Mineral Intensity of Clean Energy Technologies

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

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

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

As mentioned in chapter 1, the new infrastructure required to support a low-carbon transition has not been addressed, nor have other clean energy options, such as hydrogen-based vehicles, where platinum would play a key role. The need to connect some 840 million people without electricity access today as well as build the motors and chassis to electrify 135 million electric vehicles that are expected to come online in the next 10 years to decarbonize the transportation sector (IEA 2019b) are examples of new energy infrastructure that also have not been captured in this analysis. Additionally, the materials needed to install these low-carbon technologies, such as cement to stabilize wind turbines' installation, have not been addressed in this analysis.

Table 3.1 Mapping Minerals with Relevant Low-Carbon Technologies

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

Solar Photovoltaic

Solar photovoltaic (PV) has been the most rapidly deployed renewable energy technology globally, with installed capacity reaching 485 GW in 2018 (IRENA 2019b), outpacing all other technologies in growth between 2017 and 2018, growing by 24 percent. The high learning rate[15] of solar PV (22–40 percent) has resulted in dramatic cost reductions, with the global-weighted average levelized cost of energy (LCOE) falling by 77 percent between 2010 and 2018 (IRENA 2019c), making it one of the most attractive technologies for renewable energy investors worldwide.

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

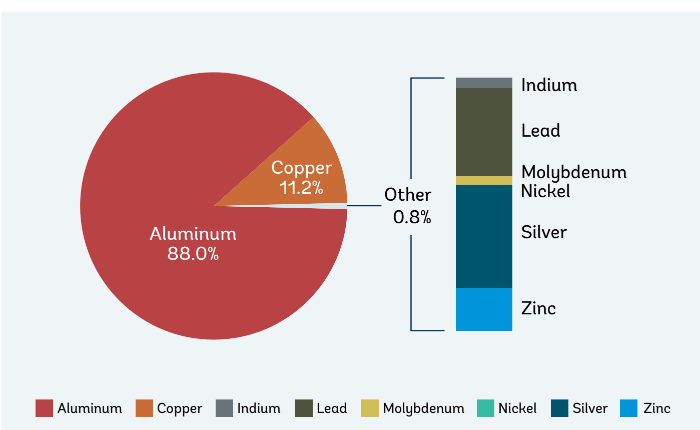
Four widely used solar PV subtechnologies are represented in this analysis:

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

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

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

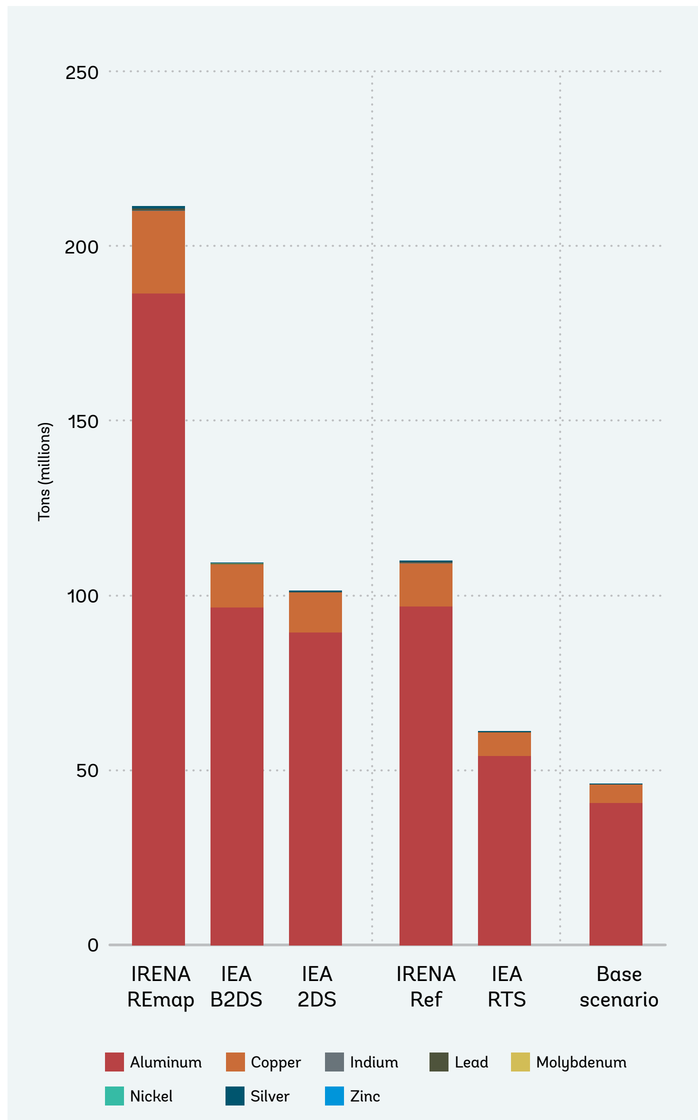
Figure 3.1 Share of Mineral Demand from Solar Photovoltaic Under the IEA 2DS Through 2050



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

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

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

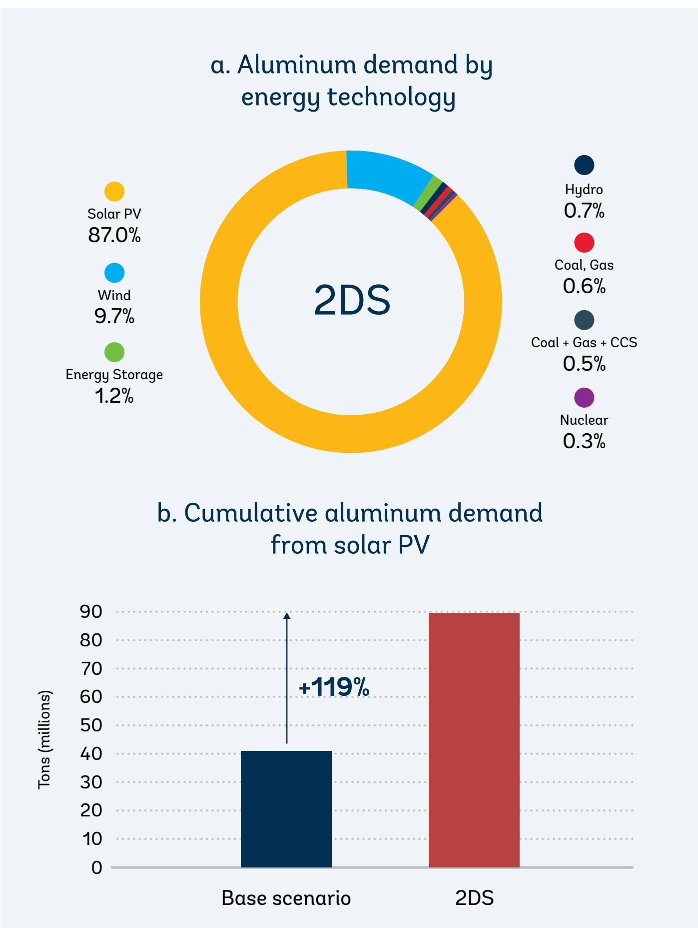


Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap = renewable energy roadmap scenario, RTS = reference technology scenario.

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

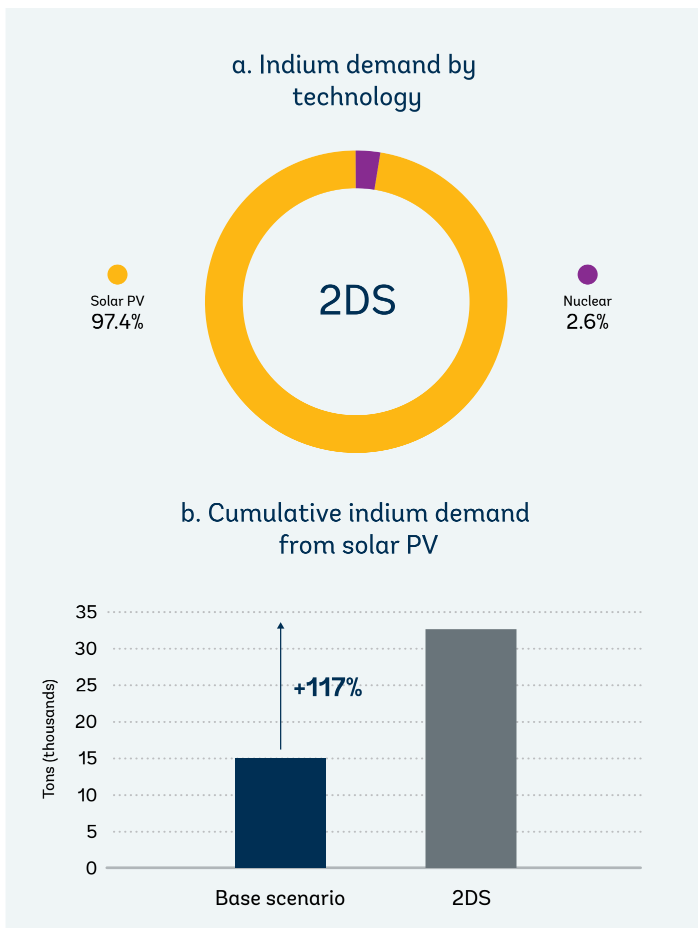
Indium is another critical element that is used almost exclusively for solar PV. Figure 3.4 shows the cumulative demand for indium by technology. The vast majority of indium (97 percent) is used in solar PV, predominantly in CIGS solar cells, with the remaining 3 percent used in nuclear power. The relative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

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



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

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



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

Trade-Offs in Solar PV Subtechnologies

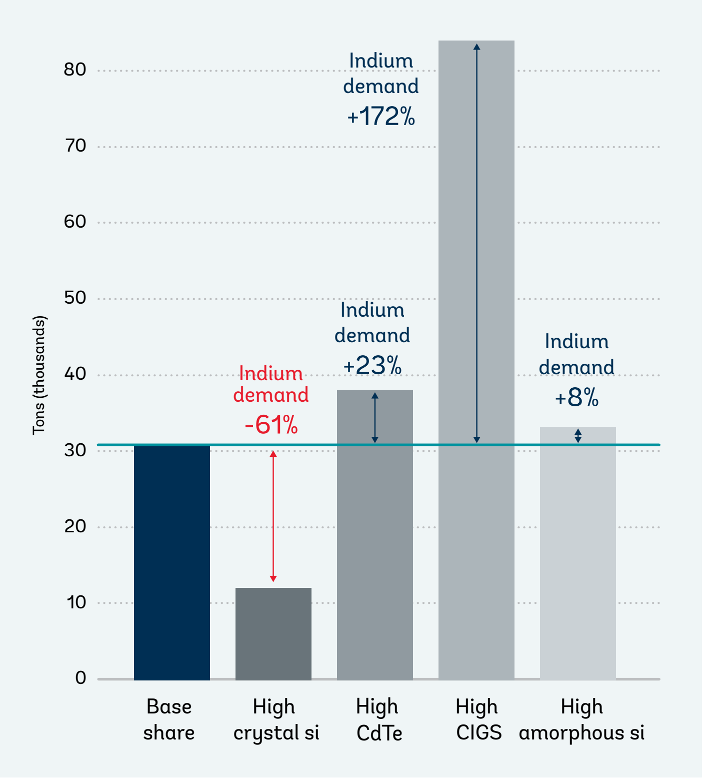
There are trade-offs in mineral demand from solar PV technology, depending on which subtechnologies end up being deployed most through 2050. Each technology for constructing solar PV cells has distinct advantages and disadvantages, as well as differing mineral content.

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

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

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

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



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

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

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

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

Wind

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

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

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

Figure 3.6 Evolution of the Wind Turbine

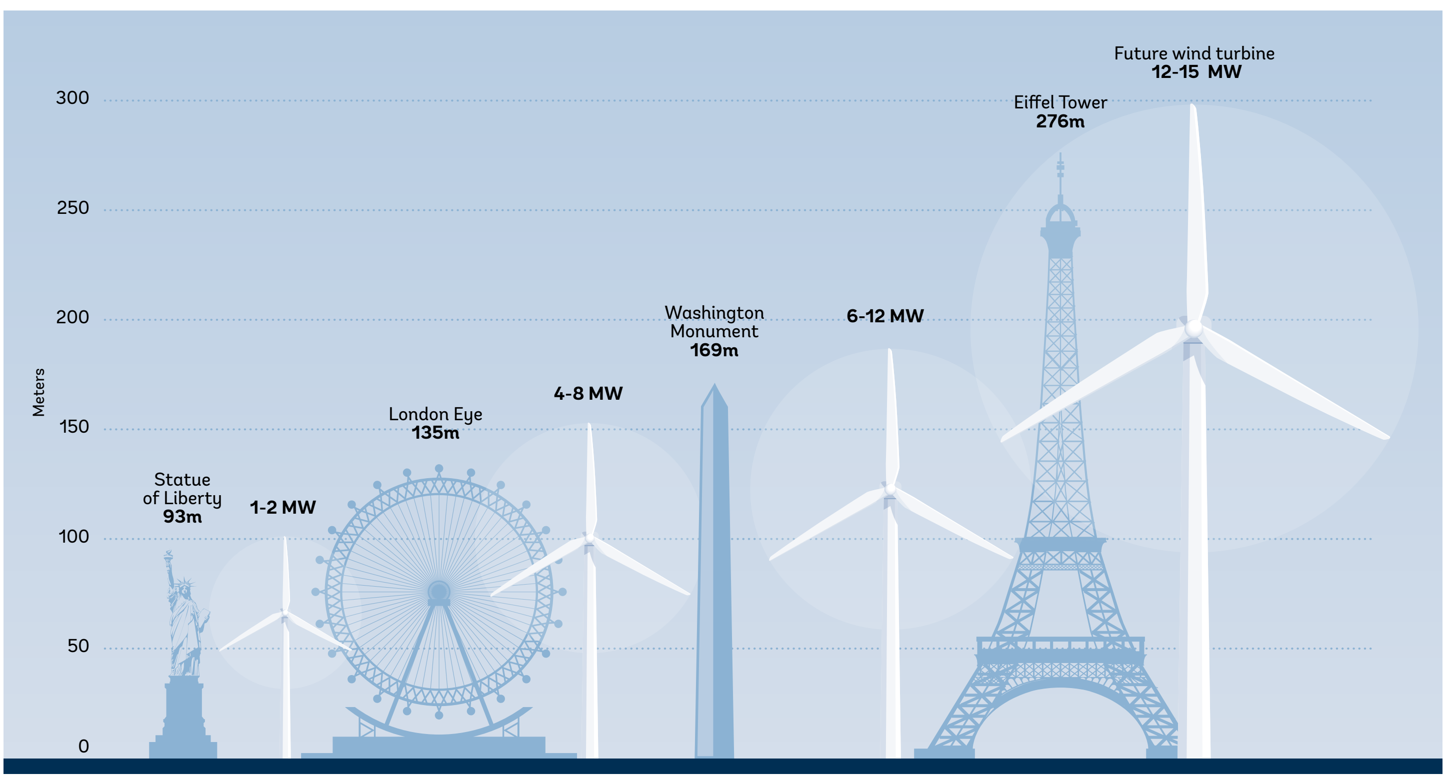


Illustration adapted from various sources (for example, https://www.researchgate.net/figure/Evolution-of-wind-turbine-size-and-output-Liebreich-2017_fig3_331249559; Power Technology, https://www.power-technology.com/features/haliade-x-look-ges-supersized-new-wind-turbine/attachment/ge-infographic-1-haliade-x/).

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

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

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

1. **Geared turbines** make up roughly 80 percent of global installed capacity. These "Danish design" machines use a gearbox to convert the relatively low rotational speed of the turbine rotor (12–18 rpm) to a much higher speed (1,500 rpm) for input to a generator. The vast majority of these generators are double-fed induction generators, which use significant amounts of copper and iron. Geared turbines have achieved a very low cost with a high level of reliability, although they generally require more frequent maintenance because of the higher number of moving parts relative to their direct-drive counterparts.

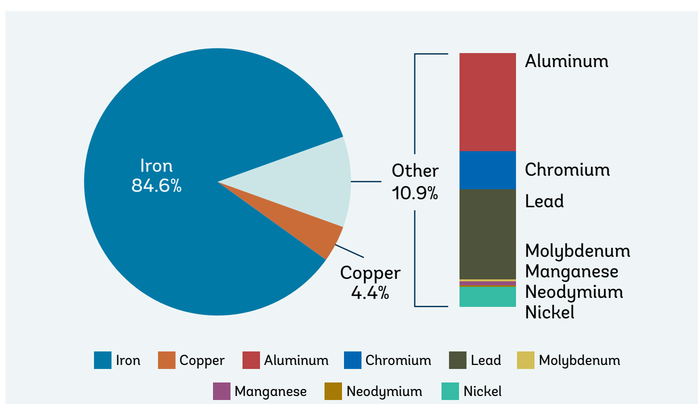
2. **Direct drive wind turbines** feature generators that are fixed directly to the rotor and therefore turn at the same speed. Certain models (for example, those produced by Goldwind) employ a generator with permanent magnets consisting of rare earth minerals such as neodymium and dysprosium. Other models (for example, those produced by Enercon) use an electrically excited rotor utilizing significant amounts of copper. Direct-drive turbines tend to be initially more expensive per megawatt, although this can be offset by lower maintenance during the turbine's operation.

In general terms, geared turbines tend to dominate onshore installations, where maintenance is relatively straightforward. Conversely, direct-drive turbines are preferred in offshore wind applications, where maintenance is much more challenging. The difference in how these subtechnologies are deployed between onshore and offshore wind has implications in how the model derives mineral demand from wind technologies.

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

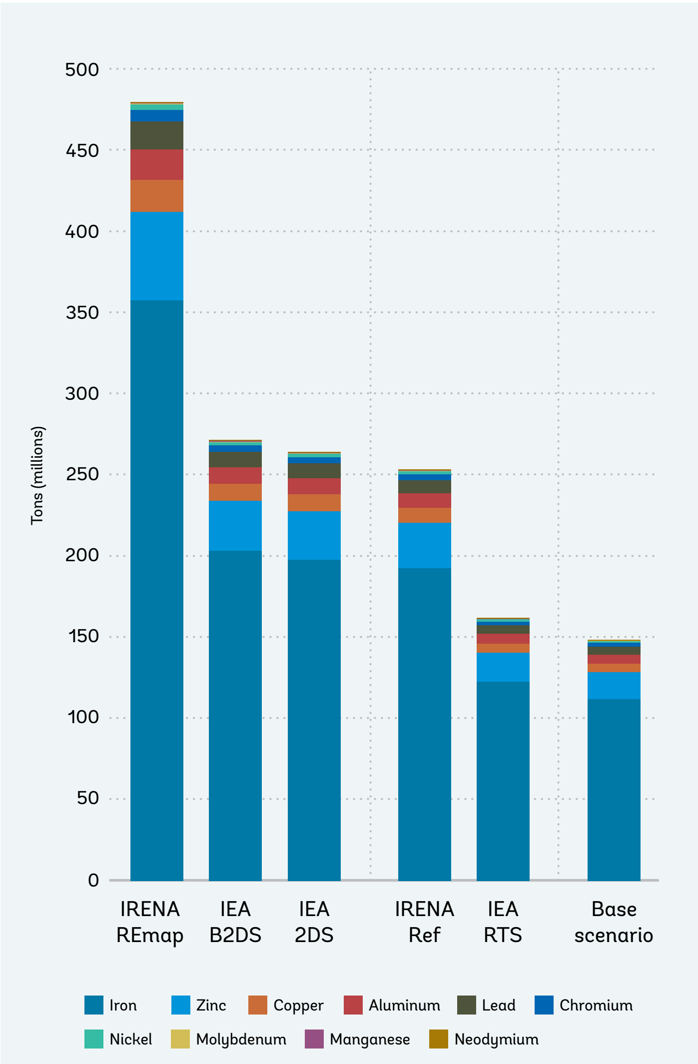
Figure 3.7 shows the major minerals used to supply wind installations through 2050, with iron accounting for 84.6 percent of demand and copper 4.4 percent. Note, the iron reported here is that which is used directly in the turbine, in either the generator core, the mainframe, or the rotor hubs; it does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

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



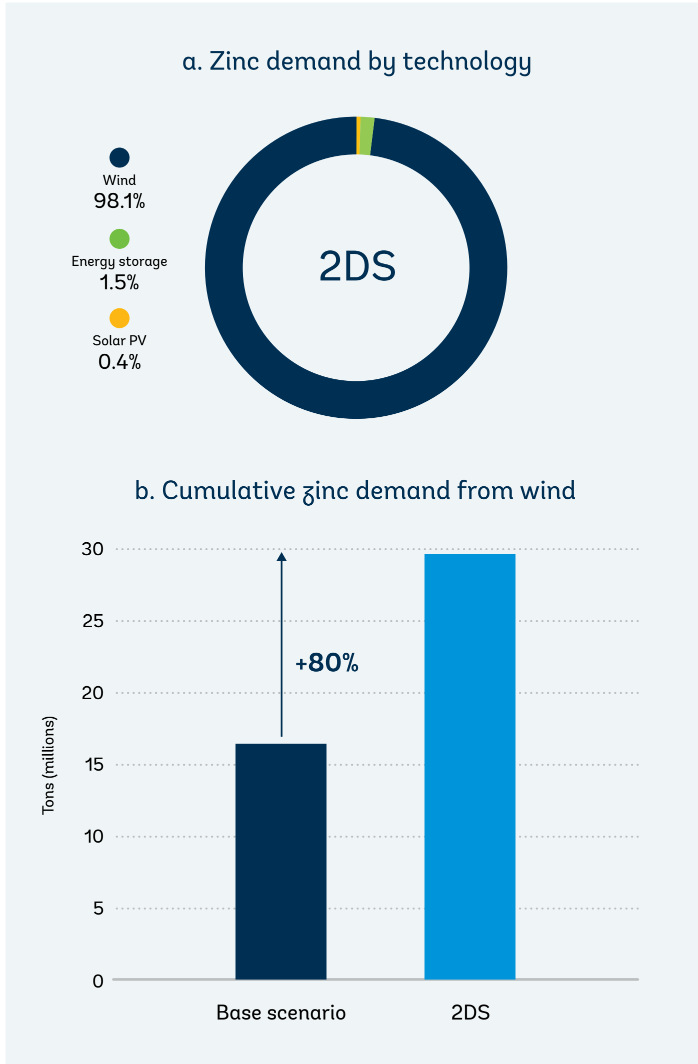
Note: 2DS = 2-degree scenario, IEA = International Energy Agency.

Figure 3.8 Cumulative Demand for Minerals Needed for Wind Through 2050



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

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



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

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

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

Trade-Offs in Wind Subtechnologies

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

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

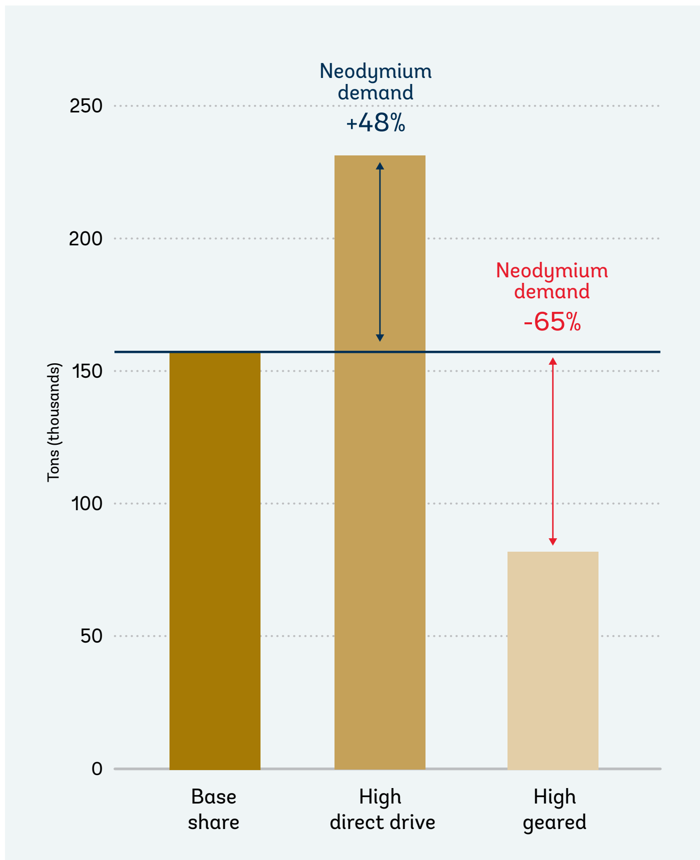
The first scenario has a higher share of direct-drive turbines,[16] rising to 40 percent of onshore turbines and 90 percent of offshore turbines by 2050, compared with 25 percent and 75 percent in the mixed base scenario. The second scenario has higher shares of geared turbines, accounting for 90 percent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

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

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

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

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



Note: 2DS = 2-degree scenario.

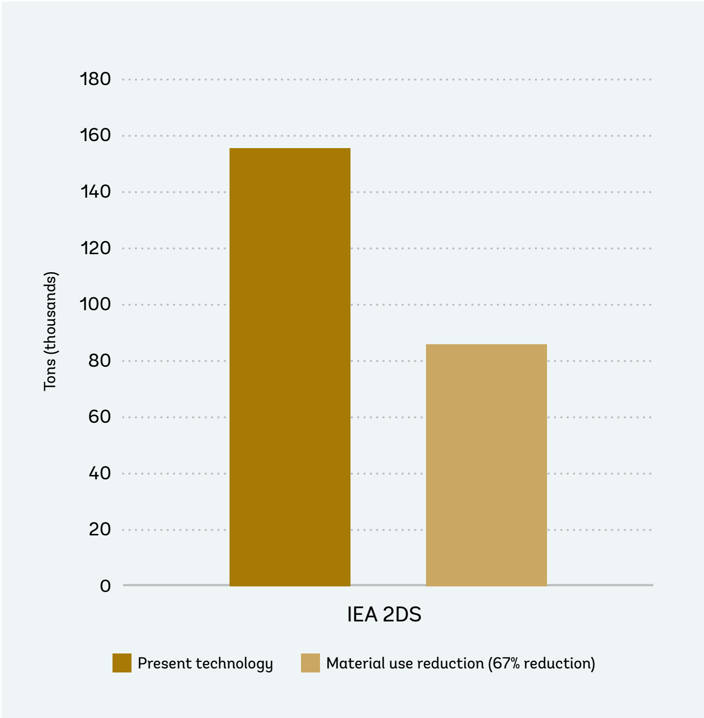
16 It should be noted that not all direct-drive turbines use permanent magnets and thus demand neodymium. Data on the neodymium concentration in direct-drive turbines are drawn from a number of sources in the literature and a central point was used. The substitution between different direct-drive turbines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

Material Use Improvements in Wind Turbines

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

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

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



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

Geothermal

Geothermal energy currently accounts for less than 1 percent of global electricity generation capacity (IEA 2019c) and is actively being used in more than 20 countries;[17] the United States is the world's largest producer, at about 2.5 GW in 2018.[18] Geothermal energy can be used for electricity generation, direct or indirect use, or co-generation. There are limitations with the use of geothermal energy since electricity can only be generated in locations with high or medium temperatures, typically close to tectonically active regions.[19] Countries such as Indonesia, Iceland, the Philippines, and New Zealand—countries in tectonically active regions—actively use geothermal to meet their electricity needs. Indonesia recently announced a plan to build 7.2 GW of geothermal by 2025 given its comparative advantage in this resource to meet its growing energy demand.[20]

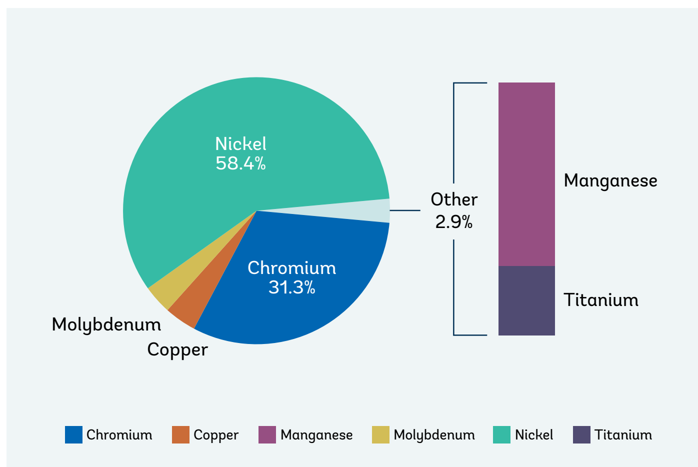
Geothermal generates electricity from thermal energy located below the earth's surface, whether in liquid, trapped steam, or rock. Therefore, geothermal requires a very high level of quality steel to be able to carry reservoirs of steam and hot water for electricity generation. Corrosion-resistant alloys,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

Geothermal uses relatively more steel than wind, approximately 6–10 times as much per megawatt of capacity. Unlike wind—which also requires a large amount of steel, primarily manufactured from a mix of nickel and iron ore—geothermal requires steel alloys with a large quantity of titanium to cope with the high heat and pressure in geothermal power generation. Literature on geothermal production is more limited than for wind and solar PV, and given that a large share of mineral demand for the technology comes from the use of elements to create various alloys of steel, steel has, again, been excluded from this analysis to avoid double-counting.

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

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

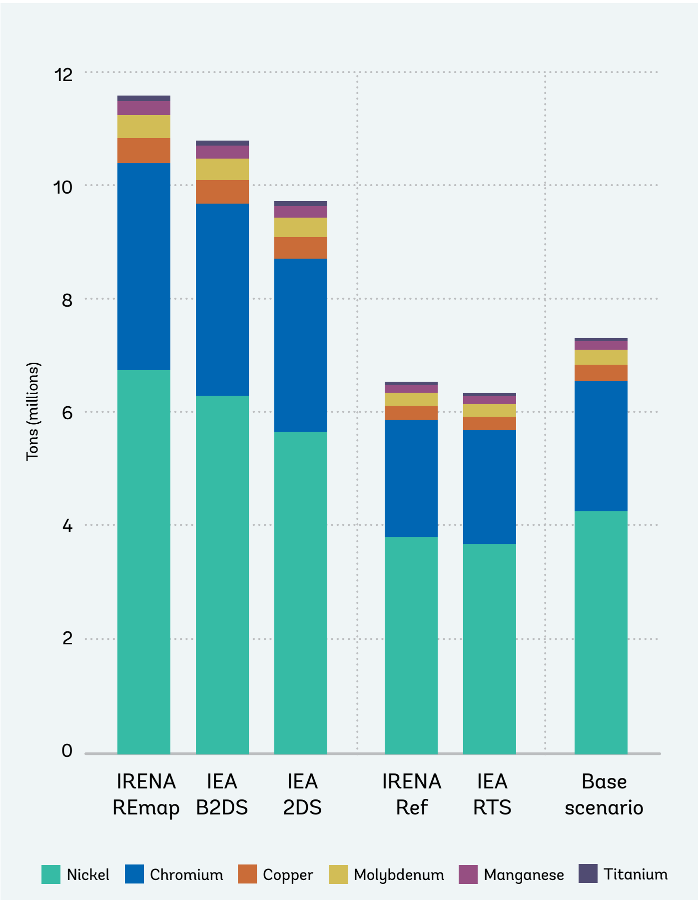
Figure 3.12 Share of Mineral Demand from Geothermal Under 2DS Through 2050



Note: 2DS = 2-degree scenario.

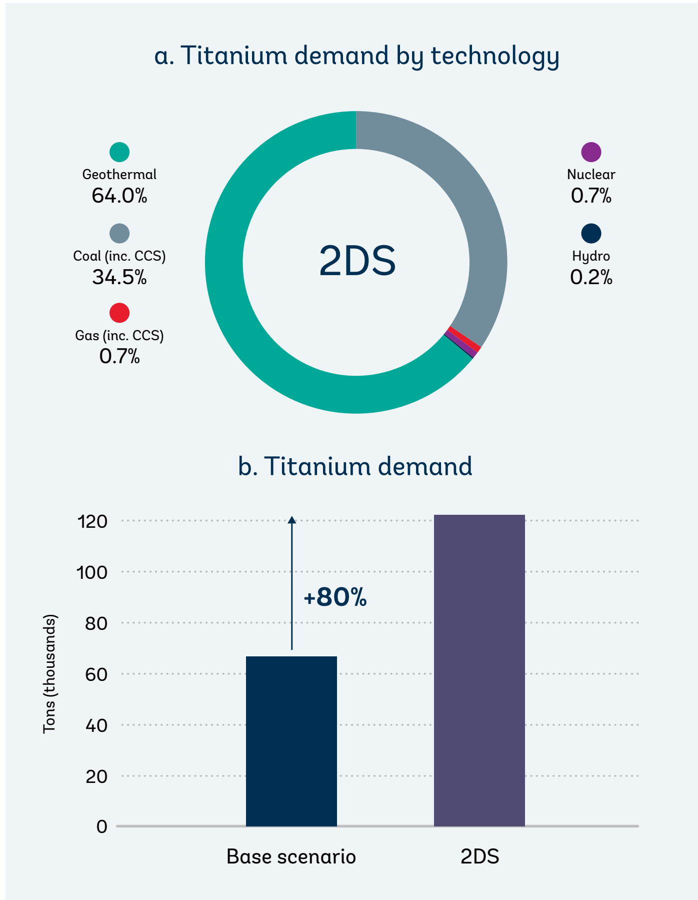
17 "Geothermal Energy," National Geographic, https://www.nationalgeographic.com/environment/global-warming/geothermal-energy/.
18 "Geothermal Energy," International Renewable Energy Agency, https://www.irena.org/geothermal.
19 Ibid.
20 "Indonesia Needs $15 Billion Investment to Meet Geothermal Target by 2025," Reuters, August 13, 2019, https://www.reuters.com/article/us-indonesia-geothermal/indonesia-needs-15-billion-investment-to-meet-geothermal-target-by-2025-idUSKCN1V30R0.
21 Data used in the model is an average of three plants—a 50 MW facility with 25 wells at depth of 5 kilometers; a 10 MW facility with 5 wells 1.5 kilometers deep, and 48.4 MW facility with 22 wells 2.5 kilometers deep—and covers both plant facilities and well pipes (Moss et al. 2013).

Figure 3.13 Cumulative Demand for Minerals Needed for Geothermal Through 2050



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

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



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

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

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