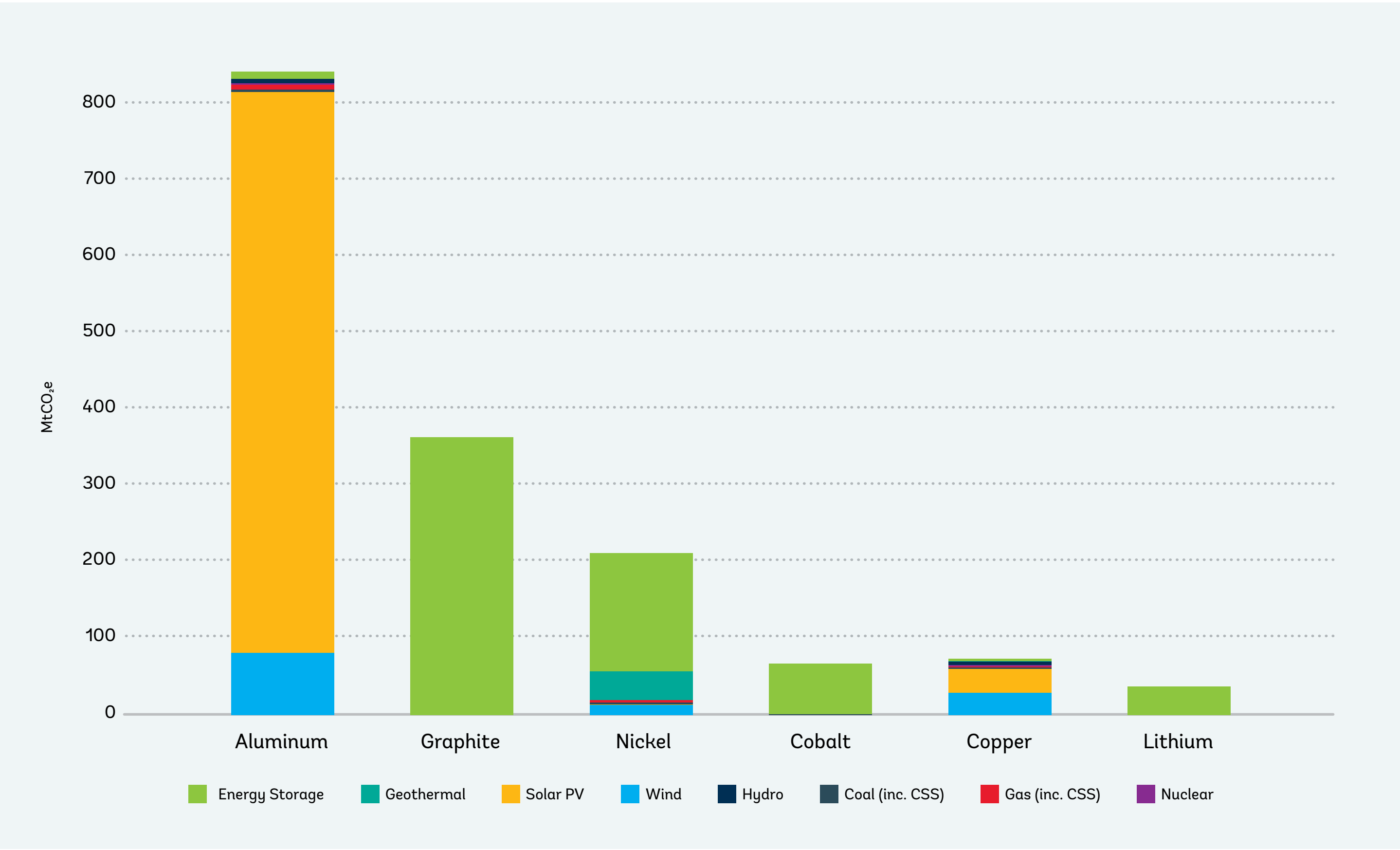
Figure 5.3 Cumulative GWP from Extraction and Processing of Minerals, Not Including Operations, Using Cradle-to-Gate Through 2050 Under 2DS



Note: 2DS = 2-degree scenario, CCS = carbon capture and storage, CSP = concentrated solar power, GWP = global warming potential, $MtCO_2e$ = 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 $GtCO_2e$, 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 $MtCO_2e$, representing 73 percent of total nickel emissions from energy technologies—while it accounts for 100 percent of graphite's carbon footprint equivalent (363 $MtCO_2e$).

As a cross-cutting mineral, copper is used across all energy technologies, with a total carbon footprint of 74 $MtCO_2e$ 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 dissembled 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 dissembled, 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

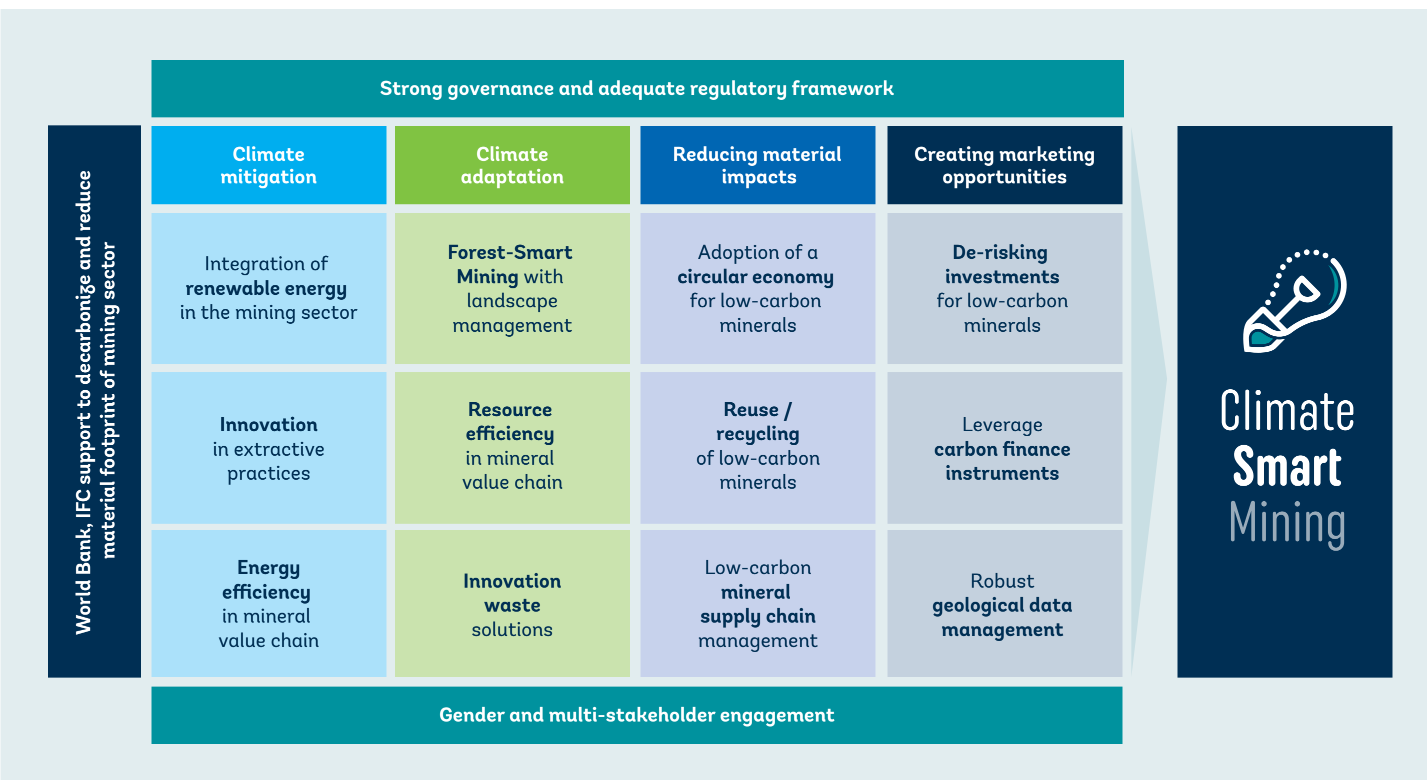
The Climate-Smart Mining Initiative will help resource-rich developing countries benefit from the increasing demand for minerals and metals, while ensuring the mining sector is managed in a way that minimizes its environmental and climate footprints.[57]

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 CO_2 (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 $MtCO_2e$ to 550 $MtCO_2e$ under the 2DS (reducing to 454 $MtCO_2e$ 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 CO_2 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.

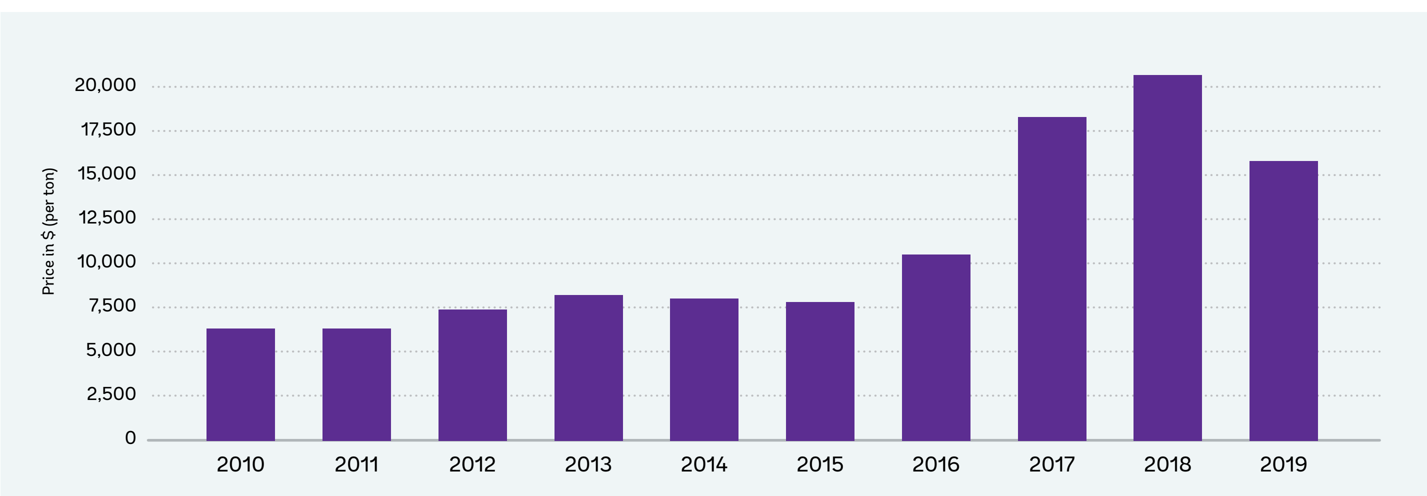
Higher levels of demand for commodities could lead to higher prices, which induce two major effects: (1) Those involved in the extraction and production of commodities increase their supply, and (2) those demanding those minerals are incentivized to reduce their use in their products, either by substituting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

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