by subtracting from 1 the largest percentage share of demand from one technology. For example, if 60 percent of demand from a mineral comes from wind, then this would be calculated as $1 - 0.6 = 0.4$. The idea behind this is that the lower the share from any one technology, the more cross-cutting the mineral.

2018–2050 Production-Demand Index

The 2018–2050 production-demand index is calculated on an average of absolute and relative demand, as discussed above. The data used to calculate this index are given in table B.2.

Table B.1 Implication of Clean Energy Transition on Mineral Demand Challenges

Quadrant	Category	Implication
Quadrant 1	Medium-impact minerals	Quadrant 1 minerals may appear to be less of a priority, but that may not necessarily be the case. Some of these minerals may be critical to key subtechnologies, and although some substitution may be possible, they may be strategically important to the clean energy transition. Since these minerals may not face the high levels of demand faced by quadrant 2 minerals, nor the stable conditions faced by quadrants 3 and 4, less priority may be given to these minerals, but in turn, this may result in potentially increasing their criticality, if supply constraints exist.
Quadrant 2	High-impact minerals	Demand for minerals in quadrant 2 is much higher, but it is much more concentrated in certain technologies or subtechnologies. Demand growth could be substantial, but potentially more varied if shifts in policy, market conditions, or other key factors cause different types of technology or subtechnology to be deployed at greater, or lesser, levels.
Quadrant 3	High-impact, cross-cutting minerals	Quadrant 3 minerals encounter the dual challenge of meeting high levels of demand from a broad range of technologies. They do not face the same challenges of technology choice as quadrant 2 minerals, but they face higher levels of relative demand than quadrant 4 minerals. Demand pressures are thus likely to be highest and most stable in these minerals.
Quadrant 4	Cross-cutting minerals	Quadrant 4 represents stable and steady levels of demand. Minerals in this area are not so dependent on shifts in energy technology, and greater levels of climate ambition are likely to lead to increases in these minerals across the board. Demand growth is therefore likely to be predictable and steady.

Table B.2 2018 Mineral Production and 2050 Projected Annual Demand from Energy Technologies

Mineral	2018 annual production (Tons, thousands) ^a	2050 projected annual demand from energy technologies (Tons, thousands)	2050 projected annual demand from energy technologies as percent of 2018 annual production
Aluminum	60,000	5,583	9%
Chromium	36,000	366	1%
Cobalt	140	644	460%
Copper	21,000	1,378	7%
Graphite	930	4,590	494%
Indium	0.75	1.73	231%
Iron	1,200,000	7,584	1%
Lead	4,400	781	18%
Lithium	85	415	488%
Manganese	18,000	694	4%
Molybdenum	300	33	11%
Neodymium	23 ^b	8.4	37%
Nickel	2,300	2,268	99%
Silver	27	15	56%
Titanium	6,100	3.44	0%
Vanadium	73	138	189%

a. Data for 2018 annual production sourced from the U.S. Geological Survey.

b. Data sourced from Deetman et al. (2018).



Global Warming Potential

The estimates for the GWP of the minerals used in the clean energy transition presented here come with a number of caveats, and avenues for future research. They are based on GWP per kilogram from historical sources and are static—that is, they do not take into account changes in the composition of relevant low-carbon technologies. Nor do they take into account future changes in electricity mix, declining ore grades, changing technologies, shifts in relative prices, or increases in recycling activities. They also do not take into account wider environmental impacts such as health, water, and ecosystem loss from the extraction of the minerals required to build renewable energy technologies.

To calculate their data, Nuss and Eckelman (2014) drew on a wide variety of data sources, and included various production techniques for each metal, creating a weighted average of GWP per metal on the basis of historical shares of each production technique. The details behind estimate of GWP are vast and based on a wide variety of data, techniques, and assumptions. For example, copper production is based on seven different production techniques, utilizing different ore types.

The estimates of GWP per kilogram are based on a share of primary and secondary production based on historical data. Should recycling of key metals increase significantly, as discussed in the main report, then the GWP of the final

demanded metal could change substantially. For example, Nuss and Eckelman (2014) estimated the GWP of primary aluminum from bauxite ore at between 8.7 and 30.5 times the GWP of secondary aluminum (depending on the source of the scrap aluminum used). Therefore, significant increases in secondary aluminum production would reduce the overall GWP of aluminum used in energy technologies—with the caveat of there being a readily available supply of scrap aluminum.

With respect to ore grades, van der Voet et al. (2019) found little evidence for declining ore grades for bauxite, iron, or manganese, but they did find declining long-term trends for copper, zinc, lead, and nickel, which will work to increase their GWP numbers, because of higher energy inputs to extract and process the materials to obtain the same amount of ore. Declining ore grades brings increase in associated environmental impacts—for example, an increase on the volume of waste generated produces larger tailings as well as impacts on local ecosystems. For production techniques, the authors again find differing impacts, with a clear trend in improved process efficiencies reducing energy demand in steel production. No such advances have been made for processing bauxite ore into alumina and only a slow improvement in conversion efficiencies of alumina into aluminum.

The conclusion to be drawn is that there are no consistent patterns of improvement in projected future GWP per kilogram of

metals—pathways will differ from metal to metal depending on the dependence on electricity as an energy source and other factors.⁵⁸ More research is needed in this area, extending the work conducted by van der Voet et al. (2019). The model notes these key future changes to the GWP per kilogram but uses the static data from Nuss and Eckelman (2014) as a starting point to conduct analysis, noting the limitations and future changes discussed above.

Shifting Aluminum Emissions

The production of aluminum from bauxite ore is a multistaged process, creating different amounts and types of greenhouse gas emissions at the various stages (figure B.1). The carbon intensity of aluminum production is likely to change in the future because of changes in the carbon intensity of electricity, the efficiency of the technologies involved in the process, and the grade of ore extracted from the ground.

The first stage of the process is the extraction of bauxite from the ground. Emissions from this part of the process account for 0.2 percent of emissions per ton (Tan and Khoo 2005), resulting from the use of fuels to run the machinery needed to clear earth and dig mining pits, and to extract and crush the bauxite.

The next stage of the process is the transformation of bauxite to alumina, or aluminum oxide. This is done by a four-stage “Bayer” process, which involves the digestion of the bauxite with caustic soda, the clarification of liquor streams, the precipitation of alumina hydrate, and the calcination of alumina. This latter stage involves heating the alumina in a kiln to temperatures in excess of 1,000°C. Emissions at this stage account for approximately 13 percent of total emissions (Tan and Khoo 2005), resulting from the combustion of fossil fuels at various stages of the process, such as the heating of the kilns.

The final stage transforms the alumina to aluminum via the Hall-Héroult process. This stage is the most carbon-intensive part of the process, accounting for 60–90 percent of emissions (Carbon Trust 2011). It involves the use of large amounts of electricity and

therefore its emissions vary greatly depending on the source of the electricity. The process involves the electrolysis of alumina. The electrolysis process involves carbon anodes, separating the oxygen from the alumina (or aluminum oxide) and attaching it to the carbon in the anode, creating CO₂ (and other greenhouse gases) in the process. Thus, emissions come both from the electricity involved and as a direct result of the process.

Emissions may potentially shift at all three stages of the aluminum production process. The scale of these shifts will depend on the penetration of renewables into the electricity grid along with technology improvements and changes in the ore extracted. These shifts may cause the carbon intensity of aluminum to shift in different directions. Higher penetration of renewables will cause the carbon intensity to reduce, while declining ore grades are likely to increase the carbon intensity.

Estimates of the future path of emissions are scarce in the literature, although van der Voet et al. (2019) do provide estimates under adapted GEO-4 scenarios. Under the equitability first scenario—a sustainable development scenario that the authors link to the WEO 450 scenario—aluminum emissions decline by 43 percent per ton by 2050. Although the scenarios are not completely analogous, the impact of these shifts is illustrated in the estimates of the GWP of aluminum up to 2050 under the 2DS. Total aluminum emissions for use in energy technologies declines from 840 MtCO₂e to 550 MtCO₂e under the 2DS (reducing to 454 MtCO₂e if end-of-life recycling rates increase to 100 percent by 2050). This shift illustrates the scale to which the low-carbon transition itself may help mitigate some of the emissions from minerals required—but not all. Mitigation options are available at various stages of the process, including the use of inert anodes in the Hall-Héroult process and innovation focused on reducing electricity use in the electrolysis phase (IEA 2019e). However, further action is needed to reduce emissions involved in the extraction and processing of minerals—this is a crucial area of work for the Climate-Smart Mining Initiative.

58 Van der Voet et al. (2019) use the GEO-4 scenarios in their estimation of future metal demand. The differential impacts on the carbon footprint of different metals can be seen by comparing their projections of emissions per kilogram of metal under the markets first scenario (which represents a scenario dominated by global markets) with that under the equitability first scenario (representing sustainable development). They project the CO₂ equivalent per kilogram for aluminum falling by 11 percent in the markets scenario and by 49 percent in the equitability scenario. In contrast, the same figure for copper rises by 15 percent in the markets scenario and falls by 24 percent in the equitability scenario, while lead's emissions per kilogram increases by 23 percent in the markets scenarios and by 9 percent in the equitability scenario.

Market Dynamics

The demand estimates produced in this model represent underlying (or latent) demand for minerals. This is the demand that would occur, all other things being equal, crucially without changes in supply or induced substitution and efficiency.

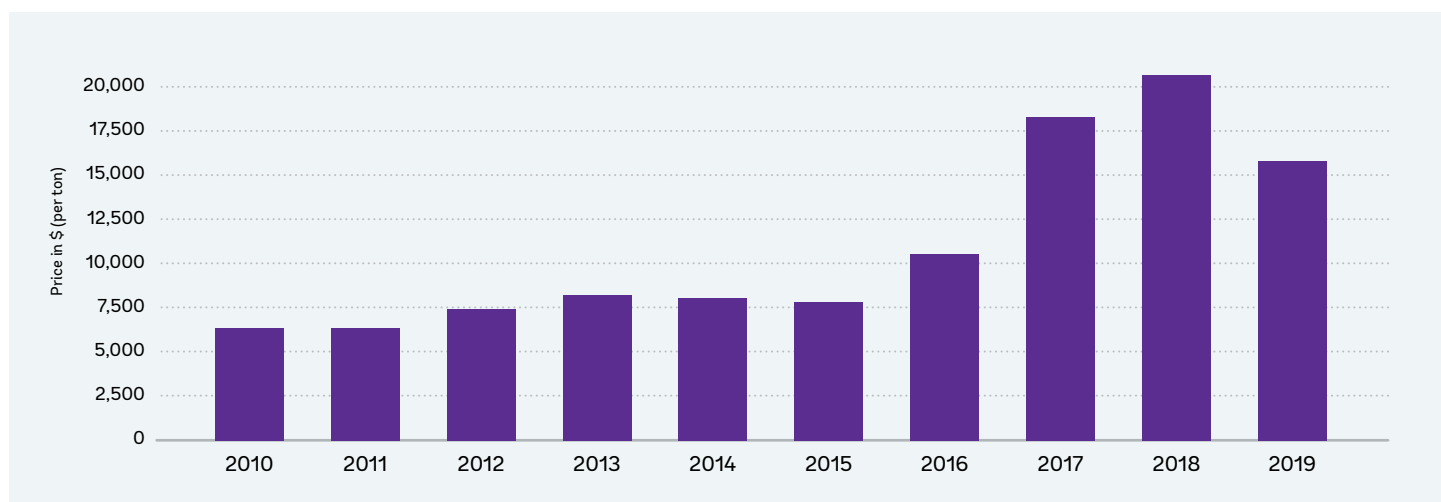
Higher levels of demand for commodities could lead to higher prices, which induce two major effects: (1) Those involved in the extraction and production of commodities increase their supply, and (2) those demanding those minerals are incentivized to reduce their use in their products, either by substituting for other minerals or by improving the efficiency of how the minerals are used.

The demand figures provided in this analysis therefore provide a scale of how far supply needs to adjust if no such substitution or efficiency improvements are possible. To fully gauge the scale at which this demand poses a risk therefore depends on both the supply aspects and the scale at which substitution and efficiency can play a role. The questions related to supply lie beyond the scope of this report, while questions of technology substitution and efficiency vary dramatically from technology to technology, and mineral to mineral. Some of these aspects are explored for lithium, cobalt, nickel, and manganese in Li-ion batteries in the Energy Storage section in chapter 3 of the main report.

Even though technology substitution and supply responses may allow large-scale increases in demand to be met, such rapid scale-ups of demand may cause price spikes and falls, creating instability and uncertainty for both the mining and renewable energy sectors. An example of this can be seen in recent movements in the lithium market. Rapid growth in the demand for Li-ion batteries from a growing electric vehicle market as well as mobile phones, laptops, and tablets has induced large increases in supply over recent years, culminating in a 98 percent increase in global production between 2017 and 2018. This in turn caused a short-term oversupply in the market, causing a drop in lithium prices in 2019.

This reduces the incentives for substitution and technical efficiency in the use of lithium, and also incentives to invest in future lithium supply. This may cause future price spikes, increasing supply. Understanding these dynamics is critical for fully understanding the impact that the low-carbon transition will have on mineral markets. Each commodity and technology has particular specificities, which means that the market dynamics will be unique to each case. Therefore, commodity- and technology-specific research are needed to understand the full picture of mineral demand and market dynamics.

Figure B.1 Lithium Prices, 2010–2019



Source: Garside 2020.

Annex C. Uncertainties

Uncertainty regarding the future mineral demand from energy technologies arises from a number of different sources: the mineral composition of the energy technologies, the amount of these technologies that will be deployed in the future, and which of the technologies will actually be deployed.

Uncertainties over the first two are captured in the model by including a range of metal composition estimates and providing comparisons across a range of scenarios. The estimates presented in the report are effectively a central point of a distribution. These distributions are, in some cases, extremely broad—for example, the use of aluminum in solar PV could be substituted for composite or synthetic alternatives. In cases where the use of the mineral is less substitutable and there is less of a range of estimates in the literature, the distribution is much smaller.

When looking at the GWP of minerals needed for a low-carbon transition, there is another source of uncertainty that is compounded with the uncertainty over future mineral demand levels: the uncertainty in the future GWP per kilogram of metal. A portion of this uncertainty is captured by including the range of estimates for GWP per kilogram from Nuss and Eckelman (2014). It should be acknowledged, however, that this is likely to underestimate the uncertainty, given potential future changes in GWP, as discussed in annex B.

The scale of this potential range can be seen by examining the range of GWP for aluminum. The GWP from the use of aluminum in solar PV varies as a result of uncertainty both in the GWP per kilogram and in the use of aluminum in solar PV panels. The uncertainty in the GWP per kilogram of mineral as given in Nuss and Eckelman (2014) is the result of the wide variation in GWP from primary aluminum and recycled aluminum (much of this is due to difference in the electricity source: because aluminum production is so power intensive, the power source—coal versus gas versus hydro—is a very significant variable).



This uncertainty is multiplied by the uncertainty of the use of aluminum in solar PV, especially in the fittings required for solar panels. An extremely wide range for this is given in the literature. Together, these highlight that although the mean GWP for the use of aluminum in solar PV is large, improvements in aluminum production, moves toward greater use of secondary aluminum, and efficiency improvements in solar PV design could reduce the GWP significantly.

References

- Ahmadi, L., S. B. Young, M. Fowler, R. A. Fraser, and M. A. Achachlouei. 2017. "A Cascaded Life Cycle: Reuse of Electric Vehicle Lithium-Ion Battery Packs in Energy Storage Systems." *International Journal of Life Cycle Assessment* 22 (1): 111–24.
- AGI (American Geosciences Institute). 2017. *Recycling as a Source of Mineral Commodities*. Factsheet 2017-001, written and compiled by B. Mander, March.
- AIP (American Institute of Physics). 2019. "Growth of Wind Energy Points to Future Challenges, Promise." *ScienceDaily*, August 13. <https://www.sciencedaily.com/releases/2019/08/190813112211.htm>.
- Bloomberg. 2019. "Mining Lithium for Electric Cars Is Hurting This Desert's Local Environment." KidsPost, *Washington Post*, June 12. https://www.washingtonpost.com/lifestyle/kidspost/mining-lithium-for-electric-cars-is-hurting-this-deserts-local-environment/2019/06/12/aa5a5f64-83b9-11e9-95a9-e2c830afe24f_story.html.
- Bomgardner, M. M., and A. Scott. 2018. "Recycling Renewables: Can We Close the Loop on Old Batteries, Wind Turbines, and Solar Panels to Keep Valuable Materials Out of the Trash?" *Chemical and Engineering News* 96 (15): 34. <https://cen.acs.org/energy/renewables/Recycling-renewables/96/i15>.
- Campero, C., and L. M. Harris. 2019. "The Legal Geographies of Water Claims: Seawater Desalination in Mining Regions in Chile." *Water* 11 (5): 886. <https://www.mdpi.com/2073-4441/11/5/886>.
- Caramia, V., and B. Boggini. 2014. "Materials Science Aspects of Zinc-Air Batteries: A Review." *Materials for Renewable and Sustainable Energy* 3 (2): 28.
- Carbon Trust. 2011. *International Carbon Flows*. London: Carbon Trust. <https://www.carbontrust.com/resources/international-carbon-flows>.
- CCSI (Columbia Center on Sustainable Investment). 2018. *The Renewable Power of the Mine*. New York: CCSI.
- Chipindula, J., V. S. V. Botlaguduru, H. Du, R. R. Kommalapati, and Z. Huque. 2018. "Life Cycle Environmental Impact of Onshore and Offshore Wind Farms in Texas." *Sustainability* 10 (6): 2022.
- Church, C., and L. Wuennenberg. 2019. *Sustainability and Second Life: The Case for Cobalt and Lithium Recycling*. Winnipeg, Canada: International Institute for Sustainable Development. <https://www.iisd.org/sites/default/files/publications/sustainability-second-life-cobalt-lithium-recycling.pdf>.
- Deetman, S., S. Pauliuk, D. P. van Vuuren, E. van der Voet, and A. Tukker. 2018. "Scenarios for Demand Growth of Minerals in Electricity Generation Technologies, Cars, and Electronic Appliances." *Environmental Science & Technology* 52 (8): 4950–59.
- ESMAP (Energy Sector Management Assistance Program). 2019. *Going Global: Expanding Offshore Wind to Emerging Markets*. Washington, DC: World Bank.
- EC (European Commission). 2018. "Report on Raw Materials for Battery Applications." Commission Staff Working Document SWD(2018) 245/2 final, European Commission, Brussels.
- Garside, M. 2020. "Lithium Carbonate Price 2019–2019." Statista, February 7. <https://www.statista.com/statistics/606350/battery-grade-lithium-carbonate-price/>.
- GCCSI (Global CCS Institute). 2019. "New Large-Scale CCS Facilities Added to Global CCS Database." Insights, November 18. <https://www.globalccsinstitute.com/news-media/insights/new-large-scale-ccs-facilities-added-to-global-ccs-database/>.
- Goldie-Scot, L. 2019. "A Behind the Scenes Take on Lithium-ion Battery Prices." BloombergNEF, March 5. <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/>.
- Guilbaud, J. J. 2016. "Hybrid Renewable Power Systems for the Mining Industry: System Costs, Reliability Costs, and Portfolio Cost Risks." Doctoral dissertation, University College London.
- Hagelüken, C. 2012. "Recycling the Platinum Group Minerals: A European Perspective." *Platinum Minerals Review* 56 (1): 29–35.
- IEA (International Energy Agency). 2016. *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*. Paris: IEA.
- . 2017. *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. Paris: IEA. <https://www.iea.org/etp/>.
- . 2018. *Global Electric Vehicle Outlook 2018*. Paris: IEA.
- . 2019a. *CO₂ Emissions from Fuel Combustion 2019*. Paris: IEA. <https://www.iea.org/reports/co2-emissions-from-fuel-combustion-2019>.
- . 2019b. *Global Electric Vehicle Outlook 2019*. Paris: IEA.
- . 2019c. *World Energy Outlook 2019*. Paris: IEA.
- . 2019d. *Renewables 2019*. Paris: IEA. <https://www.iea.org/reports/renewables-2019>.

- . 2019e. *Innovation Gaps*. Paris: IEA. <https://www.iea.org/reports/innovation-gaps>.
- . 2019f. *Exploring Clean Energy Pathways: The Role of CO₂ Storage*. Paris: IEA.
- IFC (International Finance Corporation), and ICMM (International Council on Mining and Minerals). 2017. *Shared Water, Shared Responsibility, Shared Approach: Water in the Mining Sector*. Washington, DC, and London: IFC and ICMM.
- IRENA (International Renewable Energy Agency). 2018. *Renewable Capacity Statistics 2018*. Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Mar/IRENA_RE_Capacity_Statistics_2018.pdf.
- . 2019a. *Global Energy Transformation: A Roadmap to 2050*. Abu Dhabi: IRENA.
- . 2019b. *Renewable Capacity Statistics*. Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Mar/IRENA_RE_Capacity_Statistics_2019.pdf.
- . 2019c. *Renewable Power Generation Costs in 2018*. Abu Dhabi: IRENA.
- . 2019d. "Solar Energy." <https://www.irena.org/solar>.
- Johnson Matthey. 2019. *PGM Market Report: May 2019*. London: Johnson Matthey.
- Lazard. 2018. *Lazard's Levelized Cost of Storage Analysis – Version 4.0*. Lazard. <https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf>.
- Martin, C. 2020. "Wind Turbine Blades Can't Be Recycled, so They're Piling Up in Landfills." *Bloomberg Green*, February 5. <https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills>.
- Meeus, M. 2018. "Overview of Battery Cell Technologies." Presentation at the European Battery Cell R&I Workshop, Brussels, January 11–12, 2018.
- Moss, R. L., E. Tzimas, P. Willis, J. Arendorf, P. Thompson, A. Chapman, N. Morley, et al. 2013. *Critical Minerals in the Path Towards the Decarbonisation of the EU Energy Sector: Assessing Rare Minerals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*. JRC Scientific and Policy Report. Luxembourg: Publications Office of the European Union.
- Nuss, P., and M. J. Eckelman. 2014. "Life Cycle Assessment of Minerals: A Scientific Synthesis." *PLoS One* 9 (7): e101298.
- PEI (Power Engineering International). 2019. "Khazakstan Welcomes 100 MW Solar Plant." Power Engineering International, September 19. <https://www.powerengineeringint.com/2019/09/23/khazakstan-welcomes-100-mw-solar-plant/>.
- Rodgers, L. 2018. "Climate Change: The Massive CO₂ Emitter You May Not Know About." BBC News, December 17. <https://www.bbc.com/news/science-environment-46455844>.
- Rogelj, J., M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, and M. Meinshausen. 2016. "Paris Agreement Climate Proposals Need a Boost to Keep Warming Well Below 2°C." *Nature* 534 (7609): 631.
- Sanderson, H. 2016. "Solar Power Driving New Demand for Silver." *Financial Times*, May 13. <https://www.ft.com/content/010da6e2-1863-11e6-b197-a4af20d5575e>.
- Savvantisidou, S., E. L. Morse, A. R. Syme, A. Yuen, J. Channell, and H. R. Jansen. 2013. *Energy Darwinism: The Evolution of the Energy Industry*. Citibank. www.citi.com/citigps.
- Sherman, S. B., Z. P. Cano, M. Fowler, and Z. Chen. 2018. "Range-Extending Zinc-Air Battery for Electric Vehicle." *Aims Energy* 6 (1): 121–45.
- Standridge, C. R., and M. M. Hasan. 2015. "Post-Vehicle-Application Lithium-Ion Battery Remanufacturing, Repurposing and Recycling Capacity: Modeling and Analysis." *Journal of Industrial Engineering and Management* 8 (3): 823–39.
- Tan, R. B. H., and H. H. Khoo. 2005. "An LCA Study of a Primary Aluminum Supply Chain." *Journal of Cleaner Production* 13 (6): 607–18.
- Teske, S., N. Florin, E. Dominish, and D. Giurco. 2016. *Renewable Energy and Deep-Sea Mining: Supply, Demand and Scenarios*. Sydney: Institute for Sustainable Futures.
- Timperley, J. 2018. "Q&A: Why Cement Emissions Matter for Climate Change." Emissions, Climate Brief, September 13. <https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change>.
- Tokimatsu, K., M. Höök, B. McLellan, H. Wachtmeister, S. Murakami, R. Yasuoka, and M. Nishio. 2018. "Energy Modeling Approach to the Global Energy-Mineral Nexus: Exploring Metal Requirements and the Well-Below 2°C Target with 100 Percent Renewable Energy." *Applied Energy* 225: 1158–75.
- Tsai, L., J. C. Kelly, B. S. Simon, R. M. Chalat, and G. A. Keoleian. 2016. "Life Cycle Assessment of Offshore Wind Farm Siting: Effects of Locational Factors, Lake Depth, and Distance from Shore." *Journal of Industrial Ecology* 20 (6): 1370–83.
- Tsiropoulos, I., D. Tarvydas, and N. Lebedeva. 2018. *Li-Ion Batteries for Mobility and Stationary Storage Applications Scenarios for Costs and Market Growth*. Luxembourg: Publications Office of the European Union.

- UNEP (United Nations Environment Programme). 2011. *Recycling Rates of Metals: A Status Report*. A Report of the Working Group on the Global Metal Flows to the International Resource Panel, United Nations Environment Programme. Written by T. E. Graedel, J. Allwood, J. P. Birat, B. K. Reck, S. F. Sibley, G. Sonnemann, M. Buchert, and C. Hagelüken. Nairobi: UNEP.
- USGS (U.S. Geological Survey). 2018. Mineral Commodity Summaries 2018. U.S. Geological Survey, Reston, Virginia.
- Vargi, A., R. Raccichini, S. Passerini, and B. Scrosati. 2016. "Challenges and Prospects of the Role of Solid Electrolytes in the Revitalization of Lithium Mineral Batteries." *Journal of Materials Chemistry A* 4 (44): 17251–59.
- E. van der Voet, , L. van Oers, M. Verboon, and K. Kuipers. 2019. "Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals." *Journal of Industrial Ecology* 23 (1): 141–55.
- Wade, L. 2016. "Tesla's Electric Cars Aren't as Green as You Might Think." *Wired*, March 31. <https://www.wired.com/2016/03/teslas-electric-cars-might-not-green-think/>.
- World Bank. 2017. *The Growing Role of Minerals and Metals for a Low Carbon Future*. Washington, DC: World Bank.
- . 2019. *Climate-Smart Mining: Minerals for Climate Action*. Washington, DC: World Bank. <https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action>.
- WSA (World Steel Association). 2020. "Steel's Contribution to a Low Carbon Future and Climate Resilient Societies." Position paper. World Steel Association, Brussels, Belgium.
- Ziemann, S., D. B. Müller, L. Schebek, and M. Weil. 2018. "Modeling the Potential Impact of Lithium Recycling from EV batteries on Lithium Demand: A Dynamic MFA Approach." *Resources, Conservation and Recycling* 133: 76–85.



Climate **Smart** Mining