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 or 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

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

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.

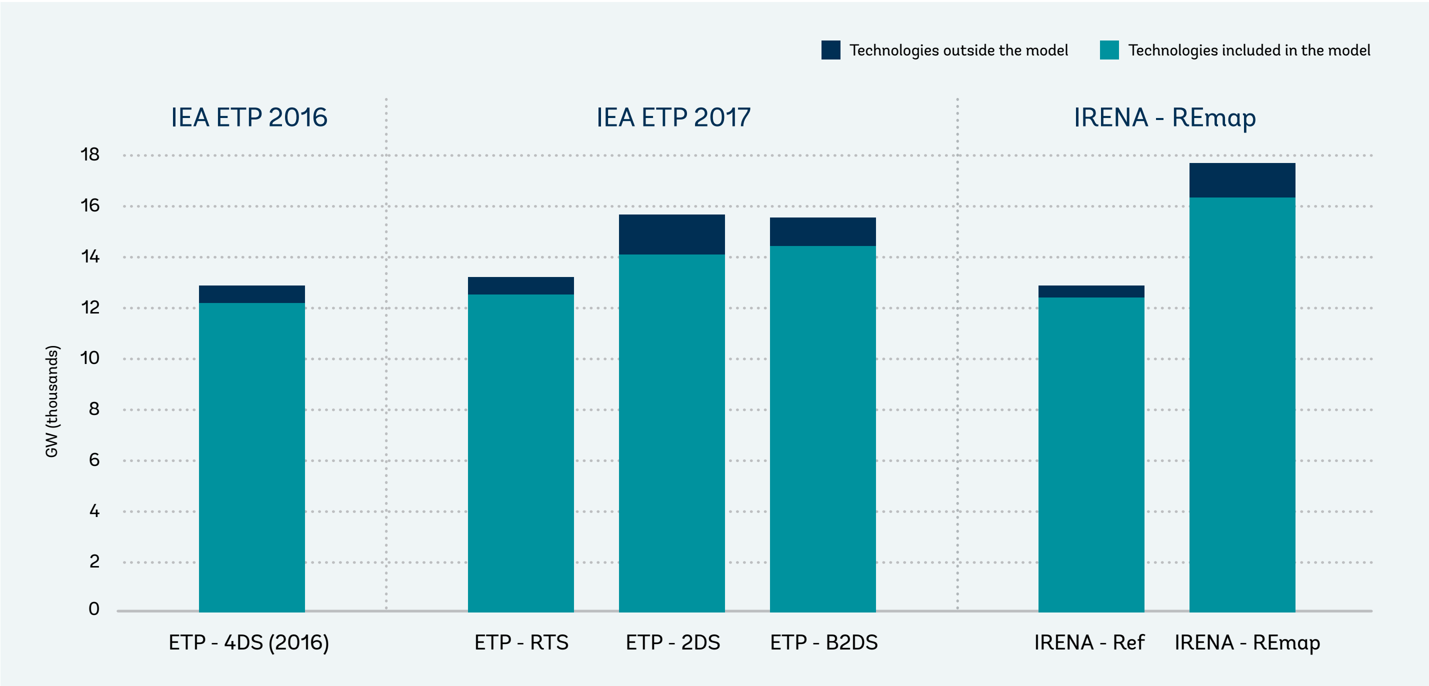
The IEA and IRENA also hold the view that the state of technology capacity is already sufficient to meet even the most ambitious of the global temperature scenarios. That said, neither agency speculates on the relative availability of the materials required to actually implement that scale of low-carbon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

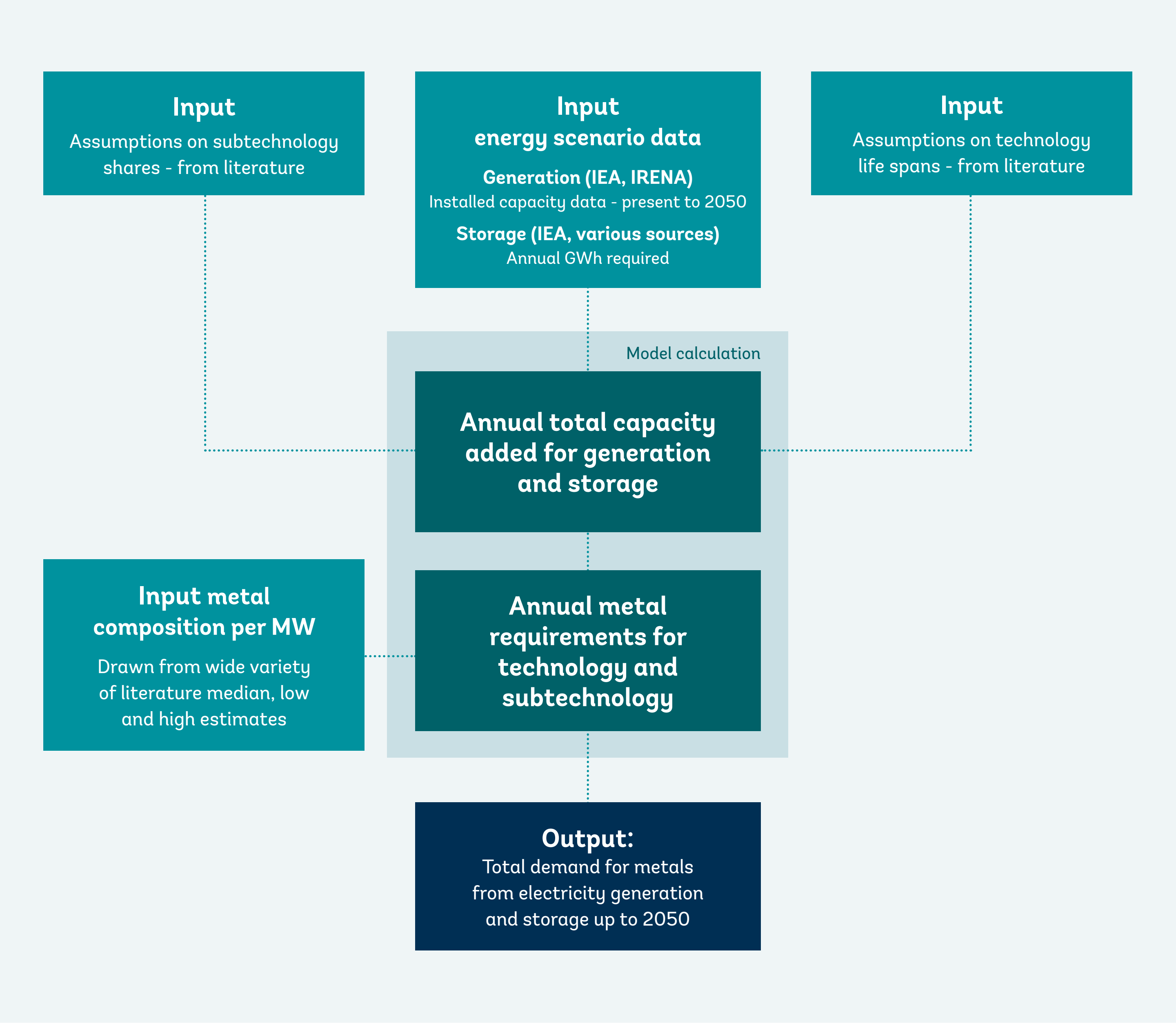
Modeling Inputs

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 ($GtCO_2$) being produced in the base scenario up to 2050, while moving to a 2DS involves an extra 6 $GtCO_2$ from building and operating renewable technologies, but it reduces emissions from fossil fuel generation by over 350 $GtCO_2$.

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.

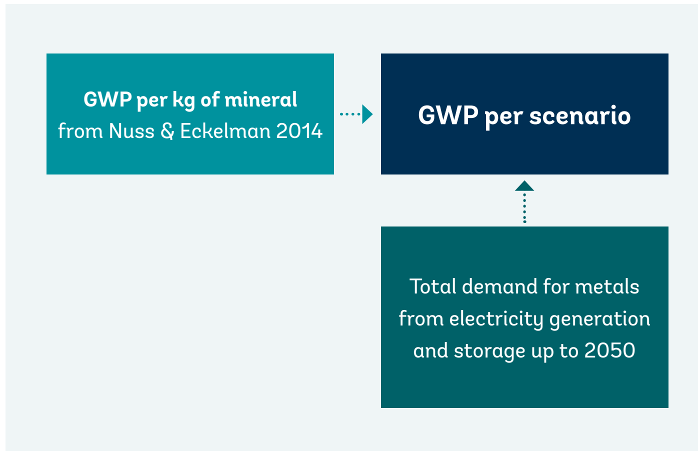
With respect to the specific minerals and metals covered in this study, the model draws on data from a paper by Nuss and Eckelman (2014). This paper gives consistent estimates of the amount of GWP of minerals in terms of carbon dioxide equivalent (CO_2e) from the direct and indirect emissions (for example, 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.

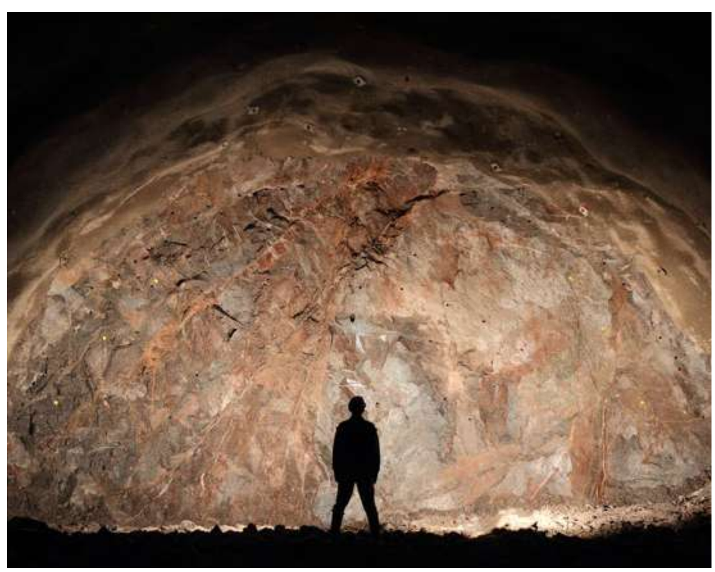
are considerable. For example, aluminum is used in solar PV for the frames; however, this service could be provided by synthetic or composite materials—and if or when aluminum is replaced, demand for that mineral could fall considerably.

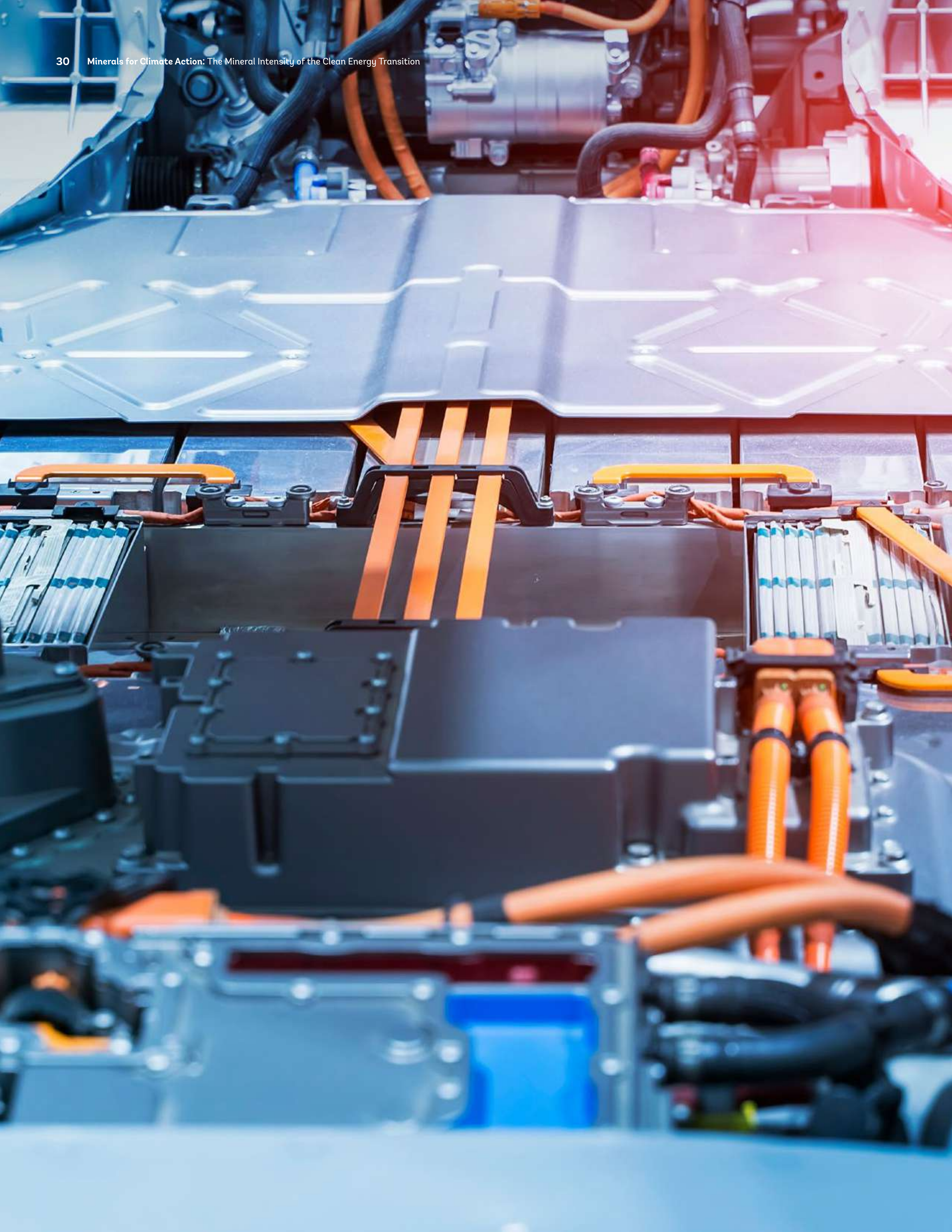
The second aspect of uncertainty relating to the share and scale of energy technology penetration is captured by the use of various scenarios. Different scenarios from the IEA are used to capture the impact of wider deployment of low-carbon energy technologies. The four IEA scenarios are used to highlight 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 $GtCO_2e$ (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**

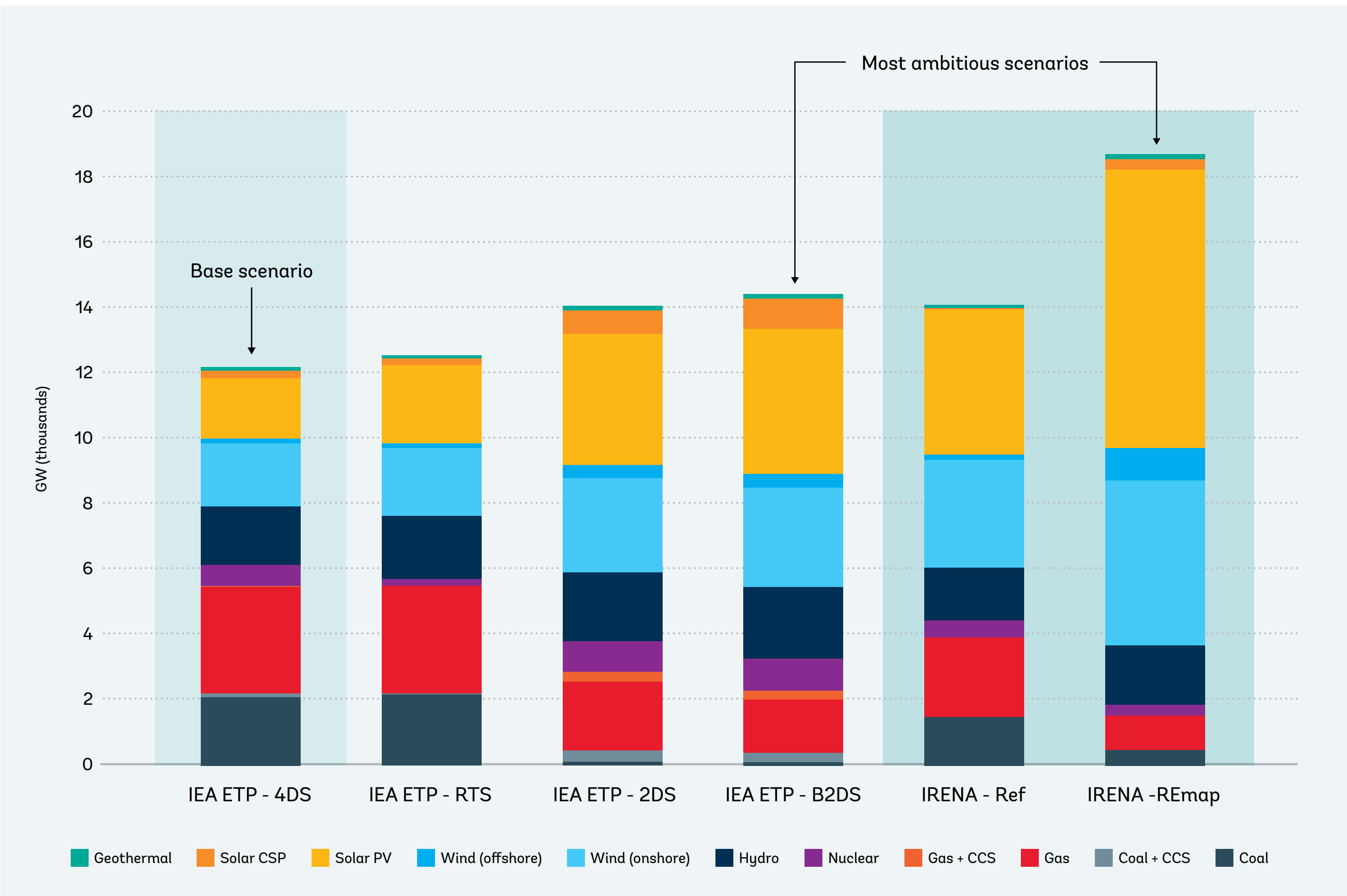
Note: 2DS = 2-degree scenario, 4DS = 4-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, NDC = Nationally Determined Contribution, Ref = reference scenario, REmap = renewable energy roadmap scenario.

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.

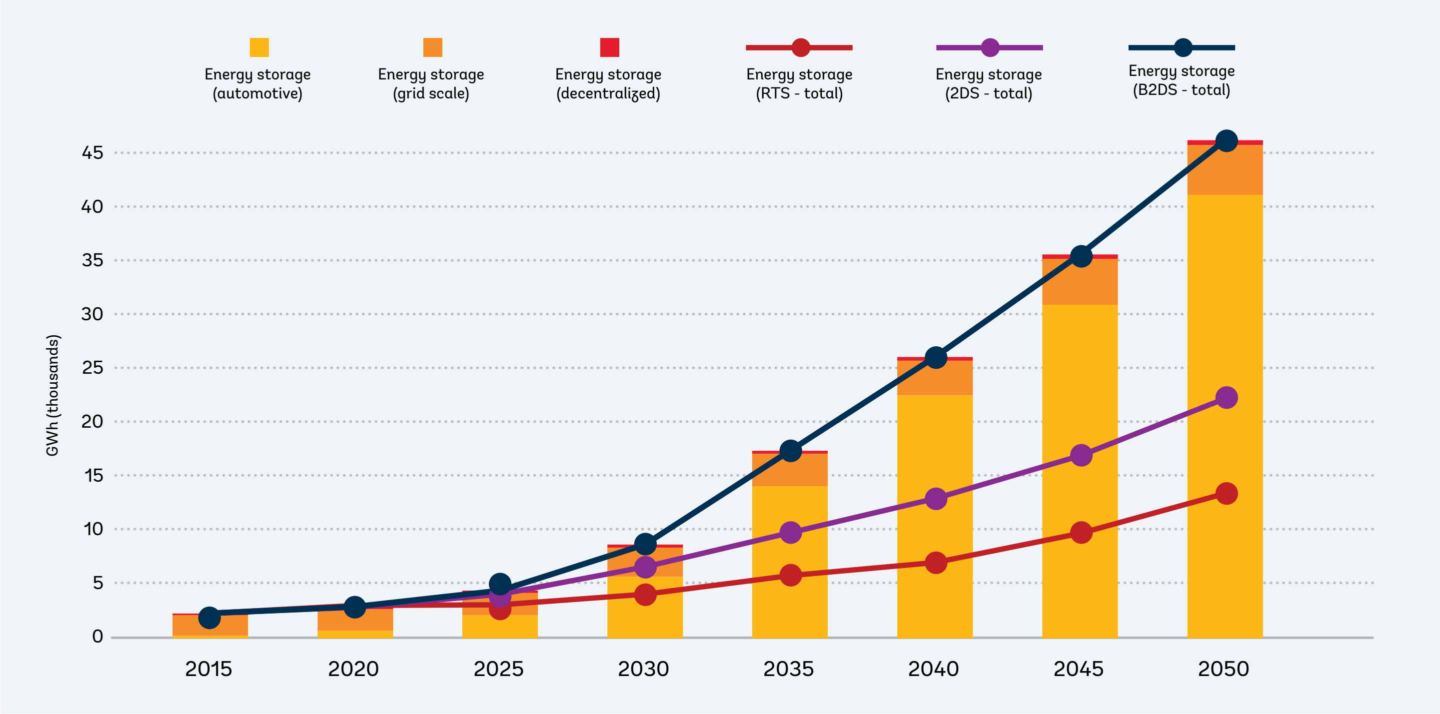
Energy Storage Projections

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.