

Minerals for Climate Action:

The Mineral Intensity of the
Clean Energy Transition

CLIMATE-SMART MINING FACILITY

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Climate **Smart** Mining

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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.



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World Bank

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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.

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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.



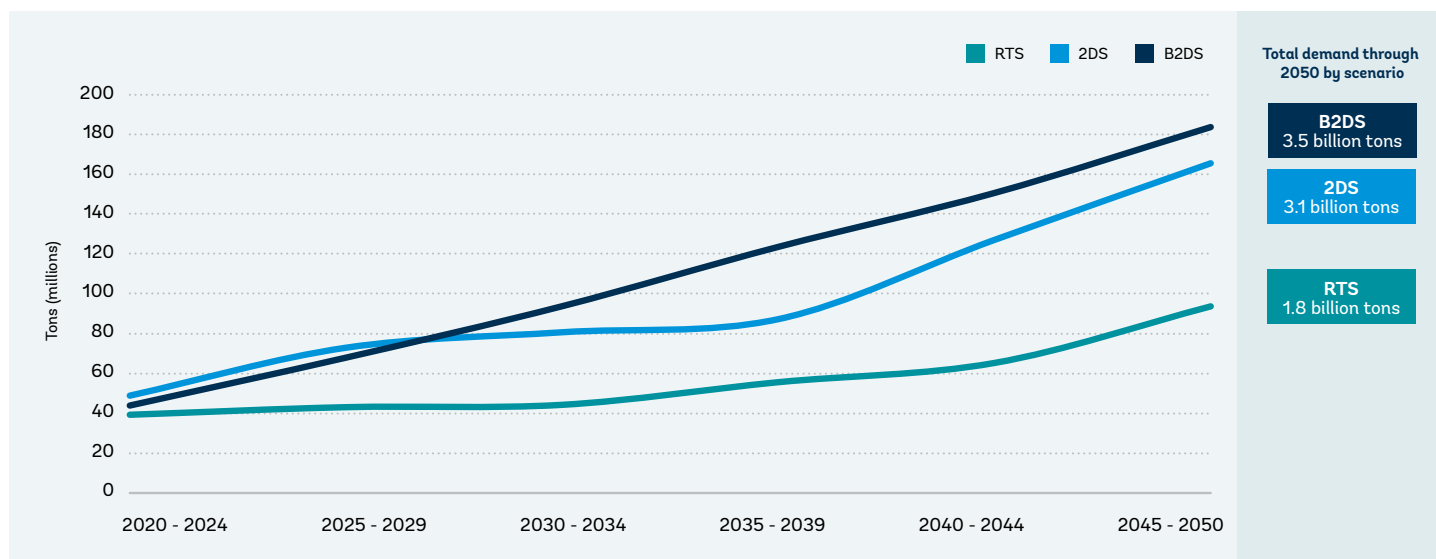
Executive Summary

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.

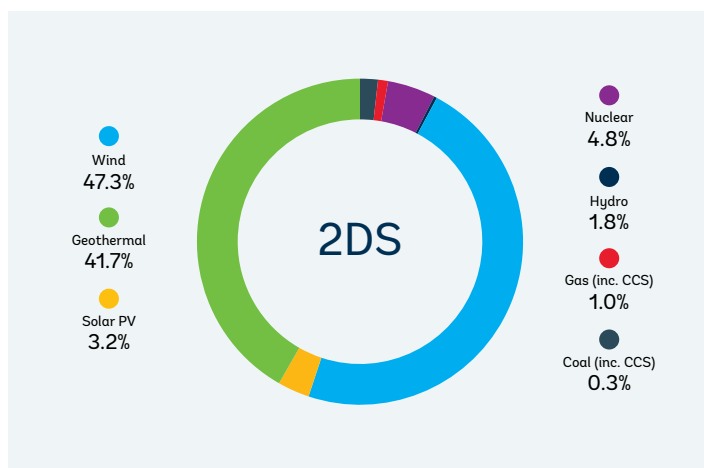
2. Each mineral carries a different demand risk depending on whether it is cross-cutting (needed across a range of low-carbon technologies) or concentrated (needed in one specific technology). Absolute production numbers and relative increases in demand for each mineral may also play a role in their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



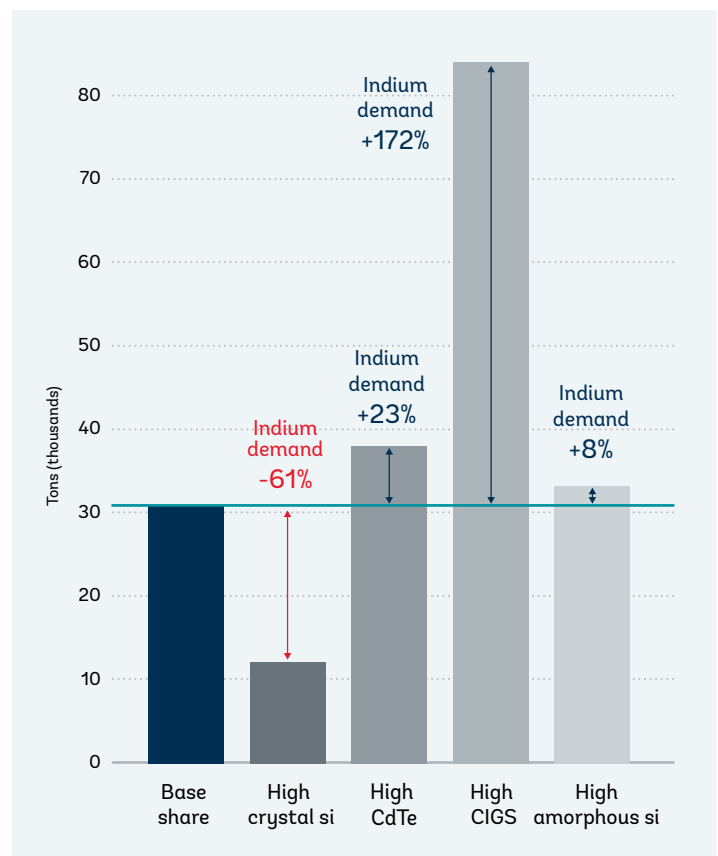
Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, PV = photovoltaic.

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



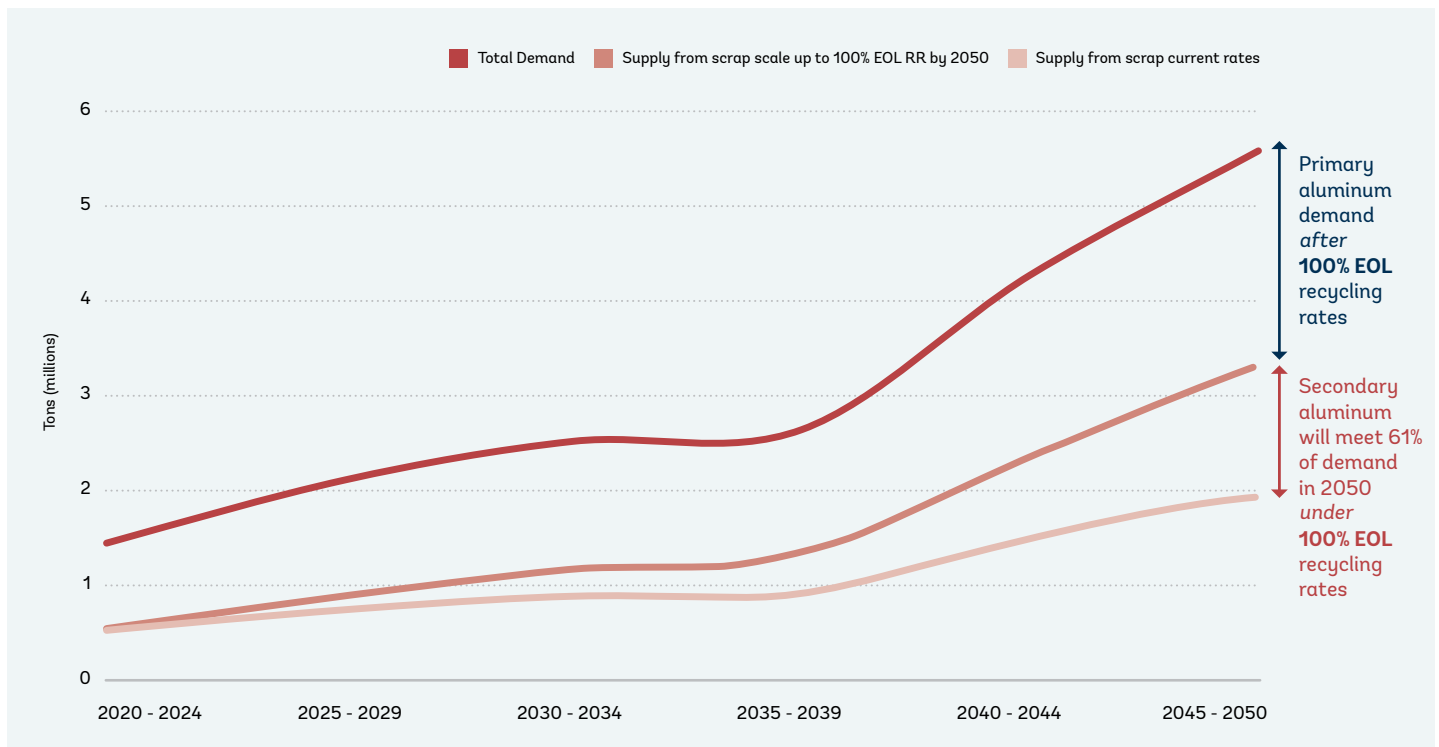
Note: 2DS = 2-degree scenario, amorphous Si = amorphous silicon, CdTe = cadmium telluride, CIGS = copper indium gallium selenide, crystal Si = crystalline silicon, PV = photovoltaic.

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



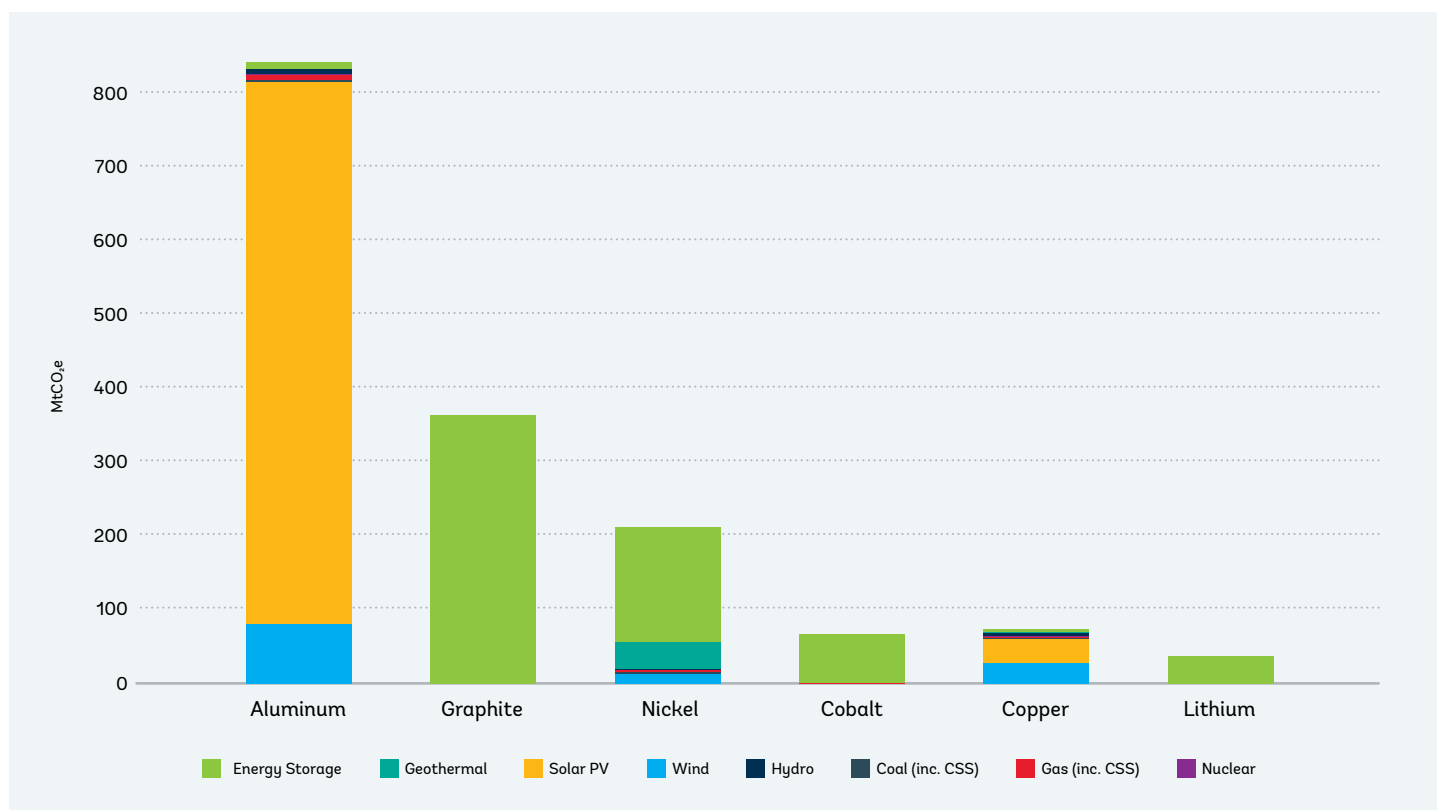
Note: EOL recycling rates are assumed to increase annually to meet 100 percent EOL by 2050. This means that secondary aluminum meets an increasing amount of aluminum demand over time. 2DS = 2-degree scenario, EOL = end of life, RR = recycling rates.

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.



