The Growing Role of Minerals and Metals for a Low Carbon Future

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Abbreviations

2DS	2 degree scenario
4DS	4 degree scenario
6DS	6 degree scenario
CCS	carbon capture and storage
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CMI	Carbon Mitigation Initiative
CSP	concentrating solar power
CO_2	carbon dioxide
DDPP	Deep Decarbonization Pathways Project
GHG	greenhouse gas
GWh	gigawatt-hours
ICMM	International Council on Mining and Metals
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LEDs	Light Emitting Diodes
ppmv	parts per million by volume
PV	photovoltaic
SDG	Sustainable Development Goals
TWh	terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
WBG	World Bank Group

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Foreword

There is growing awareness that human activities are having a major impact on the earth's ecosphere—so much so that many are now defining a new geological era: the Anthropocene, a time when humans have become the driving force in the earth's physical changes. With the global human population expected to reach over 9 billion by 2050, urbanization, access to energy, infrastructure development, and poverty reduction will result in an unprecedented strain on our planet's natural resources and environment. Given the long-term risk this presents for development, the World Bank continues to champion an integrated approach for sustainable development, including low carbon development strategies, renewable energy, and resilient cities and landscapes.

As part of the transition to a low carbon economy, we are already seeing a remarkable growth in renewable energy technologies, now accounting for about 17% of global energy consumption. The need to meet future energy demands, while striving for a low carbon future, is not however immaterial.

An impressive range of analysis covering the science and viability of response measures, including both adaptation to the impacts of climate change and measures to mitigate Greenhouse Gas (GHG) emissions, was undertaken when more than 170 countries signed on to the Paris Agreement on Climate Change in 2015. Mitigation issues typically covered the economic, policy, technology, and sustainability implications of reducing GHG emissions. However, relatively little analysis was conducted on the material implications of a carbon-constrained future.

This is why it is important to explore and analyze the implications of the rapid uptake of climate-friendly technologies for commodity demand and the mineral resources required to manufacture these new technologies.

With the release of *"The Growing Role of Minerals for a Low Carbon Future,"* the World Bank is contributing towards ensuring that this topic is given its rightful place in understanding the implications of a carbon constrained future.

Based on climate and technology scenarios developed out of the International Energy Agency's (IEA) Energy Technology Perspective, the Bank developed a set of commodities demand projections up to 2050. We did so by providing best estimates on the level of uptake of three discrete climate-friendly technologies—wind, solar, and energy storage batteries—required to help meet three different global warming scenarios of 2°C, 4°C, and 6°C.

"The Growing Role of Minerals for a Low Carbon Future" is intended to spark a more focused and coherent dialogue around the opportunities and challenges for the mining and metals industry in a carbon-constrained future. Certainly there are many technology-related issues that await further analysis, including analyzing the impact on mineral demand on a broader scope of carbon-constrained technologies than are studied in this report and the impact of recycling on extractives.

Another benefit of this analysis was to provide a critical space for opening a dialogue between the climate, clean energy, and extractive industries constituencies. For too long the dynamic between these groups has been predominated by polarization and characterizations that have turned out to be self-defeating, particularly when it comes to developing coherent climate and sustainable development policies that are effectively aligned with a given country's development plans. This lesson now needs to be communicated and integrated at the national level: mineral resource development as a complement and not competitor, to a greener, more sustainable future.

—**Riccardo Puliti**
Senior Director and Global Head
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Executive Summary

Climate and greenhouse gas (GHG) scenarios have typically paid scant attention to the metal implications necessary to realize a low/zero carbon future. The 2015 Paris Agreement on Climate Change indicates a global resolve to embark on development patterns that would significantly be less GHG intensive. One might assume that nonrenewable resource development and use will also need to decline in a carbon-constrained future. This report tests that assumption, identifies those commodities implicated in such a scenario and explores ramifications for relevant resource-rich developing countries.

Using wind, solar, and energy storage batteries as proxies, the study examines which metals will likely rise in demand to be able to deliver on a carbon-constrained future. Metals which could see a growing market include aluminum (including its key constituent, bauxite), cobalt, copper, iron ore, lead, lithium, nickel, manganese, the platinum group of metals, rare earth metals including cadmium, molybdenum, neodymium, and indium—silver, steel, titanium and zinc. The report then maps production and reserve levels of relevant metals globally, focusing on implications for resource-rich developing countries. It concludes by identifying critical research gaps and suggestions for future work.

The report first develops a framework for estimating mineral demand in a low carbon future. The World Bank, in collaboration with the International Council on Mining and Metals (ICMM), commissioned a predictive analysis of future metals demand to support the transition to a low carbon future, using the International Energy Agency's Energy Technology Perspectives 2016,[1] which focus on the renewable technology implications of meeting 2°C (2DS), 4°C (4DS) and 6°C (6DS) global temperature increase goals. Renewable energy generation (including hydropower and biomass) increases in the three climate scenarios from 14% of the current energy mix to 18% in the 6DS scenario, and a high of 44% in the 2DS scenario.

The study focuses on wind, solar, and energy storage batteries as they are commonly recognized as key elements in delivering future energy needs at low/zero GHG emission levels. That said, we recognize that many other technologies and transmission modes are necessary for meeting the strong climate commitments made at Paris, covering power, transportation, buildings, industry, and land use management sectors. We intend, through this exercise, to engender a broader discussion on this critical issue, recognizing that many other technologies and transmission systems need to be covered.

The next step addresses what materials are required in the scaled-up production of these technologies and to what degree will that demand be driven by a range of the global climate scenarios of 2DS, 4DS and 6DS. The report clearly shows that the technologies assumed to populate the clean energy shift—wind, solar, hydrogen, and electricity systems—are in fact significantly MORE material intensive in their composition than current traditional fossil-fuel-based energy supply systems. Precise estimates on the actual demand for metals is predicated by at least two independent variables: the extent to which the global community of nations actually succeeds in meeting its long-term Paris climate goals and the nature of intra-technology choices. In other words, for example, not only is it a function of **how many** wind turbines, solar panels, and low emission road vehicles will be deployed, but **which** wind, solar technologies, and zero/low emission vehicles will dominate.

The research also indicates that the low carbon technology requirements, and hence relevant metals demand, rises rapidly between the 4DS and 2DS scenarios. The most significant example of this being electric storage batteries, where the rise in relevant metals—aluminum, cobalt, iron, lead, lithium, manganese, and nickel—grow in demand from a relatively modest level under 4DS to more than 1000 percent under 2DS.

As a last step, the report examines how resource-rich developing countries might best position themselves to take advantage of the evolving commodities market responding to a low carbon energy transition. Nonrenewable mineral resources play a dominant role in 81 countries that collectively account for a quarter of world GDP, half of the world's population, and nearly 70 percent of those in extreme poverty.[2] As a result, a growing number of low-income countries focus on resource extraction and processing activities as fundamental to their economic growth plans. Such investments carry significant up-front capital costs, with key assumptions about the longevity of relevant commodities often reaching out more than half a century (due to the typical life span of mines).

It is important that developing countries become better positioned to decide how to take advantage of the future commodities market responding to climate goals and related Sustainable Development Goals (SDGs). The report provides a comprehensive series of global commodity maps tracking known production levels and reserves of the metals, as noted above, that are assumed to play a potentially prominent role in the energy shift to a carbon-constrained future.

The shift to low carbon energy will produce global opportunities with respect to a number of minerals. The Latin America region (Chile, Brazil, Peru, Argentina, and potentially Bolivia) is in an excellent position to supply the global climate-friendly energy transition. The region has a key strategic advantage in copper, iron ore, silver, lithium, aluminum, nickel, manganese, and zinc. Africa, with its reserves in platinum, manganese, bauxite, and chromium, should also serve as a burgeoning market for these resources.

With respect to Asia, the most notable finding is the global dominance China enjoys on metals—both base and rare earth—required to supply technologies in a carbon-constrained future. Both production and reserve levels, even when compared with resource-rich developed countries (such as Canada and the United States, and to a lesser extent Australia) often dwarf others. India is dominant in iron and steel and titanium, and Indonesia has opportunities with bauxite and nickel, as does Malaysia and Philippines—with cobalt—to a lesser extent. Finally, in Oceania, the massive reserves of nickel to be found in New Caledonia should not be overlooked.

The research showed that significant gaps exist in providing current and robust data on mapping relevant mineral/metal resources in developing country regions (Africa, Latin America, and Asia). Also notable are anomalies in the geographical distribution of key metals regarding production activities vs. reserve levels. For example, with respect to bauxite, developing countries (without China) represent only 30% of bauxite production, but represent 63% of global reserves. In the case of Africa (Guinea), it represents just 6.5% of global production, but 26% of known reserves.

In its concluding section, the report provides a series of recommendations regarding areas for further research or that fall into two categories: policy and technological.

Policy-related areas of inquiry include the following:

- Implications for future environmental and material impact performance. Studies on commodity implications of a carbon-constrained future typically focus on current reserves and the relative level of availability and access to materials to supply clean technology production scenarios. However, there is also an increasing sensitivity that supplying clean technologies required for a carbon-constrained future could create a new suite of challenges for the sustainable development of minerals and resources. A dialogue is required at the national and civil society levels within resource-rich developing countries, between the mining–metals and climate–environmental–clean-energy constituencies, to develop a path forward that aligns a potential growing market for key commodities with a sustainable future.

- Mapping minerals in developing countries. There is a significant gap in data and mineral mapping in many developing country regions, particularly Africa. Capacity in this area is critical for resource-rich developing countries to best benefit from potential economic growth in their respective countries.

- Predicting technology choice based on supply constraints and demand patterns. As documented above, much of the uncertainty relating to the potential demand for many metals arises as much from intra-technology choices as it does from inter-technology choices. Understanding where supply constraints may lie, and where prices are most likely to rise, may help inform the possible direction of some of these choices, which, in turn, can help clarify demand.

- Developing networks and raising awareness. One of the outcomes of this analysis is the realization that the implications of this work go far beyond the traditional minerals and metals community. Linkages should be pursued and facilitated among research and social communities.

Technology-related areas of inquiry pertain mostly to expanding the scope of future clean technologies.

Areas to be covered might include the following:

- Electrical cabling and high-efficiency electric motors.

- Light-weighting of vehicles.

- Energy-efficient technologies and buildings.

- Transmission and distribution.

- Metal intensity of traditional and next-generation fossil fuel plants and nuclear facilities.

- Metal supply and metal families.

- Further work would also be useful with respect to key rare earth metals, with regard to both disaggregation capacity for these products (rare earth metals are typically not economically or physically retrievable as discrete ores, but often enmeshed with other base metals, as mentioned above for zinc) and their geological location.

- Recycling rate. The recycling of metals from end-of-life products can improve the future availability of those metals, but data on both current and future metal recycling rates are often poor. To further this analysis of metal criticality in the energy industry, data on current and future recycling rates should be improved.

By taking a close look at subsets of two of those critical components—power and batteries used to fuel future transportation—this report is a first step in examining the implications of changing material requirements for the mining and metals industry in supplying the low carbon energy future. It is intended to engender a broader dialogue between the clean energy, climate, and extractives communities on their respective roles in being part of the global solution for a carbon-constrained future. Going forward, the World Bank intends to work with these key constituencies in further defining the minerals and metals implications of a carbon-constrained future and developing appropriate policies and measures that will help ensure that the transition is managed in a way that complements the full array of sustainable development priorities, from environmental and other material impact issues to supporting continued economic and equitable growth in developing countries.

Notes

1. http://www.iea.org/etp.
2. http://www.worldbank.org/en/topic/extractiveindustries/overview.

Introduction

With respect to prospects for the mining industry, much attention has been paid to the implications for the sector of a decline in the demand for coal over time (notwithstanding the potential for carbon capture and storage to help manage associated GHG emissions). In comparison, little attention has been paid to the implications of growing demand for materials required in the construction of renewable technologies and zero emission infrastructure. Minerals and metals will play a key role in the transition to a significantly lower carbon future, with potentially significant changes for the minerals and metals market. Metals are crucial to the way in which energy is generated and used. The future move to a low carbon economy, based on low carbon electricity generation and energy-efficient energy-using technologies, has huge potential to shift both the scale and composition of the demand for minerals and metals.

An article in *Nature* explains, "a transition to a low carbon society, [is] a change that will require vast amounts of metals and minerals. Mineral resourcing and climate change are inextricably linked, not only because mining requires a large amount of energy, but also because 'the world cannot tackle climate change without adequate supply of raw materials to manufacture clean technologies'" (Ali et al. 2017, 367).

A review of the literature shows that the issue of commodities supply of the carbon-constrained future typically focuses on the minerals and metals that are required for specific technologies, concerns about the capacity of the industry to supply elements required to meet a low carbon future, the environmental and energy-use impacts of increased extraction of those resources, and the relative vulnerability of developed countries to the supply of critical elements required for the clean energy transition. This study provides a summary of the material implications of a low carbon transition. It uses wind, solar, and energy storage batteries as proxies, and focuses on base metals, including aluminum, copper, iron ore, nickel, lithium, and steel and some key rare earth metals such as molybdenum, neodymium, and indium. These metals were chosen because they are commonly identified as elements required for the manufacturing of greenhouse-gas-free technologies. The report then maps production and reserve levels of relevant metals globally, focusing on implications for resource-rich developing countries. It concludes by identifying critical research gaps and suggestions for future work.

While the study's intended audience is the World Bank Group and relevant client governments, it is also meant to engender a broader dialogue between the mining and metals constituency and the climate change and clean energy community. Too often, effective collaboration between the two has been hampered by perceptions of conflicting interests: this study is an attempt to break through that logjam, effectively demonstrating that a low carbon energy shift will be very much dependent on a robust, sustainable, and efficient mining and metals industry.

The report's objective—building awareness of the opportunities provided by a changing commodity market for mineral-rich developing countries—is relevant given the following:

- The high priority the WBG has assigned to playing an active role in supporting the global net zero carbon transition.

- The lack of awareness, particularly among mining and metals actors in developing countries, of zero carbon future scenarios and even less of its implications for the commodities market.

- The opportunity it can provide for mineral-rich developing countries to contribute to addressing climate change while meeting national development and economic goals.

The report is organized along the following lines:

- Using the International Energy Agency's 2015 Energy Technology Perspectives (IEA 2015a) as the main reference climate and energy use scenario, chapter 1 provides a framework for defining the implications of a carbon-constrained future for the mining and metals industry.

- Chapter 2 estimates the mineral and metals implications of an accelerated increase in the deployment of three low carbon technologies—wind, solar, and energy storage batteries.

- Chapter 3 maps these metals to their known reserves globally, intending to identify specific implications for mineral-rich developing countries.

- Chapter 4 identifies key conclusions and research gaps and makes recommendations for follow-up activities to this study.

- Annex A summarizes the literature review conducted to establish which technologies and metals are most likely to play a significant role in a carbon-constrained future.

- Annex B provides an elaboration on energy storage battery scenarios.

- Annex C briefly reviews several deep GHG reduction scenarios.

1. Research Methodology

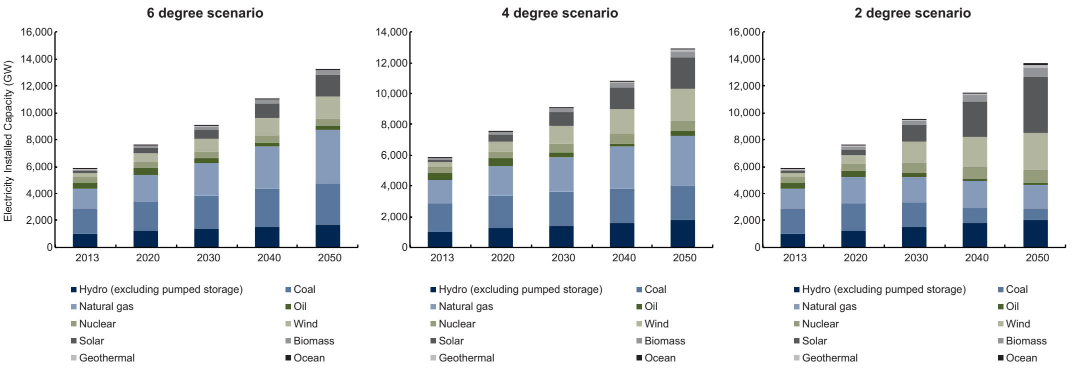
Numerous peer-reviewed scenarios have been developed over the past decade examining different options for the global transition from a carbon-based economic model. For the purposes of this report, these scenarios can be divided into two groups: The first set examines the likeliest prospects for making such a transition, irrespective of political goals established at national, regional, or international levels. These scenarios typically emanate from the private sector,[1] and although they tend to regard decarbonization trends as potentially significant over the century, they are not anything close to the extent required to meet the Paris Agreement's objective of avoiding a 2 degree Celsius (2°C) temperature rise. Hence, there is an assumption in these scenarios that over the next few decades, fossil fuels will continue to dominate, with renewables penetration still significant, but far from the levels necessary to avoid a 2°C rise.

The second group of scenarios does not prejudge or examine whether the commitment to avoiding a global warming target well below 2°C is realistic or even achievable.[2] These studies, in fact, go significantly beyond the 2°C scenario, and so tend to exaggerate potential growth prospects for the relevant metals.[3] Others work on the basis of "development scenarios" with no specific linkage to climate change objectives.[4] For a more in-depth analysis of future low carbon scenarios, please see annex C.

As a result, the World Bank, in collaboration with the International Council on Mining and Metals (ICMM), commissioned a predictive analysis of future metals demand to support the transition to a low carbon future, drawing on the most current data available: the International Energy Agency's (IEA's) Energy Technology Perspective (ETP) scenarios, published in 2015 (IEA 2015a), which focus on the renewable technology implications of meeting 2°C (2DS), 4°C (4DS), and 6°C (6DS) global temperature warming scenarios. Although other scenarios were also taken into consideration, mostly to confirm assumptions about metal concentrations for particular technologies, the ETP scenario is the basis for projections of future demand for mining and metals emanating from a low carbon future.

Figure 1.1 illustrates the technology implications derived from the IEA's ETP scenarios.

FIGURE 1.1 IEA Technology Scenarios for Electricity Installed Capacity



Source: IEA 2016.

Note: GW = gigawatt; IEA = International Energy Agency.

Renewable energy generation (including hydropower and biomass) increases in the three scenarios (2DS, 4DS, 6DS), from 14 percent of the current energy mix to 18 percent in the 6DS scenario, and a high of 44 percent in the 2DS scenario. Given that wind and solar generation are the two renewable technologies whose use is expected to grow the most between 2013 and 2050 to meet a low carbon future, this report focuses on these two key energy generation technologies.

It is also important to note that this study is limited to examining the metals used to manufacture these energy technologies, but does not investigate any additional metal requirements that may result from the growth of transmission infrastructure associated with a proliferation of distributed energy systems. When the power sector is expanded beyond generation to transmission, it is assumed that transmission infrastructure requirements will grow exponentially from business-as-usual cases to the building of smart grid systems integrated with solar and wind installations.

Energy-using technologies abound throughout the global economy and vary greatly in scope and composition. This analysis focuses on one potential energy-using technology that is predicted to play a crucial role in the transition to a low carbon economy: battery storage units required for electric vehicles. Addressing climate change will be impossible without mitigating transportation emissions, which account for about 20 percent of the total (Bajželj, Allwood, and Cullen 2013). A significant electric vehicle fleet, and its supporting charging infrastructure, might also be used as widespread decentralized energy storage facilities. This could help a future low carbon energy system adapt to the inherent variability in wind and solar electricity generation. Electric vehicles therefore are a crucial part of a low carbon transition for both the generation and the use sides of the equation. For this study, the analysis is exclusively focused on potential battery storage facilities necessary for electric vehicles and intermittent renewable energy generation.[5]

The ICMM–World Bank collaborative analysis was designed with a three-step methodology in mind:

1. *Literature scoping study*—A review of literature on metal use in energy supply and energy-using technologies, relying on sources documented in annex A of this report, was completed. Based on this review, a list of metals for inclusion in the analysis (table 1.1) was developed along with a list of energy technologies (table 1.2) to investigate that were directly relevant to the three renewable options that are the focus of this study. A full literature review, covering other, but not all, clean technologies, is provided in annex A.

   During this literature review, data were collected on the weight of metals in table 1.1 necessary to produce an amount of electricity generation capacity for the technologies in table 1.2, typically expressed in units of kilograms per installed megawatt. These data were categorized into "low," "median," and "high" data points if multiple conflicting data were found for the use of a metal in a particular energy technology.

2. *Calculation of anticipated metal use for energy technologies in climate scenarios*—The metal use per unit of installed capacity was multiplied by the projected yearly capacity

TABLE 1.1 Metals Identified by the Literature Review for Inclusion in the Scenario Study

Metal	Metal	Metal
Aluminum	Iron	Molybdenum
Chromium	Lithium	Silver
Copper	Lead	Steel
Indium (Rare earth)	Manganese	Zinc

Note: Other metals were investigated (see annex A), but this subset was selected as the most relevant for this study.

TABLE 1.2 Energy Technologies Included in This Study

	Technology
1a	Wind electricity generation—onshore
1b	Wind electricity generation—offshore
2a	Solar photovoltaics—crystalline silicon
2b	Solar photovoltaics—CdTe
2c	Solar photovoltaics—CIGS
2d	Solar photovoltaics—amorphous silicon
3a	Energy storage—automotive (split between lithium-ion, lead-acid, and other)
3b	Energy storage—grid scale (split between lithium-ion, lead-acid, and other)
3c	Energy storage—decentralized (split between lithium-ion, lead-acid, and other)

Note: CdTe = cadmium telluride; CIGS = copper indium gallium selenide. Other energy technologies were investigated (see annex A), but this subset of technologies was selected as the most relevant for this study.

installation for each energy technology under consideration. The IEA's 2DS, 4DS, and 6DS scenarios were used for the energy system projections. These projections were supplemented by other scenarios for the split between subtechnologies. For example, Elshkaki and Graedel (2013) cite a projection that the split between installed capacity for onshore and offshore wind will change from 98 percent and 2 percent, respectively, in 2007 to a 50/50 split by 2050. The energy scenarios used are described in table 1.3.

3. *Construction of a Microsoft Excel model using these energy scenarios and metal data*—Using this model, the annual demand between 2007 and 2050 for a particular metal in a particular energy technology was calculated by choosing (1) the energy technology, (2) the metal of interest, (3) the energy scenario, and (4) whether to use the low, median, or high metal-per-unit-capacity data (if multiple data points were available). The asset lifetime and the split among subtechnologies could be adjusted as well.

TABLE 1.3 IEA Energy Scenarios Used in This Analysis

Scenario	Description
IEA Energy Technology Perspectives 2° scenario (2DS)	The 2DS is the primary focus of the IEA's *Energy Technology Perspectives.* The 2DS lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50 percent chance of limiting the average global temperature increase to 2°C. The 2DS limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1,000 $GtCO_2$. The 2DS reduces CO_2 emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60 percent by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached.
IEA Energy Technology Perspectives 4° scenario (4DS)	The 4DS accounts for recent pledges by countries to limit emissions and improve energy efficiency, which help limit the long-term temperature increase to 4°C. It should be noted that although the 4DS scenario is certain to result in harmful climate change worldwide, it would still require significant changes from current policy and technology practices. Moreover, capping the long-term temperature increase at 4°C requires significant additional cuts in emissions in the period after 2050.
IEA Energy Technology Perspectives 6° scenario (6DS)	The 6DS is largely an extension of current trends. Primary energy demand and CO_2 emissions would grow by about 60 percent from 2013 to 2050, with about 1,700 $GtCO_2$ of cumulative emissions. In the absence of efforts to stabilize the atmospheric concentration of GHGs, the average global temperature rise above preindustrial levels is projected to reach almost 5.5°C in the long term and almost 4°C by the end of this century.

Source: IEA (http://www.iea.org/publications/scenariosandprojections/).

Note: CO_2 = carbon dioxide; GHG = greenhouse gas; $GtCO_2$ = gigatons of CO_2.

Scenarios for energy storage are not explicitly included in the IEA Energy Technology Perspectives 2015 scenarios, so they were taken from other literature. See annex A for a detailed explanation of how this analysis included scenarios for energy storage batteries, but suffice it to say at this point that the three climate scenarios (6DS, 4DS, and 2DS) assume that 189 gigawatt (GW), 305 GW, and 500 GW[6] of grid-scale energy storage output are needed, respectively. Decentralized ("behind the meter") energy storage was assumed to be 10 percent of grid-scale energy storage in any given year.

Table 1.4 provides some key assumptions used in the analysis.

TABLE 1.4 Key Assumptions Linking Metal Demand with Carbon-Constrained Scenarios

	Assumption	Description	Risks and mitigation
1	Assumption that metal demand per unit of installed capacity will remain constant	It was assumed that the amount of metal per unit of capacity will remain constant through 2050.	Future metal demand could be overestimated in this analysis if substitute materials are found, or if ways are found to build certain technologies with smaller amounts of specific metals. This assumption is mitigated somewhat by including “low,” “median,” and “high” data points for metal use, where available.
2	Assumption of the mixes of sub-technologies in future energy scenarios	The mixes among sub-technologies were assumed based on the literature review.	Leaving the split among subtechnologies as the default value may introduce scenario error. This parameter can be adjusted in the Excel model to mitigate this risk. However, the model does not take into account technology replacement rate limits when changing the technology mix.[a]
3	Assumption of technology lifetimes	The lifetime of energy technologies was assumed to match today’s average values.	This lifetime value is necessary for calculating the amount of capacity to replace retirements every year. If technology lifetimes increase, then less new capacity would need to be built every year, lowering metal demand. This value can be modified in the Excel model for any technology, but at present cannot change year to year.
4	Metal recycling rates	Metal recycling rates were ignored in this analysis.	This analysis calculates energy technologies’ total demand for metals, but does not include a factor for what portion of that demand could be met by recycled metal. Including a recycling rate would lower demand for virgin metal by the amount that is recycled annually.

[a] For example, if a user sets the portion of onshore wind turbines that are direct drive in 2050 at 100 percent, the model will assume that all geared turbines have been replaced by 2050, regardless of whether this is realistic with respect to the rate of geared turbines coming out of service through 2050.

One final word: notwithstanding the care taken to provide a series of credible scenarios in this study, a number of challenges need to be kept in mind, including the following:

- *A lack of consistent projections for a large range of generation and energy-using technologies*. The IEA's energy-generation scenarios do not include energy-using technologies. This study therefore combines scenarios from different sources, which raises consistency challenges. Many other scenarios (covered in annex B) do not directly address specific climate-based goals but use other parameters, so it is difficult to compare those results with the IEA's Energy Technology Perspectives, which serve as the basis for this analysis.

- *A lack of depth in projections for intra-technology choices*. The choice between onshore and offshore wind may be as fundamentally important for metal demand as the overall scale of wind generation. However, there are few if any projections for such a choice.

- *Large variation in estimated values for tons per megawatt for various metals for different technologies in the literature*. Estimating where in this range future metal intensity of technologies will lie is difficult, increasing the overall uncertainty of the final estimates for metal demand in all scenarios.

Notes

1. Examples would include Shell's "New Lens Scenarios" (Shell International BV 2015) and the March/April 2016 edition of CIM Magazine, entitled "Mining in the New Energy Landscape."
2. It should be noted that as part of the IPCC's 5th Assessment Report, the Synthesis Report concludes that it is technically possible to reach 450 parts per million by volume (ppmv) CO_2 equivalent by 2100, which roughly corresponds to a likely chance of maintaining temperature change below 2°C this century; however, implementing the necessary technological and behavioral options (to meet 450 ppmv) poses substantial social, institutional, and technical challenges.
3. Examples include Vidal and others (2013) and Kleijn and others (2011).
4. See Elshkaki and Graedel (2013) and work in Yale University's Industrial Ecology program.
5. Clearly, a plethora of other clean technologies and transmission modes are required for the effective realization of a low carbon future—carbon capture and storage, hydro systems, nuclear power, tidal renewables, decentralized grid systems, and gas turbines to mention a few. Although some of these additional technologies are lightly covered in the literature review in annex A, much more work will be required in these areas to gain a full appreciation of the implications of a low carbon future for material demand.
6. The 500 GW figure for the 2DS energy storage scenario corresponds to the maximum necessary grid-scale energy storage output projected by the IEA.

2. Implications of a Carbon-Constrained Future for Mining and Metals

The 2015 Paris Agreement on Climate Change appears to indicate a global resolve to embark on development patterns that would significantly be less GHG intensive, with potentially significant implications for the commodities market. An assumption prominent in some parts of civil society and the media is that natural resource–based economic activities will become less prominent in a carbon-constrained future. This chapter tests that assumption and examines the commodities for which demand will rise as a result of a globally carbon-constrained future.

Material Requirements in Key Technologies

Chapter 1 established a framework for estimating demand for materials in a low carbon future. This analysis is focused on three key technologies for realizing a low carbon future over this century: wind, solar, and energy storage (batteries). Of course, many other technologies and transmission modes are necessary for meeting the strong climate commitments made at Paris, covering power, transportation, buildings, industry, and land use management sectors; this report acknowledges that these other areas should also be covered, but remains focused on the three technologies identified above,[1] given the prominent role they are assumed to play in a "net zero" or carbon-constrained future. That takes us to the next step: what materials are required in the scaled-up production of these technologies and to what degree will they be required to meet a range of global climate scenarios?

Before proceeding, it is worthwhile to note that the vast majority of climate and carbon scenarios have paid little, if any, attention to the implications of the requirements for the materials necessary to "feed" the carbon-constrained future. However, that situation is changing, with a growing body of research—industrial ecology—examining the material implications of different development scenarios (Clift and Druckman 2016).[2,3] The International Resource Panel has also recently provided updated research on the material implications of a carbon-constrained future.[4] Some nationally funded initiatives are also examining the material needs of new "green" technologies and their ready availability for countries. Examples include the US-based Critical Materials Institute[5] and the European Union–based Ad Hoc Working Group on Defining Critical Raw Materials (European Commission 2014). In addition, the International Union of Geological Sciences has launched an initiative addressing the long-term goal of ensuring a supply of mineral, energy, and water resources for global society for the next century, which will also be focusing on servicing the material needs of clean technologies.[6] It should be noted that the objective of these efforts is to examine potential shortages in the supply of minerals and metals for clean carbon technologies; the objective of this report is simply to identify the critical elements for a specific set of technologies and then strategically assess the potential for the commodities market in mineral-resource-rich developing countries.

The results of the International Council on Mining and Metals–World Bank analysis identifying metals and minerals impacts of three key low carbon technologies follows:

Key Metals for Wind Technologies

The technology options for wind are numerous and include the size of the turbine and whether it rotates vertically or horizontally. To minimize cost, the industry has converged on large, horizontally rotating turbines. For these designs, the basic choice, with significant impacts on metal demand, is geared turbines versus direct-drive turbines.

Geared turbines currently make up the bulk of the installed base. They use a system of gears to convert the relatively low rotation speed of the turbine to a much higher speed (thousands of revolutions per minute) for the generator. Geared turbines use coil-driven generators that require significant amounts of copper, but do not have permanent magnets. In 2009, 85 percent of all installed wind turbine capacity was made up of geared models (Morris 2011). Geared turbines have traditionally had a cost advantage over direct-drive turbines, which must use a more expensive generator. But the reliability of geared turbines has traditionally been worse because of the complicated gearbox.

Direct-drive wind turbines do not have a gearbox, so they are generally more reliable than geared models. However, they do use a more complicated and expensive low-speed generator, which is generally constructed with permanent magnets containing rare earth metals. This design has traditionally led to higher costs than for geared turbines. Because direct-drive turbines do not have the complicated arrangement of bearings and gears that geared turbines do, they have generally been used in places where higher wind speeds would put more stress on the gearboxes and it would be more difficult to access the turbine to perform maintenance. Both factors have led to direct-drive turbines being installed more in offshore locations with higher wind and more difficult access, while geared turbines have been installed in onshore locations with lower wind speeds and easier access.

Wind Power International states that "The share of global wind turbine installations held by direct drive turbines increased from around 18.2% in 2006 to 19.8% in 2011, and is expected to increase to 29.6% in 2020."[7]

Among the metals examined in this study, the significant metal content of these two types of technologies do differ, as seen in table 2.1.

TABLE 2.1 Comparison of Metal Content in Geared and Direct-Drive Wind Turbines

	Geared	Direct drive
Aluminum	X	X
Chromium	X	X
Copper	X	X
Iron	X	X
Lead		X
Manganese	X	X
Neodymium		X
Nickel	X	X
Steel	X	X
Zinc	X	X

Key Metals for Solar Technologies

Each technology for constructing solar photovoltaic (PV) cells has distinct advantages and disadvantages, as well as differing metal content. This section investigates four widely used technologies:

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

In 2015, the market share of all thin film technologies amounted to about 8 percent of total annual production.

Among the metals examined in this study, the significant metal content of these technologies differs widely, as seen in table 2.2.

TABLE 2.2 Comparison of Metal Content in Solar Photovoltaic Technologies

	Crystalline silicon	Copper indium gallium selenide	Cadmium telluride	Amorphous silicon
Aluminum	X			
Copper		X	X	
Indium		X		
Iron	X			
Lead	X			
Nickel	X			
Silver	X			
Zinc			X	X

Key Metals for Energy Storage Batteries

The total energy storage infrastructure for each of the three climate scenarios was split between three technologies: lead-acid, lithium-ion, and "other." The "other" category includes many other battery chemistries, such as nickel-metal-hydride and sodium-sulfur

TABLE 2.3 Comparison of Significant Metal Content in Lead-Acid and Lithium-Ion Batteries

	Energy storage batteries	
	Lead acid	Lithium ion
Aluminum		X
Cobalt		X
Lead	X	
Lithium		X
Manganese		X
Nickel		X
Steel	X	X

batteries, as well as non-battery energy storage such as pumped-storage hydro, flywheels, and hydrogen. Lead-acid and lithium-ion batteries have distinct advantages and disadvantages, as well as differing metal content:

1. Lead-acid batteries are the more mature technology, and have traditionally had a cost advantage over lithium-ion batteries. They have poor power-to-weight and energy-to-weight ratios.

2. Lithium-ion batteries have excellent energy-to-weight ratios, and prices have decreased drastically in the past decade.

The significant metal content of these technologies is dependent on the charge carrier, either lithium or lead, as seen in table 2.3; both battery types typically use either plastic or steel construction.

Metal Demand Trend Predictions

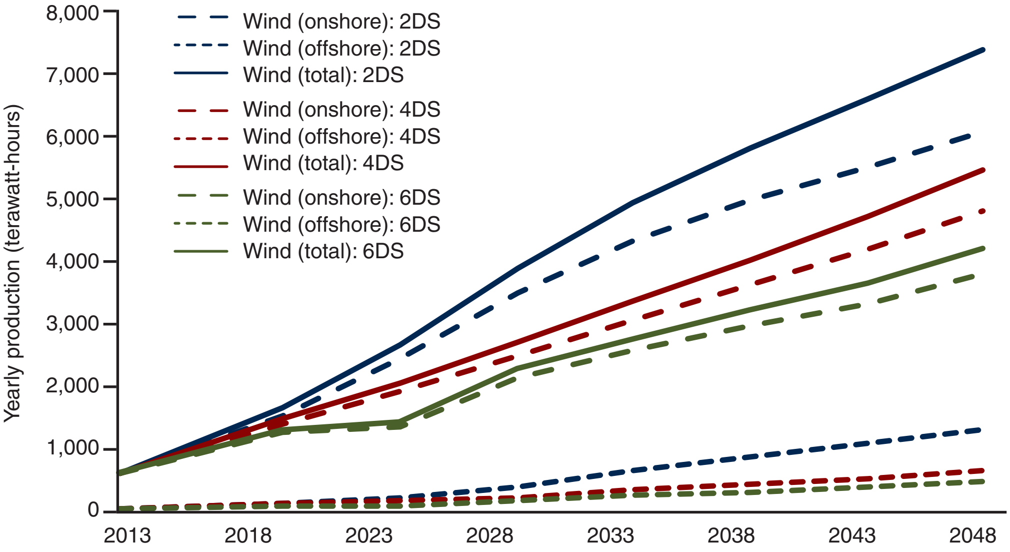
This section discusses demand trends for the metals supplying the three technologies—wind power, solar photovoltaics, and energy storage—in more depth.

Wind Power

Increases in wind turbine size, combined with economies of scale, have lowered wind electricity generation prices to the point that it is competitive with fossil fuel generation in many areas, and, according to Channell et al. (2013, 53), is even "approaching the average wholesale electricity price in a number of large markets—including Italy, Spain, the UK and China—and has already attained and surpassed parity in Brazil."

Figure 2.1 shows the wind energy production curves for the 2 degree, 4 degree, and 6 degree Celsius scenarios (2DS, 4DS, and 6DS, respectively). In these scenarios, electricity production from wind power, particularly onshore wind, will rapidly increase through 2050.

FIGURE 2.1 Wind Electricity Generation Scenarios for the International Energy Agency Energy Technology Perspectives Scenarios



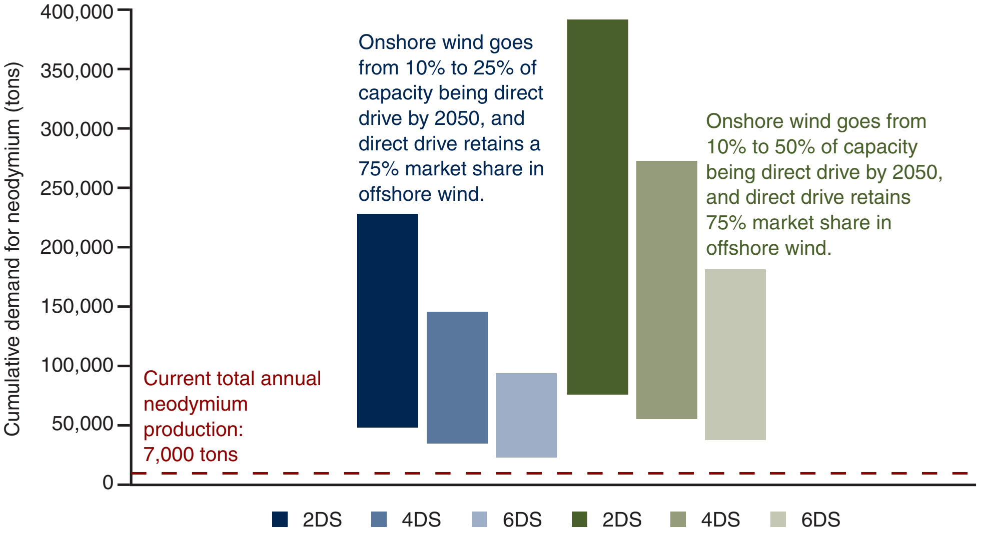
Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario.

It should be noted that although these three scenarios cover a range of possible future outcomes for the energy system in general, recent evidence points to overly conservative estimates of expected penetration levels of renewable technologies. For example, the International Energy Agency's (IEA's) Blue MAP scenarios,[8] published in 2010, extrapolated that the world would produce approximately 300 terawatt-hours (TWh) of electricity from wind energy in 2015, when in fact the actual production in 2015 was 700 TWh, indicating a much more rapid build out of wind capacity than had been anticipated.

Future metal demand. Future metal demand in the wind industry will depend on both the total amount of capacity installed and the choices between these two competing technologies. Elshkaki and Graedal (2013) assume that offshore wind turbines, which are assumed to be almost completely of the direct-drive design in the future, will be 50 percent of total installed generation capacity by 2050. But the split between onshore and offshore installations, and even between geared and direct-drive installations in these two locations, is not yet set. Morris (2011) notes that progress is being made toward increasing the reliability of geared designs and driving down the cost of direct-drive designs.

Figure 2.2 provides an interesting illustration of one element, neodymium, whose projected demand is very much influenced by the type of wind technology that will gain prominence during this century.[9]

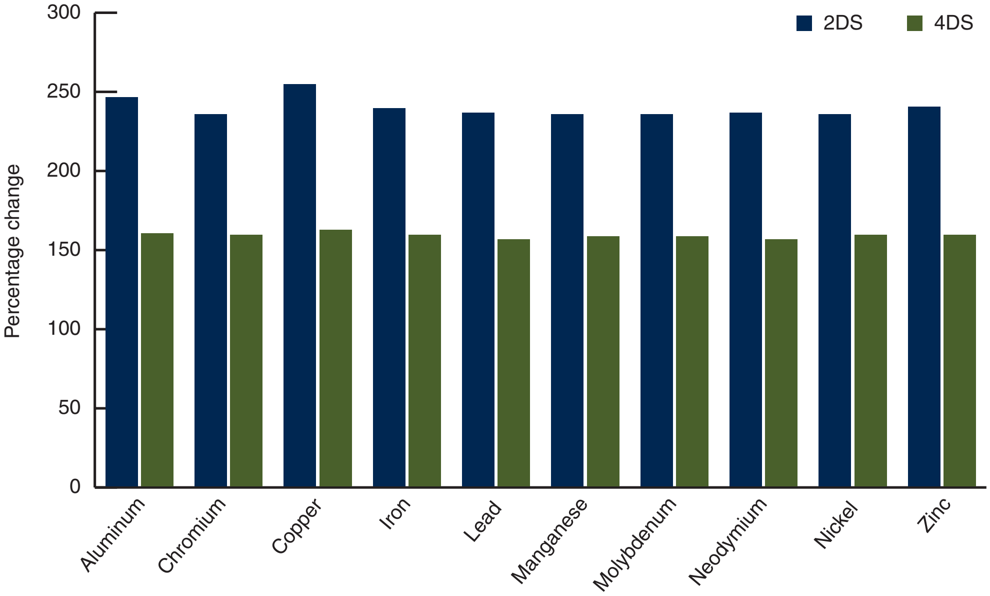
FIGURE 2.2 Ranges for Cumulative Neodymium Demand for Global Wind Turbine Production through 2050



Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario. Each bar represents an energy scenario (2DS, 4DS, or 6DS) and set of assumptions about the market penetration of direct drive vs. geared wind turbine technologies. The height of the bar is the uncertainty in the intensity of metal demand (high versus low estimates of the amount of neodymium in each generator). In this figure, offshore wind turbines have a consistent 75/25 split for direct-drive and geared systems, respectively, from 2013 through 2050. In the blue scenarios, onshore wind turbines have a consistent 25/75 split for direct-drive and geared systems, respectively, from 2013 through 2050. In the green scenarios, direct-drive systems in onshore wind turbines move from a 25 percent market share in 2013 to a 50 percent market share in 2050.

Figure 2.3 lays out a "median" scenario for wind technologies' resultant impact on key metals demand under 2DS and 4DS as compared with 6DS, showing a 150 percent increase in metal demand for wind technologies under 4DS and close to a 250 percent increase for virtually all relevant metals under a 2DS.

FIGURE 2.3 Median Metals Demand Scenario for Supplying Wind Technologies through 2050

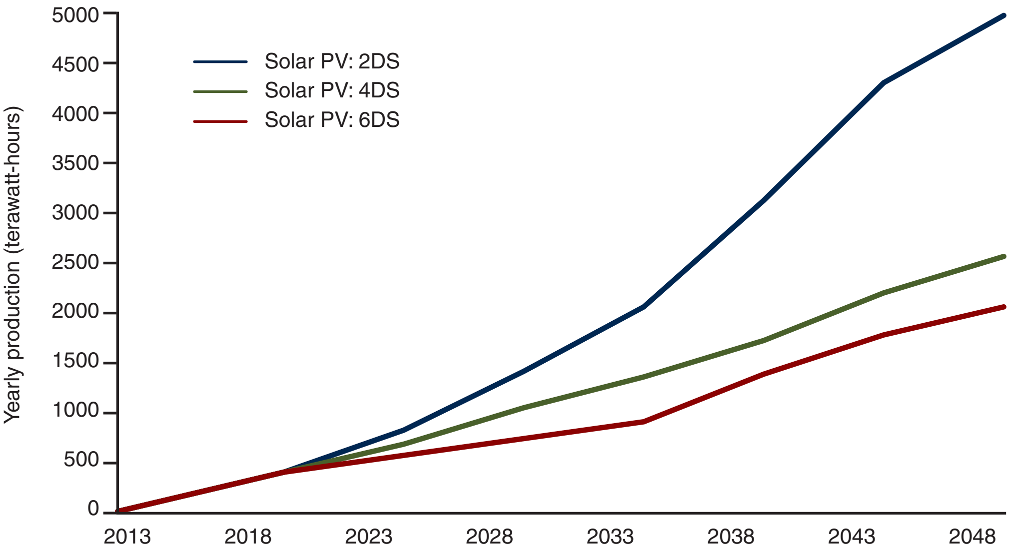


Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario. Figure shows change in metal demand for wind technologies as compared with the 6DS.

Solar Photovoltaics

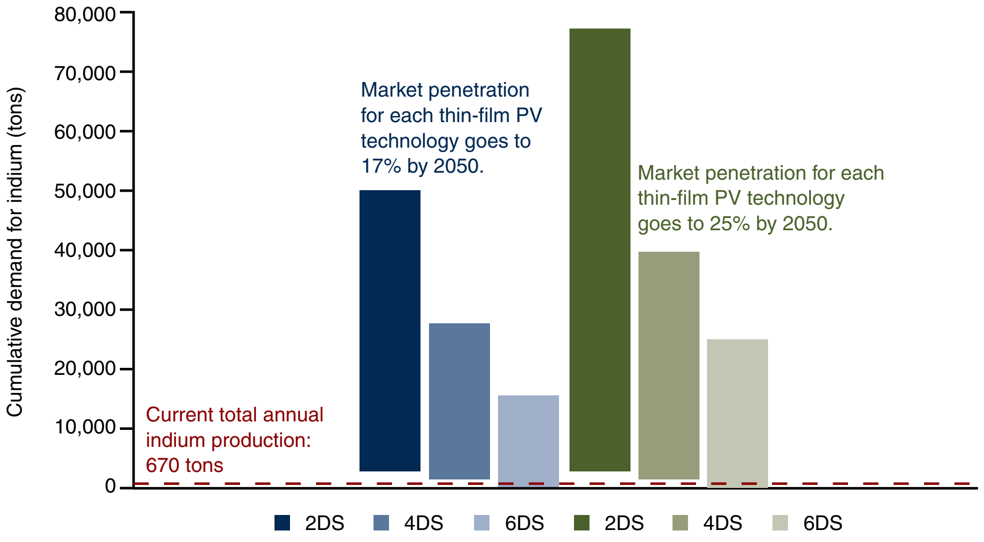
Solar PV technology converts sunlight directly to electricity. The high learning rate[10] for solar PV, between 22 percent and 40 percent, has resulted in marked price reductions in solar PV technology costs in recent years—approximately $1 per watt currently, and projected to be $0.50 by 2025. Solar PV is now common at small scales (for example, for individual appliances in off-grid areas on house rooftops), at medium scale (for individual businesses), and at large scale (for example, solar PV farms generating many megawatts of electricity). Figure 2.4 lays out projected yearly electricity supply from solar PV for the 2DS, 4DS, and 6DS IEA Energy Technology Perspectives scenarios (IEA 2015a). Global PV electricity production in 2013 was approximately 140 TWh, and is projected to rapidly increase in all scenarios. However, the IEA data do not specify the mix of solar technologies that might be used in the future.

FIGURE 2.4 Solar PV Electricity Production



Future metal demand in the solar industry will depend on both the total amount of solar PV installed and choices between competing solar technologies. For example, the demand for indium depends not only on the penetration of solar PV, but also on what percentage of those installations are CIGS technology. Many studies assume that the majority of future solar PV installations will be of the crystalline silicon variety. As seen in figure 2.5, total demand through 2050 varies greatly depending on small changes in CIGS market penetration. These numbers can be compared with current annual indium production of 700 tons.

FIGURE 2.5 Ranges for Cumulative Demand for Indium for CIGS Solar PV Technology through 2050

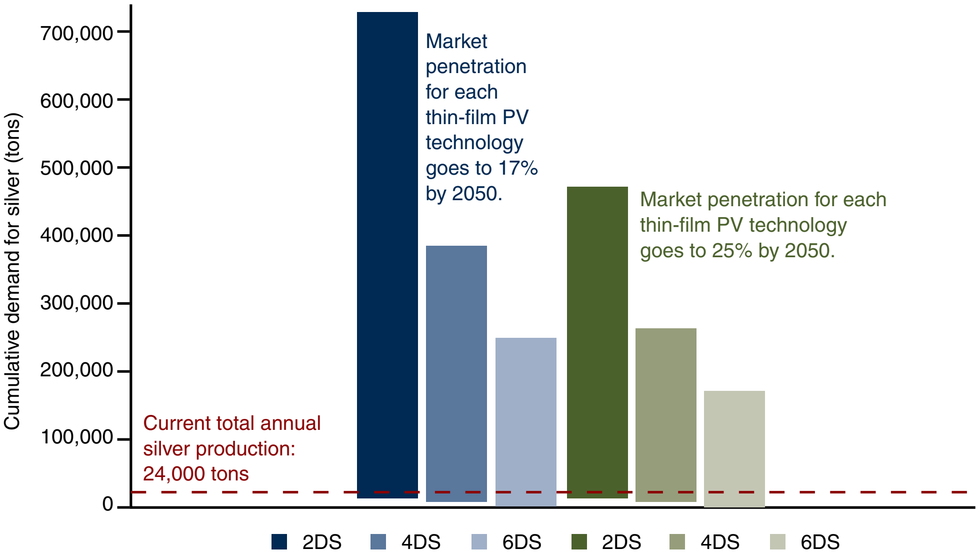


Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario; CIGS = copper indium gallium selenide; PV = photovoltaic. Each bar represents an energy scenario (2DS, 4DS, or 6DS) and a set of assumptions about the market penetration of different PV technologies. The height of the bar is the uncertainty in the intensity of metal demand (high versus low estimates of the amount of indium in each solar cell). In the blue-colored scenarios, CIGS increases its market share from roughly 7 percent today to 17 percent in 2050. In the green-colored scenarios, CIGS technology moves from a 7 percent market share in 2013 to a 25 percent market share in 2050, with a corresponding increase in demand for indium.

Figure 2.6 plots the range of cumulative demand for silver from PV technologies. Silver is another example of a metal whose potential rising demand in a carbon-constrained future is very much subject to intra-technology choices. In contrast to the potential demand for indium, scenarios in which thin film technologies see increased market penetration reduce demand for silver in the PV industry, because only crystalline silicon PV cells use significant amounts of silver.[11]

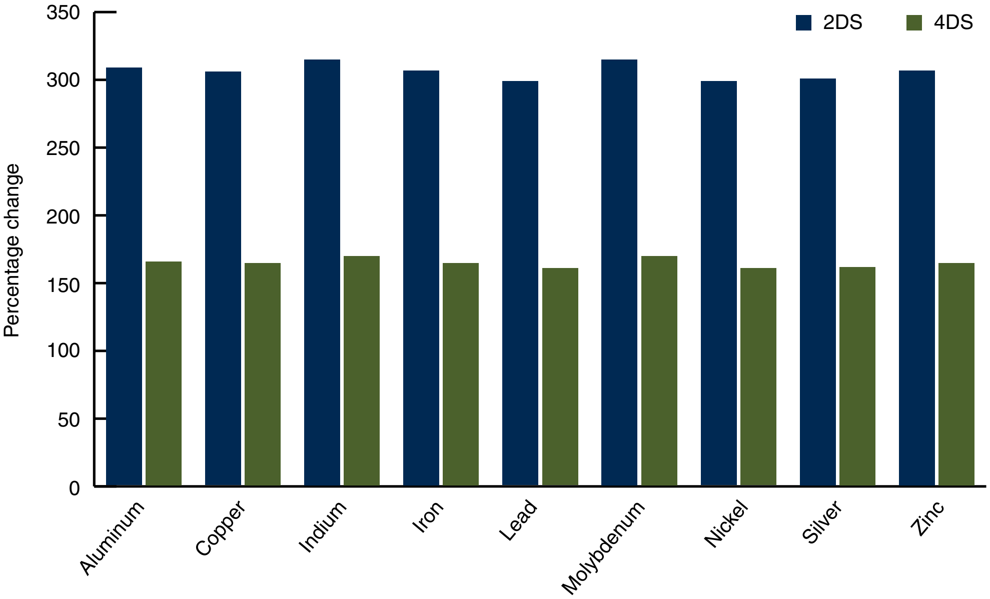
Figure 2.7 lays out a median scenario for solar PV and the resultant impact on key metals demand for 2DS and 4DS as compared with 6DS. The difference in projected metal demand for solar PV between 4DS and 2DS is even more marked than it is for wind technologies, with output of relevant metals projected to increase about 300 percent for solar PV (under wind, 2DS sees a 250 percent rise).

FIGURE 2.6 Ranges for Cumulative Demand for Silver for Solar PV Technology through 2050



Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario; PV = photovoltaic. Each bar represents an energy scenario (2DS, 4DS, or 6DS) and a set of assumptions about the market penetration of different PV technologies. The height of the bar is the uncertainty in the intensity of metal demand (high versus low estimates of the amount of silver in each solar cell). In the blue-colored scenarios, thin film technologies each increase their market share from roughly 7 percent today to 17 percent in 2050. In the green-colored scenarios, thin film technologies each move from a 7 percent market share in 2013 to a 25 percent market share in 2050, with a corresponding decrease in demand for silver (which is used in crystalline silicon PV cells).

FIGURE 2.7 Median Metals Demand Scenario for Supplying Solar Photovoltaics through 2050



Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario. Figure shows change in metal demand for solar photovoltaic technologies as compared with the 6DS.

Energy Storage

Energy storage technology stores energy at the time it is generated for later use when it is needed. This analysis divides energy storage into three applications: automotive, grid scale, and decentralized. The energy storage landscape for automobiles (and other wheeled ground vehicles, including buses, vans, and trucks) is changing rapidly. All vehicles today have some battery energy storage, almost always a lead-acid battery, to help start the engine and to power vehicle electronics. New technologies to improve energy efficiency all require increased energy storage capacity. These technologies, from the smallest to the largest increase in energy storage capacity, are start-stop vehicles, micro-hybrid vehicles, hybrid vehicles, and electric vehicles. The increased market penetration of start-stop vehicles is likely to increase demand for lead-acid batteries, while lithium-ion battery technology is likely the only viable candidate for full electric vehicles because of its high energy-density-to-weight ratio. Energy storage technology choices for future hybrid vehicles are less certain, with lead-acid batteries, lithium-ion batteries, nickel-chemistry batteries, compressed air storage, and flywheel energy storage all competing for market share.

Grid-scale energy storage is used for a number of different purposes, including regulation of grid voltage (on very short time scales) and to store electricity produced by intermittent generation sources (solar PV and wind) for use when needed. Because grid-scale energy storage infrastructure does not require the high energy-density-to-weight ratio of automotive applications, there are many more competing technology options, including pumped-storage hydro, compressed air, a number of flow battery chemistries, hydrogen, lead-acid batteries, and lithium-ion batteries. Current grid-scale energy storage infrastructure is almost exclusively (more than 99 percent) pumped-storage hydroelectricity, where water is pumped up to a height to store energy and is then released to flow downhill and spin turbines to generate electricity.

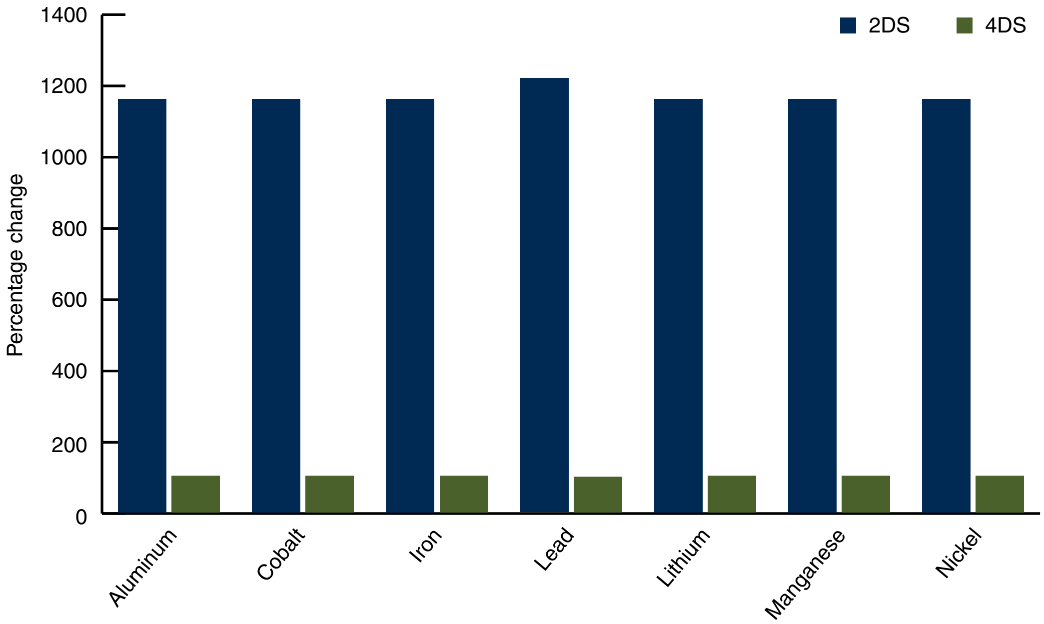
It is likely that batteries will gain an increasing share of future grid-scale energy storage because of declining costs and the limited number of new sites suitable for pumped-storage hydro. Decentralized (or "behind the meter") electricity storage is used with individual, small-scale, renewable energy installations. For example, a home or business might use decentralized energy storage to store electricity from a rooftop solar PV panel for use during the night. These installations typically use battery technology (for example, lead acid or lithium ion), or a solution such as flywheels or thermal energy storage.

Of the three energy technologies examined in this report, the future market for energy storage is regarded as the most difficult to predict and therefore the most uncertain. The IEA's Energy Technology Perspectives scenarios (IEA 2015a) do not contain explicit scenarios for energy storage. Figure 2.9 projects trends for battery energy storage for electric vehicles and other energy storage types.

Future metal demand in the battery industry is highly dependent on the overall demand for storage in the energy system, the choice of energy storage technologies, and the development of less-metal-demanding technologies, particularly for lithium-ion batteries.

Figure 2.8 illustrates a median scenario for energy storage technologies and the resultant impact on demand for key metals demand under 2DS and 4DS as compared with 6DS.

FIGURE 2.8 Median Metals Demand Scenario for Supplying Energy Storage Technologies through 2050

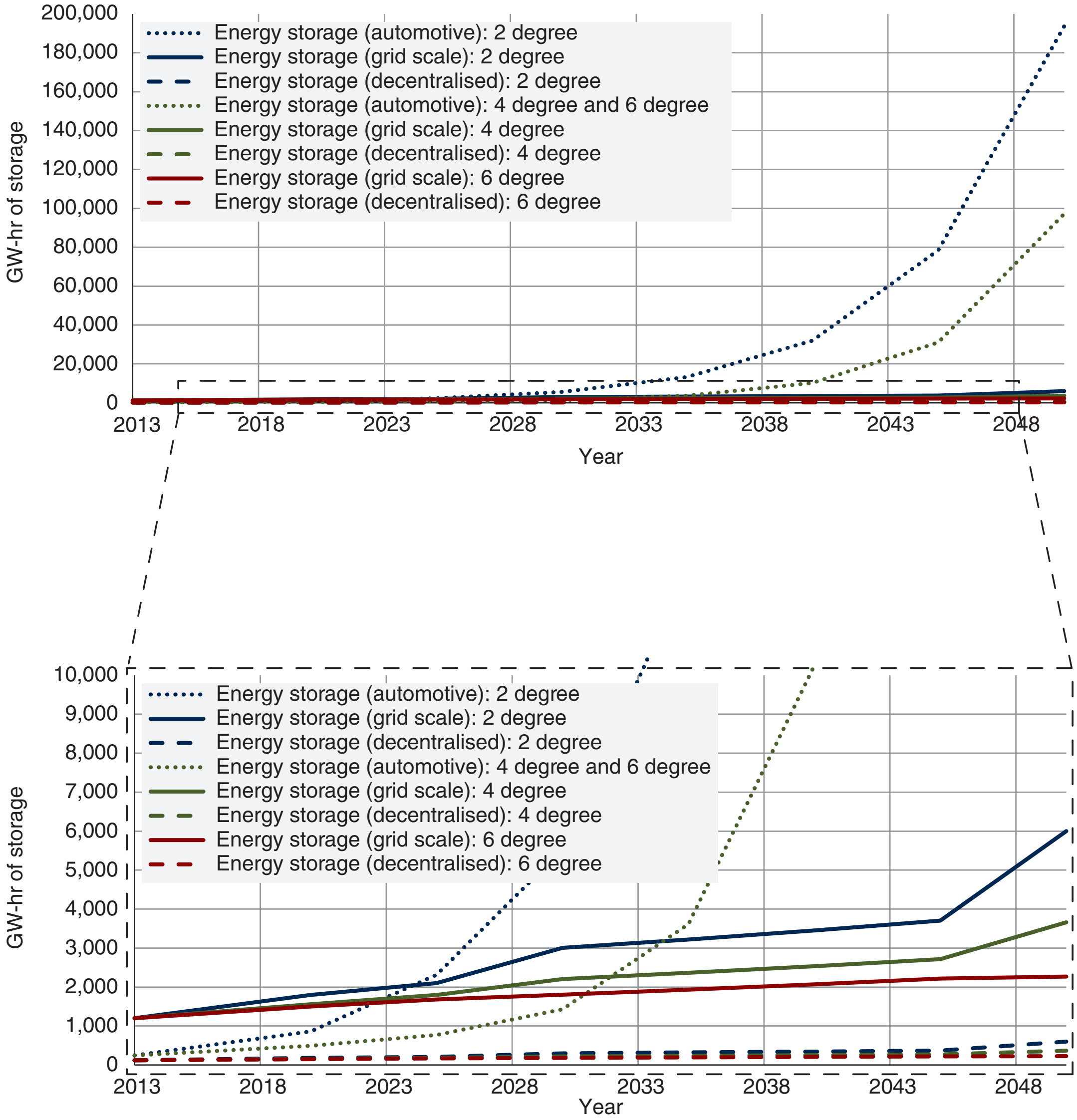


Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario. Figure shows change in metal demand for energy storage technologies as compared with the 6DS.

Metals not shown in this figure are not used to any great extent in this technology. Most noteworthy is the remarkable difference in projected demand for relevant metals between the 2DS and 4DS configurations. Demand is expected to rise gradually under 4DS but is likely to rise more than 1,000 percent should 2DS come into effect.

In this analysis, the energy storage required (in gigawatt-hours) for each of the three applications was projected from 2013 to 2050, as seen in figure 2.9. In figure 2.9, the potential extreme 2DS electric vehicle trend is clear. In this scenario (documented in International Energy Agency [2016a]), there are 140 million electric vehicles in operation by 2030, versus approximately 25 million units in the more pessimistic 4DS and 6DS scenarios. Due to the lack of scenario data, the projections for automotive battery energy storage after 2030 are based on growth rate assumptions of approximately 20% per year. The bottom panel of figure 2.9 provides a zoomed-in view of the energy storage capacity for other energy storage types.[12]

FIGURE 2.9 Global Energy Storage Capacity Scenarios



Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario. Global energy storage scenarios. Data obtained from the IEA Energy Technology Perspectives scenarios (2015a), as well as scenarios described in International Electrotechnical Commission (2009).

Note: Global energy storage scenarios, zoomed in to see detail for all scenarios other than the 2DS electric vehicle scenario. Data obtained from the IEA Energy Technology Perspectives scenarios (2015a), as well as scenarios described in International Electrotechnical Commission (2009).

Demand for Metal Will Increase, but for What Metals?

The clear conclusion to be drawn from the above discussion is that the acceleration in deployment of the key low carbon technologies in the wind, solar, and energy storage areas has real implications for the commodities market, and not only rare earths, such as indium and neodymium. Aluminum, copper, silver, bauxite, iron, lead, and others all stand to potentially benefit from a strong shift to low carbon technologies. It would be reasonable to expect that all low carbon energy systems are more likely than not to be more metal intensive than high-carbon systems. In fact, all literature examining material and metals implications for supplying clean technologies agree strongly that building these technologies will result in considerably more material-intensive demand than would traditional fossil fuel mechanisms.

The next critical question is *which* metals will experience strong increases in demand: the answer remains far from clear, for the ways in which metal demand will increase depend on both inter-technology choices, such as the balance between wind and solar power, and intra-technology choices, such as the balance between onshore and offshore wind, the choice between different types of solar PV cells, and the extent to which vehicles become fully electric or mild hybrid and what types of batteries dominate.

These different choices have profound implications for the demand for individual metals. Predicting the overall energy balance between individual renewable technologies, or the extent to which electric vehicles will penetrate the market, is complicated enough, let alone predicting the balance between specific technological choices within each renewable energy category.

This analysis attempts to quantify the three largest sources of uncertainty for metal demand:

- Evolution of the energy system
- Competition between different designs for the same technology, which may have higher or lower requirements for metals
- Innovation that may be able to reduce the amount of metals used in a particular technology per unit of service delivered.

Although exactly predicting the demand for specific metals is impossible, clear ranges for their demand can be derived, and it can be clearly stated that any move to a more renewable-energy-intensive economy will result in greater overall demand for metal.

Wind power shows the scale of the challenge. The technology as a whole is predicted to become an increasingly important component of many countries' energy systems, especially those with significant wind resources. However, within wind energy, two main types of technology choices are available: onshore and offshore wind. The main technology difference between these geographically separated technologies is the use of permanent magnets in offshore wind versus the use of geared drives in onshore. Permanent magnets are a more expensive and metal-intensive option, but the use of such technology requires less maintenance and replacement, and is therefore more suited to the challenging conditions in which offshore wind operates.

Thus, an energy scenario that involves greater penetration of offshore wind would result in much greater demand for permanent magnets and rare earth metals such as neodymium. The demand for neodymium will therefore depend on the penetration of offshore wind, which will, in turn, depend on a wide range of factors such as local planning restrictions for onshore wind, marine management zoning decisions, developments in the robustness of offshore wind and its related infrastructure, and even the demand for rare earth metals from other sources, which will affect the price of permanent magnets and the choice between offshore and onshore wind.

Solar PV cells are also predicted to become a crucial part of the overall energy mix, ranging from 2 percent of total energy production in the baseline scenario to 25 percent in the scenario that predicts the greatest penetration of renewable technologies. Yet within this broad category are at least four potential technology choices (with a much greater range of future options that are not commercially available): crystalline silicon, CIGS, CdTe, and amorphous silicon. The balance between these alternatives has huge implications for metals such as indium, silver, and zinc. Crystalline silicon PV requires much greater amounts of silver compared with the other technologies, while CIGS requires much more indium than the others. Thus, how the various technologies within the solar PV class develop, and how the economic and technological choices between these technologies evolve, will define the demand for a wide range of metals.

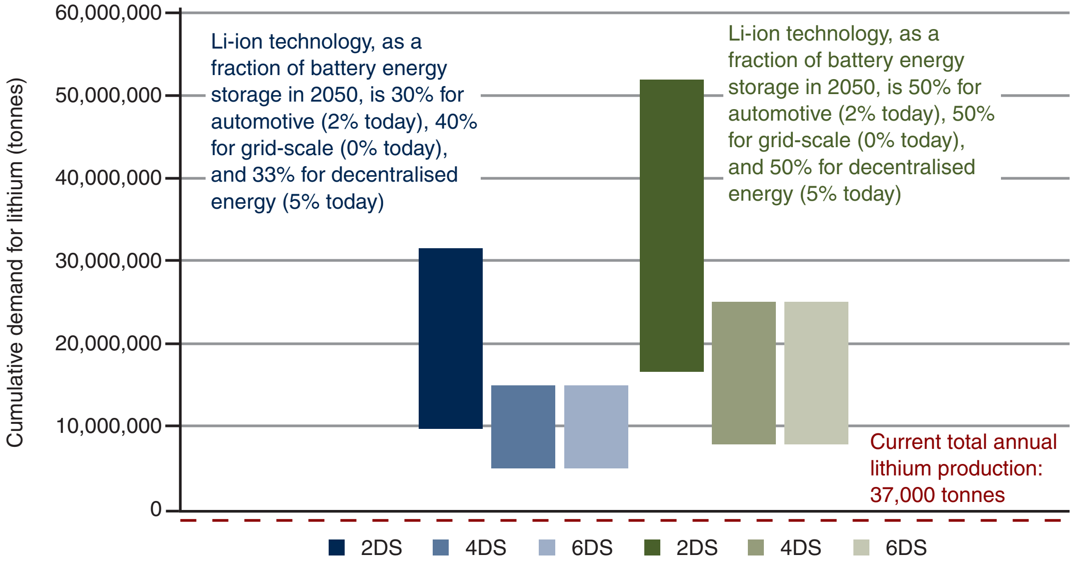
Energy-storage technologies also lead to potential uncertainty for demand for specific metals. A major question that arises in predicting the future of transportation is not just the number of vehicles on the road, but the extent to which the vehicle fleet in the next few decades will be fully electric, dominated by hybrid vehicles that use both electricity and traditional gasoline, or even populated by vehicles that use previously predicted “golden bullets” such as hydrogen fuel cells.

The emergence of one of these three options will define whether lithium, lead, or the platinum group of metals experiences large increases in demand. Any of these three options would require large changes from a baseline of the continuation of an internal combustion fleet, but more significant is the choice between the three options. A fully electric fleet is predicted to involve massive increases in the demand for lithium, used in the lithium-ion batteries in electric vehicles. In contrast, a fleet that involves less penetration by electrical technology and is dominated by mild hybrid vehicles could lead to much lower levels of lithium demand but much higher demand for lead for use in lead-acid batteries. If hydrogen fuel cell vehicles predominate, then demand for platinum group metals could increase rapidly. Which of these choices (if any) emerges again depends on a wide variety of factors, such as the scale of cost reductions in battery technology; the extent to which electric-charging infrastructure can be cheaply and feasibly constructed; the requirements for a vehicle fleet that can also be used as storage for intermittent renewable generation; shifting consumer preferences for low-emission, efficient vehicles; and even the relative costs of the key constituent metals.

Predicting the groups of metals for which demand is likely to grow is therefore extremely difficult, although it can be stated with some confidence that one of these three clean energy vehicles is likely to grow dramatically. These three examples of how intra-technology choices for personal vehicles can affect overall demand for individual metals shows the scale of the task of understanding long-term demand for individual metals. Predicting the growth of any technology class is difficult, and predicting specific choices within each class is doubly so. Yet it is these choices that will define the demand for individual metals.

Figure 2.10 provides an example of how one metal’s demand—in this case, lithium-ion—carries a considerable range of possibilities, depending on the penetration of energy storage batteries in servicing automotive, grid scale and decentralized energy.

FIGURE 2.10 Demand for Lithium-Ion Battery Technology through 2050



Note: Each bar represents an energy storage scenario (2DS-ES, 4DS-ES, or 6DS-ES) and scenario for lithium-ion battery technology market penetration. The height of the bar is the uncertainty of the intensity of metal demand (high versus low estimates of the amount of lithium per unit of battery energy storage). In the blue-colored scenarios, lithium increases its market share from about 2 percent today to 30 percent in the automotive sector in 2050 (measured by total energy storage capacity in gigawatt-hours), as well as from 0 percent to 40 percent in grid-scale energy storage, and 5 percent to 33 percent in decentralized energy storage. In the green-colored scenarios, lithium-ion batteries increase to 50 percent market penetration in all three sectors by 2050.

As an illustration of how the metals market could be affected by carbon-neutral technologies, Oliveira (2017) reports in *Mining Weekly* that demand for key metals, such as lithium, is at risk of exceeding current production levels, with the potential to hold low carbon technology manufacturers hostage to lithium suppliers' proclivities and capacities. Peer-reviewed academic journals are carrying the same narrative, with Fizaine and Court (2015) suggesting that interdependency between metals and energy production is increasing, in most part because of growth in carbon-neutral or -constrained technologies.

Another example of volatility in the commodities market caused by rapid shifts in demand for carbon-neutral technologies is silicon. Over the past few years, silicon, a major element in crystalline silicon solar, has gone from undercapacity to overcapacity in a relatively short time, but there is still a risk that demand may once again outstrip supply should solar continue to grow at current rates, causing consequent impacts on the overall and long-term economic feasibility of specific solar technologies (Bye and Ceccaroli 2014).

These examples drive home the message that producers need to be better prepared to not only meet increased overall demand for metals under low carbon scenarios but also to be flexible enough to meet shifting demand for individual metals as economic and technical developments cause these broad choices between technologies to begin to narrow.

Figure 2.11 provides a very preliminary glimpse of how overall demand for metals by 2050 might be affected by an increase in demand for the technologies identified in this report. This figure is intended to begin a story with respect to the links between metals and a carbon-constrained future, namely, that technologies supporting a carbon-constrained future will cause demand for a wide range of base metals, as well as for rare earth metals, to increase. It is important to keep in mind that this initial study does not include a number

FIGURE 2.11 Mean Cumulative Demand, 2013–50, for the Technologies Examined in This Study (Impact on cumulative demand of relevant metals by 2050, under the 2DS scenario, as a fraction of cumulative demand if the 2013 production levels are sustained to 2050.)

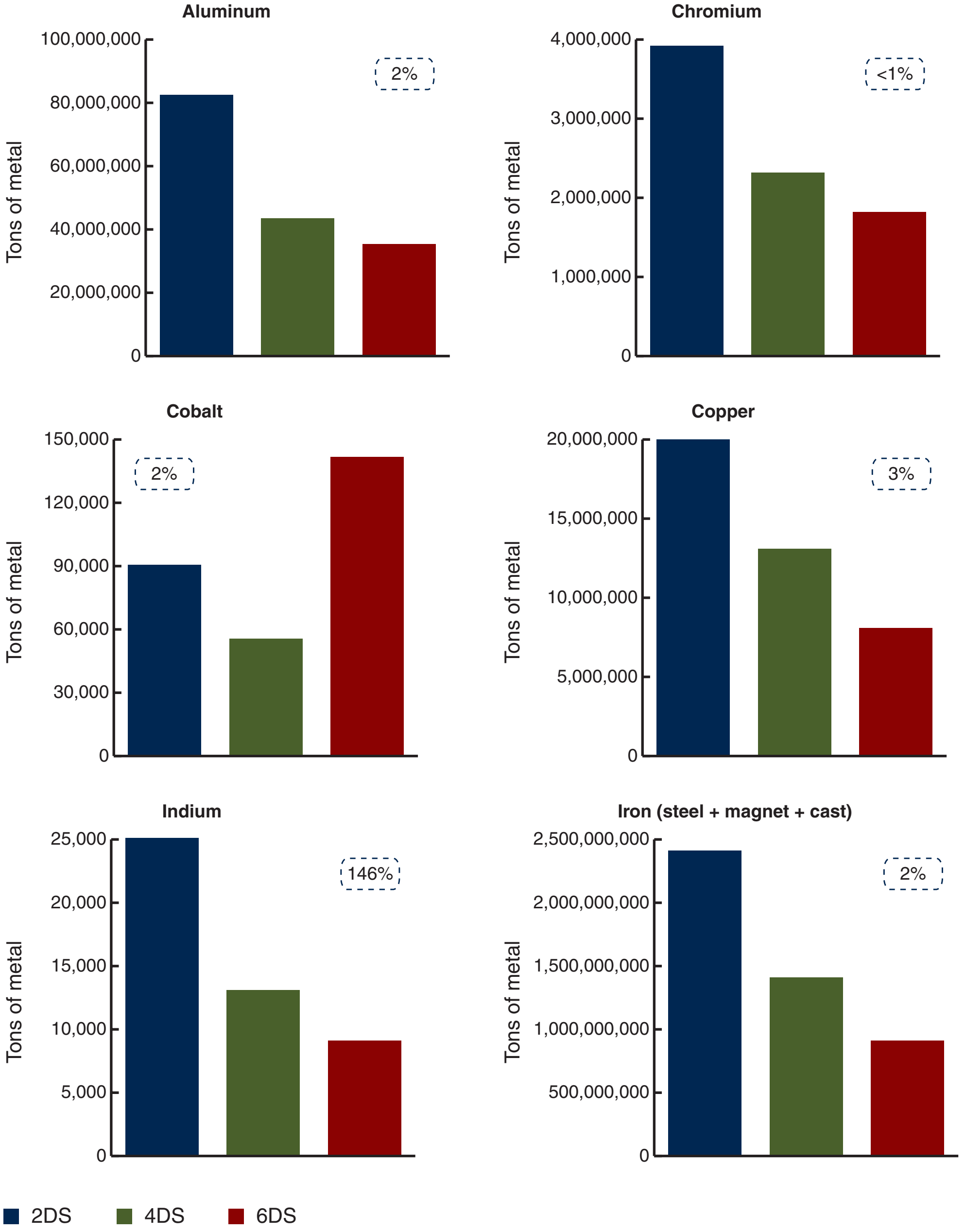
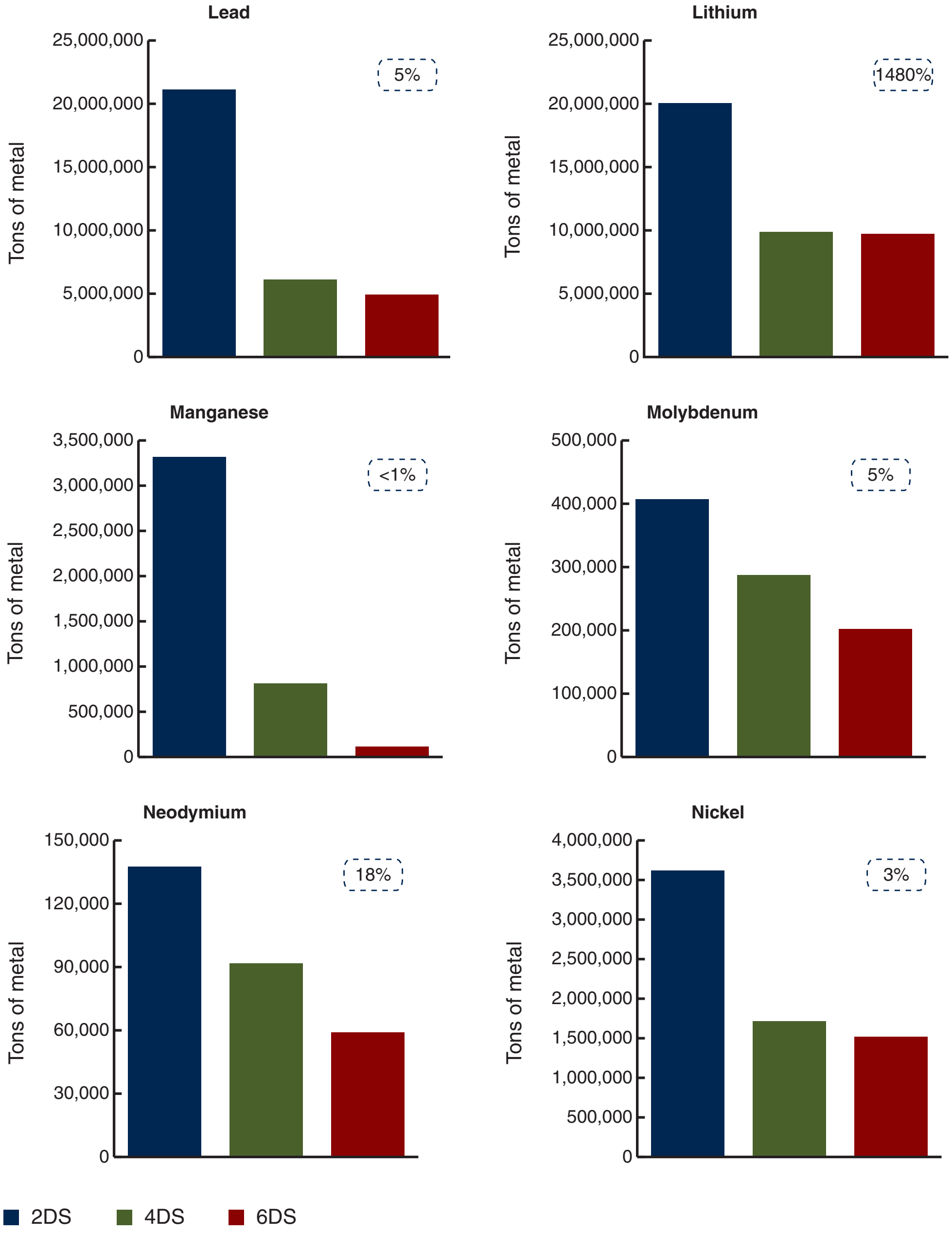
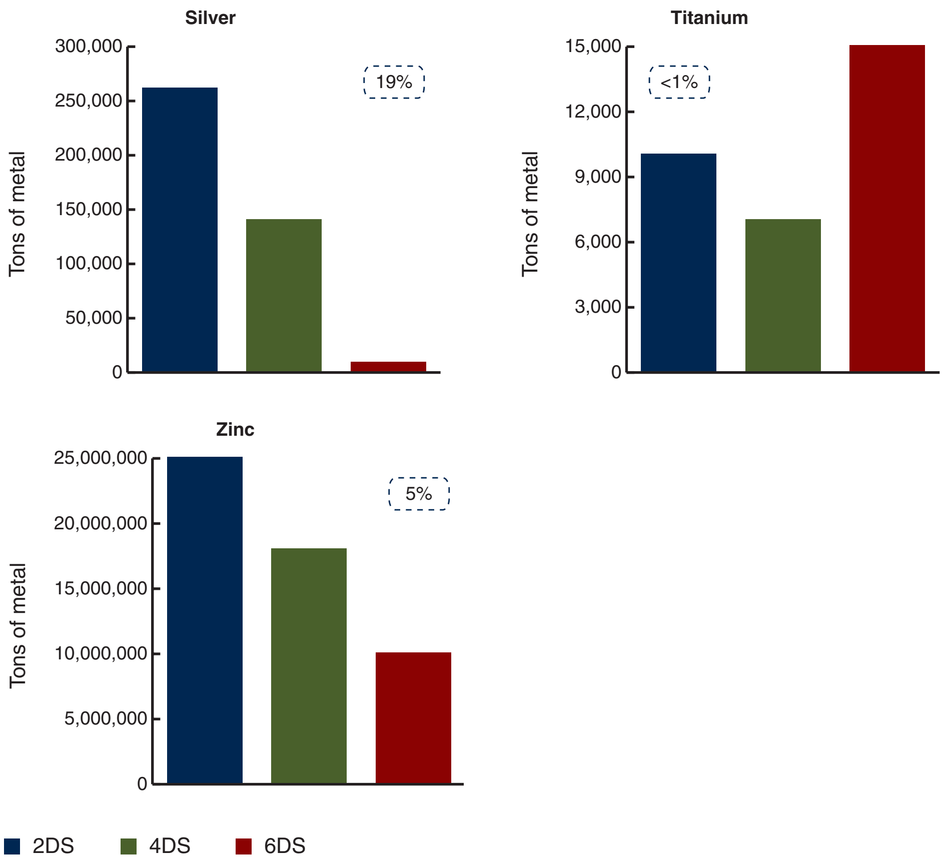


FIGURE 2.11 *Continued*



(continued)

FIGURE 2.11 *Continued*



of key technologies and modalities that would have further impacts on overall demand for key metals. For instance, this study's scope (and budget) did not include an examination of the implications of electric motors for vehicles; where, a recent study claims that the future electric vehicle market could create a huge increase in demand for copper and cobalt (*Economist* 2014).

Notes

1. Some of the other clean technology options are lightly covered in the literature review in annex A.
2. Despite this progress, it should be noted that the IPCC in its 5th Assessment Report (IPCC 2015), consistent with all previous assessment reports, does not explicitly address the issue of material implications of a range of climate-development scenarios.
3. The School of Natural Resources and Environment at the University of Michigan provides the following description of Industrial Ecology (Garner and Keoleian 1995, 4): "There is still no single definition of industrial ecology that is generally accepted. However, most definitions comprise similar attributes with different emphases. These attributes include the following:
    - a systems view of the interactions between industrial and ecological systems
    - the study of material and energy flows and transformations

- a multidisciplinary approach
- an orientation toward the future
- a change from linear (open) processes to cyclical (closed) processes, so the waste from one industry is used as an input for another
- an effort to reduce the industrial systems' environmental impacts on ecological systems
- an emphasis on harmoniously integrating industrial activity into ecological systems
- the idea of making industrial systems emulate more efficient and sustainable natural systems
- the identification and comparison of industrial and natural systems hierarchies, which indicate areas of potential study and action."

4. IRP (2017): *Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies.* Suh, S., Bergesen, J., Gibon, T. J., Hertwich, E., Taptich, M. A Report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya, 2017.
5. Critical Materials Institute website: https://cmi.ameslab.gov/.
6. More on this initiative may be found at http://iugs.org/index.php?page=resourcing-the-future-initiative. This study is just commencing and is expected to cover a number of years.
7. Worldwind Technology. "Gear up for Growth: The Global Wind Energy Market" (http://tinyurl.com/h6rzsgn).
8. See http://erpuk.org/wp-content/uploads/2015/03/ERP-Scenario-analysis-IEA-BLUE-Map.pdf.
9. Key sources used for this analysis, and to which the reader is referred for further information, include Zepf et al. (2014), who document metals critical to the energy industry and provide good data for and explanations of the demand for rare earth elements for magnets and potential substitutes, and Elshkaki and Graedel (2013), who document the metals used in various solar PV technologies in their analysis of future metal use for renewable energy technologies.
10. "Learning rate" is defined as the fractional reduction in cost for each doubling of cumulative production.
11. Key sources used for this analysis include Elshkaki and Graedel (2013), who document the metals used in various solar PV technologies in their analysis of future metal use for renewable energy technologies; Channell et al. (2013), who provide excellent data on historical and projected solar PV penetration rates and prices; and the Fraunhofer Institute, which has data on market penetration of thin film and crystalline silicon solar technologies.
12. Key sources used for this analysis, and to which the reader is referred for further information, include Kempener and Borden (2015), who provide documentation on scenarios for grid-scale energy storage deployment; Inage (2009), who provides calculations for the demand for future energy storage; Pillot (2015), who provides projections for the lithium-ion battery market; and Teske et al. (2015), who provide data on lithium use per unit of stored energy for several lithium-ion battery technologies.

3. Implications for Developing Countries

As noted in the World Bank's Overview of the Extractive Industries,[1] nonrenewable mineral resources play a dominant role in 81 countries that collectively account for a quarter of world GDP, half of the world's population, and nearly 70 percent of those in extreme poverty. As a result, a growing number of low-income countries focus on resource extraction and processing activities as fundamental to their economic growth plans. Such investments carry significant up-front capital costs, with key assumptions about the longevity of relevant commodities often reaching out more than half a century (due to the typical life span of mines). It is important that developing countries become better positioned to decide how to take advantage of the future commodities market responding to climate and related Sustainable Development Goals, promoting, for example, affordable and clean energy.

This chapter provides a comprehensive series of global commodity maps tracking known production levels and reserves of the following commodities assumed to play a potentially prominent role in the energy shift to a carbon-constrained future:[2] aluminum (including alumina and bauxite), chromium, cobalt, copper, iron ore and steel, indium, lithium, manganese, molybdenum, nickel, platinum group metals, rare earth metals (which include cadmium, indium, and neodymium), silver, titanium, and zinc.

For the purpose of this report's objective—building awareness of the opportunities for mineral-rich developing countries resulting from a changing commodities market caused by a global shift to climate-friendly technologies—drawing coherent conclusions from the mapping exercise is not easy. In fact, the most striking conclusion to draw is that significant gaps exist in providing current and robust data with which to map relevant mineral and metal resources in developing country regions (Africa, Asia, and Latin America). For example, the U.S. Geological Survey's 2016 global mapping of production and reserve levels of metals covered in this exercise show NO profile for potential contributions from Africa for cadmium, molybdenum, silver, rare earth metals, and zinc, and relatively small profiles for copper, iron ore, and lithium.

Also notable are anomalies in the geographical distribution of key metals for production activities versus reserve levels versus estimated resources. For example, with respect to bauxite (figure 3.3; table 3.3), a key metal required for aluminum production, developing countries, excluding China, account for 30 percent of bauxite production, but 63 percent of global reserves. Africa, Guinea specifically, accounts for 6.5 percent of global production, but 26 percent of known reserves. The survey estimates that 94 percent of the world's bauxite is found in developing country regions.

Lithium (figure 3.12; table 3.12) is another example of a key metal required for the carbon-constrained future (particularly for energy storage batteries in electric vehicles) for which reserves are prominently located in developing country regions, especially in South America. Production is not high, but the actual resources are significantly higher. For example, in Latin America, Bolivia is listed as having no accessible reserves but is estimated to actually have some 9 million tons embedded in its geological formations. In Africa, only Zimbabwe is listed with relatively small reserves, but the Democratic Republic of Congo is estimated to have 1 million tons in resources. The same can be said of **manganese** (figure 3.13; table 3.13)—while Africa is estimated to have about 32 percent of the globe's reserves, the U.S. Geological Survey estimates that South Africa alone contains 75 percent of manganese resources worldwide.

It is striking that aside from China, Brazil, India, and Malaysia there are no recorded production, reserve, or resource data for **rare earth metals** (figure 3.17; table 3.17) available from any developing country regions. Although these critical metals can be found in these areas, no concerted efforts have been undertaken to accurately map their existence, an activity no doubt complicated by the reality that many of these elements are "secondary" minerals embedded in base metals, such as **zinc** (figure 3.21; table 3.21).

Notwithstanding the limited data available at this point for some areas of the world, particularly Africa and some other low-income countries worldwide, some trends are still noteworthy. With respect to mineral-rich developing countries, it is evident that Latin America is in a relatively strong position to become a "supplier" for the global climate-friendly energy transition, with Brazil, Chile, Argentina, and Peru being the best positioned countries. Bolivia is also potentially set to benefit should it be able to translate its resources, such as lithium, into recognized reserves. Particular metals for which Latin America holds a key strategic advantage include **copper** (figure 3.7; table 3.7), **iron ore** (figure 3.10; table 3.10), **silver** (figure 3.19; table 3.19), and **lithium**; the region is also active in the **aluminum, nickel, manganese,** and **zinc** sectors.

Africa's potential role is also potentially significant given its ore reserves in **platinum** (figure 3.16; table 3.16), **manganese, bauxite,** and **chromium** (figure 3.5; table 3.5). Most of these reserves and production activities are limited to the southern African region, with the exception of Guinea. And as mentioned, the lack of data and information on metals outside of the south may be more the result of survey gaps than the actual absence of those metals. For example, it is a relative certainty that Africa does, in fact, contain rare earth metals. What has NOT occurred is any comprehensive survey of its potential resources and how difficult it might be to translate those resources into reserves.

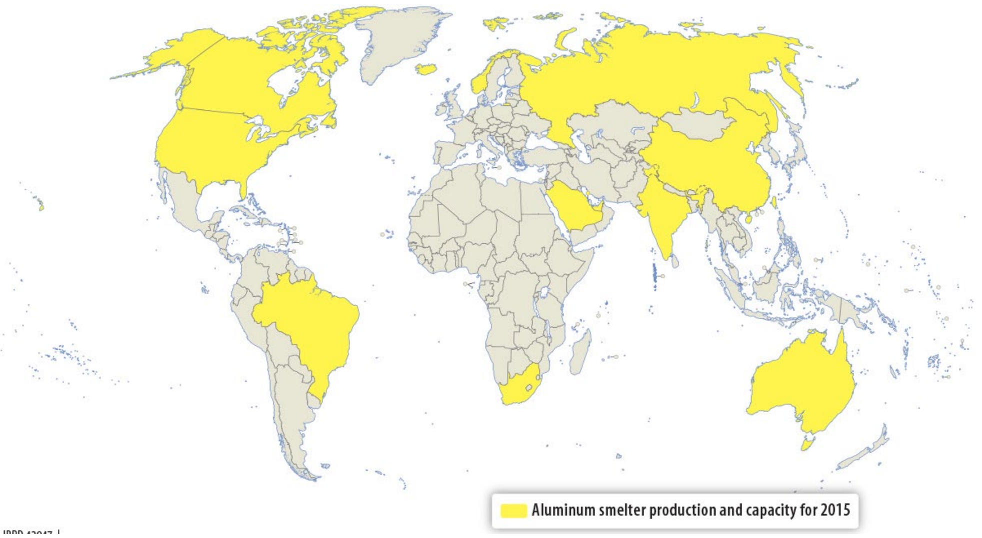
With respect to Asia, the most notable finding is the global dominance China enjoys on the metals—both base and rare earth—required to supply technologies in a carbon-constrained future. Both production and reserve levels, even when compared with resource-rich developed countries (such as Canada and the United States, and to a lesser extent Australia) often dwarf that of others. India is dominant in iron and steel and titanium, and Indonesia has opportunities with bauxite and nickel, as does Malaysia, to a lesser extent. Finally, in Oceania, the massive reserves of nickel to be found in New Caledonia should not be overlooked.

Global Distribution of Reserves and Production Levels of Key Metals Critical to a Clean Energy Future

For the purposes of this exercise—mapping reserves to critical metals in the carbon-constrained future—the following minerals and metals are the specific focus of this annex: steel and its iron ore component, aluminum (including alumina and bauxite), cadmium, chromium, cobalt, copper, indium, lithium, manganese, molybdenum, nickel, rare earth metals, platinum group metals, silicon, silver, titanium, and zinc. This annex maps these resources' production and reserve levels and examines how well positioned mineral-rich developing countries are for supplying that market. The source for this information is the United States Geological Survey (USGS) Mineral Commodities Survey of 2016, which has been confirmed by cross-references to the Organisation for Economic Co-operation and Development's Trade in Raw Materials website. We fully recognize that the data provided may not be fully consistent with other surveys, notwithstanding that the USGS data is assumed to be the most comprehensive currently available to the public. Comparison with OECD's database for its "Trade in Raw Materials" website was performed and found data to be fairly consistent with USGS data.

Also as a clarification, although the maps address production and reserve levels for the relevant metals, the USGS also, at times, alludes to "resource" levels, to be distinguished from reserves. The USGS Mineral Resources Program 2012 defines resources as "a concentration of naturally occurring solid, liquid or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially *feasible*,"[3] whereas reserves are defined as "that part of the reserve base which could be economically attractive or produced at the time of determination."[4] This report formally "maps" only reserve and production levels for the relevant metals; however, potential resource levels are noted when found relevant to the discussion. Specific mapping, however, of resource levels was not included because data were inconsistently applied across metals and regions.

FIGURE 3.1 Aluminum Production



Source: USGS 2016, 23.
Calculation of developing-countries' share does not include "Other countries" row in table 3.1.

TABLE 3.1 Aluminum Smelter Production and Capacity, 2015 (*thousand metric tons*)

	Production	Capacity
China	32,000	36,000
Russia	3,500	4,180
Canada	2,000	3,270
India	2,350	3,850
United Arab Emirates	2,340	2,400
Australia	1,650	1,720
United States	1,600	2,000
Norway	1,320	1,550
Bahrain	960	970
Iceland	820	840
Brazil	780	1,600
Saudi Arabia	740	740
South Africa	690	715
Qatar	640	640
Other countries	2,340	2,400
Total	**58,300**	**68,800**

Source: USGS 2016, 23.

Developing countries' share of aluminum smelter production and capacity: With China and Middle Eastern countries, 70 percent; without them and only including Brazil, India, and South Africa, 6.5 percent.

World resources: Global resources are estimated to be between 55 billion and 75 billion tons and are sufficient to meet world demand for metal well into the future.

Substitutes: Magnesium, steel, and titanium can substitute for aluminum in ground transportation and structural uses. Composites, steel, vinyl, and wood can substitute for aluminum in construction. Copper can replace aluminum in electrical and heat-exchange applications.

FIGURE 3.2 Alumina Refinery Production

Source: USGS 2016, 33.
Calculation of developing-countries' share does not include "Other countries" row in table 3.2.

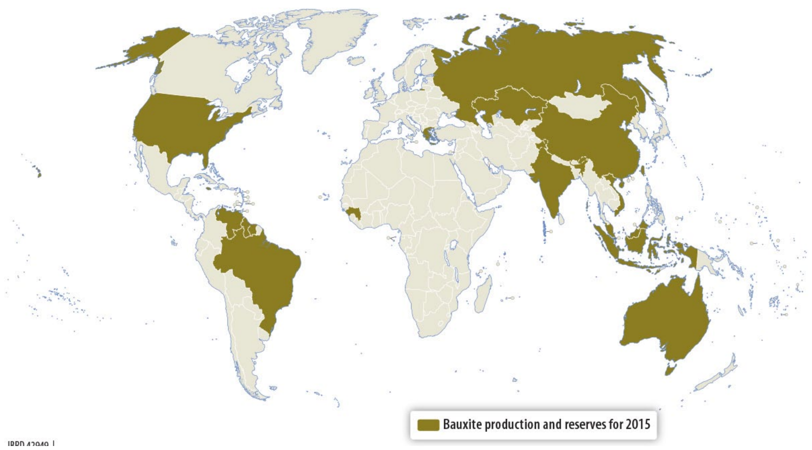
TABLE 3.2 Alumina Refinery Production, 2015 (*thousand metric tons*)

	Refinery production
China	57,000
Australia	20,200
Brazil	10,300
India	5,470
United States	4,000
Russia	2,580
Jamaica	1,950
Kazakhstan	1,600
Suriname	970
Greece	800
Venezuela	780
Vietnam	500
Other countries	11,400
Total	**118,000**

Source: USGS 2016, 33.

Developing countries' share of alumina refinery production: 67 percent; without China, 18 percent.

FIGURE 3.3 Bauxite Production and Reserves



Source: USGS 2016, 33.
Calculation of developing-countries’ share does not include “Other countries” row in table 3.3.

TABLE 3.3 Bauxite Production and Reserves, 2015 (*thousand metric tons*)

	Mine production	Reserves
Guinea	17,700	7,400,000
Australia	80,000	6,200,000
Brazil	2,000	2,600,000
Vietnam	1,100	2,100,000
Jamaica	10,700	2,000,000
Indonesia	1,000	1,000,000
Guyana	1,700	850,000
China	60,000	830,000
India	19,200	590,000
Suriname	2,200	580,000
Venezuela	1,500	320,000
Greece	6,600	250,000
Russia	6,600	200,000
Kazakhstan	5,200	160,000
Malaysia	21,200	40,000
United States	N/A	20,000
Other countries	8,500	2,400,000
Total	**274,000**	**28,000,000**

Source: USGS 2016, 33.

Note: N/A = not available.

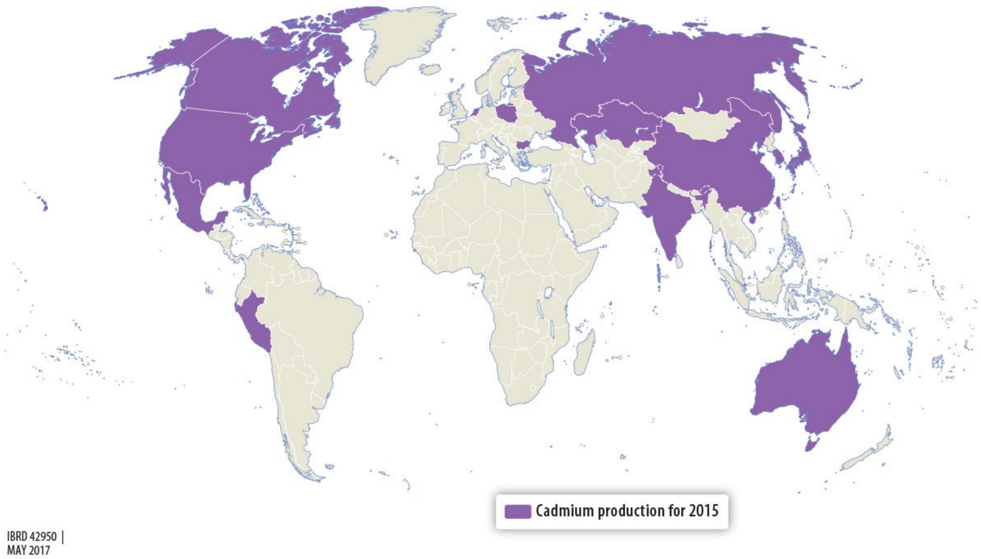
Developing countries’ share of bauxite production: 52 percent; without China, 30 percent.

Developing countries’s share of bauxite reserves: 65 percent; without China, 63 percent.

World resources: Bauxite resources are estimated to be between 55 billion and 75 billion tons: Africa (32 percent), Oceania (23 percent), South America and the Caribbean (21 percent), Asia (18 percent), and elsewhere (6 percent).

Substitutes: Bauxite is virtually the only raw material used in the production of alumina on a commercial scale in the world, but that may be changing. Although currently not economically competitive with bauxite, vast U.S. and global resources of clay are technically feasible sources of alumina. Some refineries in China recover alumina from coal ash, and processes for recovering alumina from clay were being tested in Australia and Canada to determine if they would be economically competitive.

FIGURE 3.4 Cadmium Production



Source: USGS 2016, 43.
Calculation of developing-countries’ share does not include “Other countries” row in table 3.4.

TABLE 3.4 Cadmium Production, 2015, (*metric tons*)

	Production	Reserves
China	8,090	N/A
Republic of Korea	4,250	N/A
Japan	1,970	N/A
Canada	1,480	N/A
Mexico	1,460	N/A
Kazakhstan	1,190	N/A
Russia	1,170	N/A
Peru	850	N/A
Netherlands	640	N/A
Poland	640	N/A
India	460	N/A
Australia	380	N/A
Bulgaria	340	N/A
United States	N/A	N/A
Other countries	1,130	N/A
Total	**24,200**	**N/A**

Source: USGS 2016, 43.

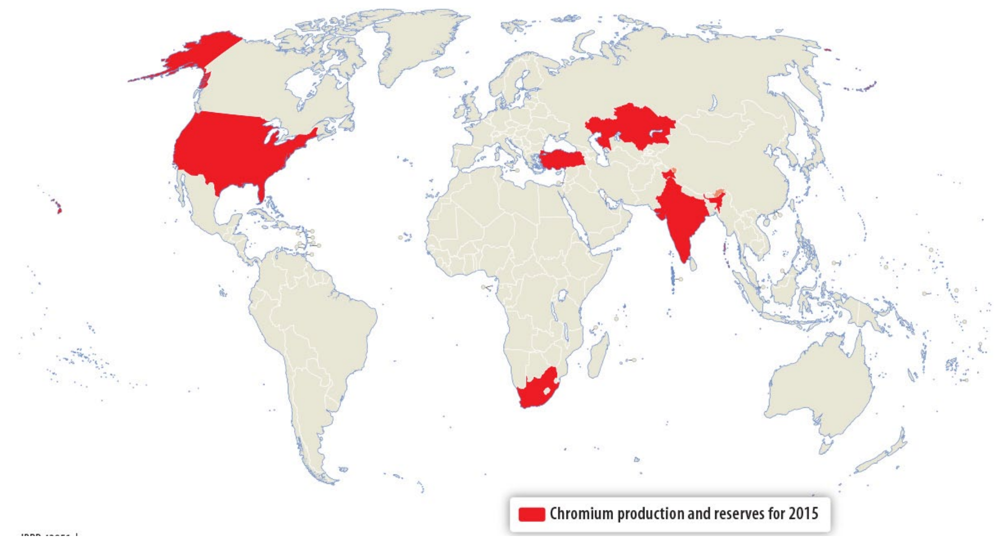
Note: N/A = not available. Quantitative estimates of cadmium reserves are not available. It is typically recovered from zinc ores at grade levels of 0.03 percent.

Developing countries' share of cadmium production: 45 percent; without China, 11 percent.

World resources: Cadmium is generally recovered from zinc ores and concentrates. Sphalerite, the most economically significant zinc mineral, commonly contains minor amounts of cadmium, which shares certain similar chemical properties with zinc and often substitutes for zinc in the sphalerite crystal lattice. The cadmium mineral greenockite is frequently associated with weathered sphalerite and wurtzite. Zinc-bearing coals of the central United States and Carboniferous-age coals of other countries also contain large subeconomic resources of cadmium.

Substitutes: Lithium-ion and nickel–metal hydride batteries are replacing nickel-cadmium batteries in some applications. However, the higher cost of these alternatives restricts their use in less expensive products. Except where the surface characteristics of a coating are critical (for example, fasteners for aircraft), coatings of zinc or vapor-deposited aluminum can be substituted for cadmium in many plating applications.

FIGURE 3.5 Chromium Production and Reserves



Source: USGS 2016, 49.
Calculation of developing-countries' share does not include "Other countries" row in table 3.5.

TABLE 3.5 Chromium Production and Reserves, 2015 (*thousand metric tons)*

	Production	Reserves
Kazakhstan	3,800	230,000
South Africa	15,000	200,000
India	3,500	54,000
Turkey	3,600	N/A
United States	N/A	N/A
Other countries	4,600	N/A
Total	**30,500**	**~ 480,000**

Source: USGS 2016, 49.

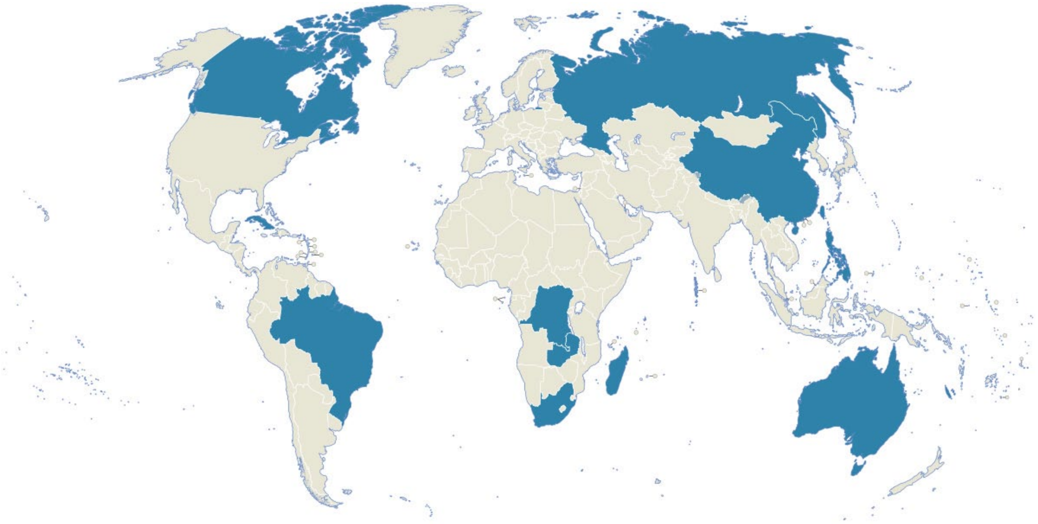
Note: N/A = not available.

Developing countries' share of chromium production: 84 percent; reserves, 100 percent.

World resources: World resources are greater than 12 billion tons of shipping-grade chromite, sufficient to meet conceivable demand for centuries. About 95 percent of the world's chromium resources are geographically concentrated in Kazakhstan and southern Africa.

Substitutes: Chromium has no substitute in stainless steel, the leading end use, or in superalloys, the major strategic end use. Chromium-containing scrap can substitute for ferrochromium in some metallurgical uses.

FIGURE 3.6 Cobalt Production and Reserves



Source: USGS 2016, 52.
Calculation of developing-countries' share does not include "Other countries" row in table 3.6.

TABLE 3.6 Cobalt Production and Reserves, 2015 (*metric tons*)

	Mine production	Reserves
Congo (Kinshasa)	63,000	3,400,000
Australia	6,000	1,100,000
Cuba	4,200	500,000
Zambia	2,800	270,000
Philippines	4,600	250,000
Russia	6,300	250,000
Canada	6,300	240,000
New Caledonia	3,300	200,000
Madagascar	3,600	130,000
China	7,200	80,000
Brazil	2,600	78,000
South Africa	2,800	31,000
Other countries	7,700	633,000
Total	**120,400**	**7,162,000**

Source: USGS 2016, 52.

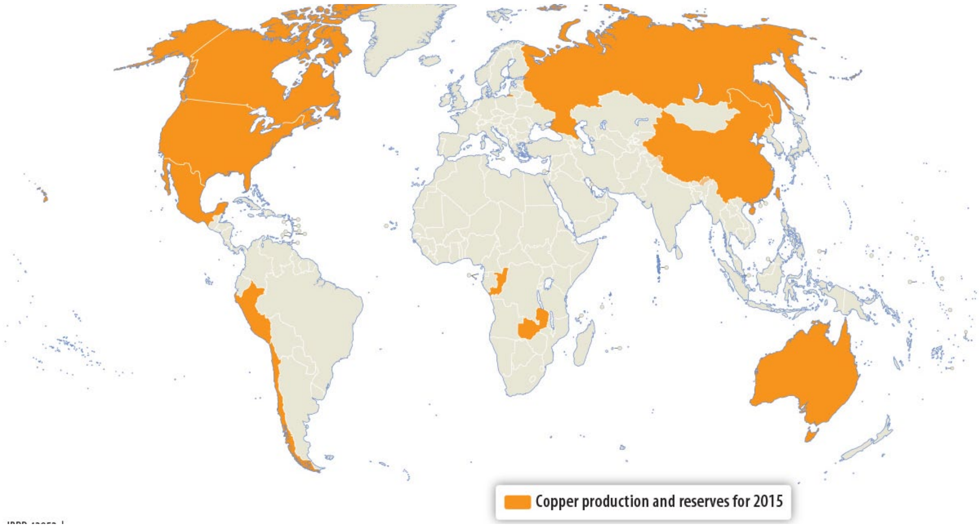
Developing countries' share of cobalt production: 75 percent; without China, 70 percent.

Developing countries' share of cobalt reserves: 68 percent; without China, 67 percent.

World resources: Identified world cobalt resources on land are about 25 million tons, and more than 120 million tons on the floors of the Atlantic, Indian, and Pacific Oceans.

Substitutes: The U.S. Geological Survey identifies more than 15 elements that could substitute for cobalt in different activities, including iron-phosphorous and manganese for lithium-ion batteries.

FIGURE 3.7 Copper Production and Reserves



Source: USGS 2016, 55.
Calculation of developing-countries' share does not include "Other countries" row in table 3.7.

TABLE 3.7 Copper Production and Reserves, 2015 (*thousand metric tons*)

	Production	Reserves
Chile	5,700	210,000
Australia	960	88,000
Peru	1,600	82,000
Mexico	550	46,000
United States	1,250	33,000
Russia	740	30,000
China	1,750	30,000
Democratic Republic of Congo	990	20,000
Zambia	600	20,000
Canada	695	11,000
Other countries	3,900	150,000
Total	**18,700**	**720,000**

Source: USGS 2016, 55.

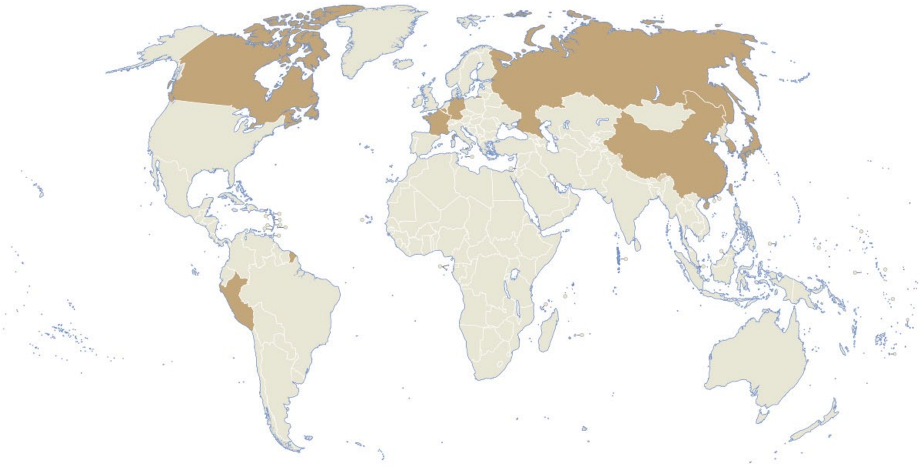
Developing countries' share of copper production: 57 percent; without China, 47 percent.

Developing countries' share of copper reserves: 50 percent; without China, 46 percent.

World resources: A 2014 U.S. Geological Survey global assessment of copper deposits indicated that identified resources contain about 2.1 billion tons of copper (porphyry deposits accounted for 1.8 billion tons of those resources), and undiscovered resources contained an estimated 3.5 billion tons.

Substitutes: Aluminum substitutes for copper in power cable, electrical equipment, automobile radiators, and cooling and refrigeration tubing; titanium and steel are used in heat exchangers; optical fiber substitutes for copper in telecommunications applications; and plastics substitute for copper in water pipe, drain pipe, and plumbing fixtures.

FIGURE 3.8 Indium Production



Source: USGS 2016, 81.
Calculation of developing-countries' share does not include "Other countries" row in table 3.8.

TABLE 3.8 Indium Production, 2015 (*metric tons*)

	Production
China	370
Korea, Republic of	150
Japan	72
Canada	65
France	38
Belgium	25
Peru	15
Germany	10
Russia	10
Total (rounded)	**755**

Source: USGS 2016, 81.

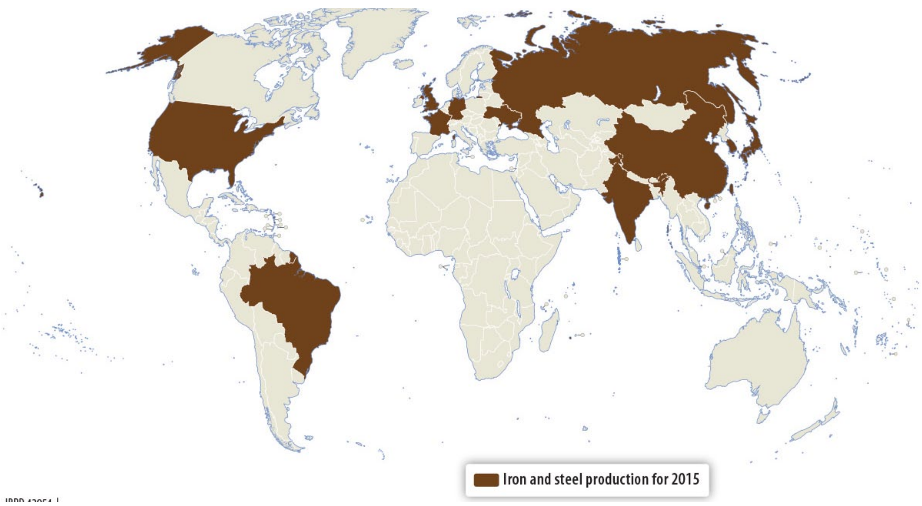
Note: Reserve levels not available.

Developing countries' share of indium production: 50 percent; without China, 1.5 percent.

World Resources: Indium is most commonly recovered from the zinc-sulfide ore mineral deposits. The indium content of zinc deposits from which it is recovered ranges from less than 1 part per million to 100 parts per million.

Substitutes: Antimony tin oxide coatings have been developed as an alternative to ITO coatings in LCDs and have been successfully annealed to LCD glass; carbon nanotube coatings have been developed as an alternative to ITO coatings in flexible displays, solar cells, and touch screens. Graphene has been developed to replace ITO electrodes in solar cells. Gallium arsenide can substitute for indium phosphide in solar cells and in many semiconductor applications.

FIGURE 3.9 Iron and Steel Production



Source: USGS 2016, 85.
Calculation of developing-countries' share does not include "Other countries" row in table 3.9.

TABLE 3.9 Iron and Steel Production, 2015 (*million metric tons*)

	Production	
	Pig iron	Raw steel
China	710	822
Japan	84	111
United States	26	81
India	54	83
Republic of Korea	47	72
Russia	51	71
Germany	54	44
Brazil	30	34
Ukraine	25	27
France	11	17
United Kingdom	9	12
Other countries	101	258
Total	**1,180**	**1,640**

Source: USGS 2016, 85.

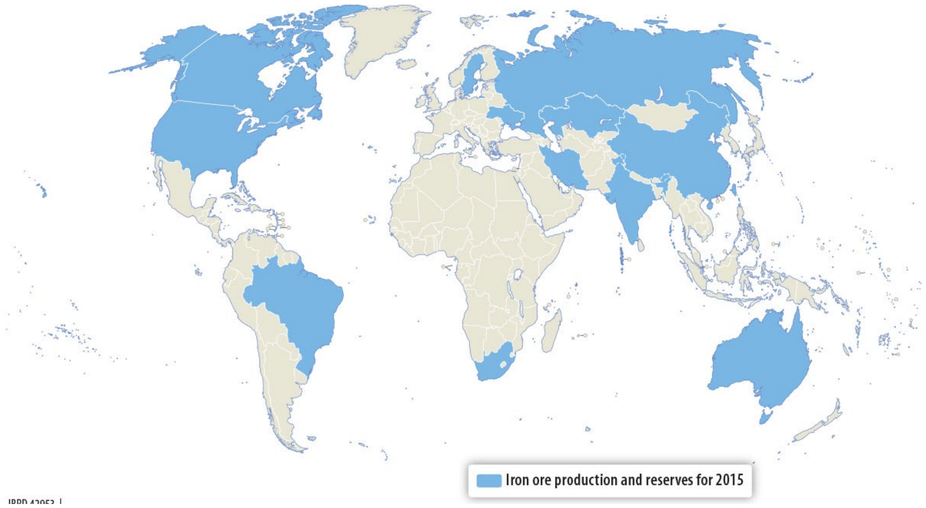
Developing countries' share of pig iron production: 67 percent; without China, 7 percent.

Developing countries' share of raw steel production: 57 percent; without China, 7 percent.

World Resources: Not applicable. See iron ore.

Substitutes: Iron is the least expensive and most widely used metal. In most applications, iron and steel compete either with less expensive nonmetallic materials or with more expensive materials that have a performance advantage. Iron and steel compete with lighter materials, such as aluminum and plastics, in the motor vehicle industry; aluminum, concrete, and wood in construction; and aluminum, glass, paper, and plastics in containers.

FIGURE 3.10 Iron Ore Production and Reserves



Source: USGS 2016, 91.
Calculation of developing-countries' share does not include "Other countries" row in table 3.10.

TABLE 3.10 Iron Ore Production and Reserves, 2015 (*million metric tons*)

		Reserves	
	Production	Crude ore	Iron content
China	1,380	23,000	7,200
Australia	824	54,000	24,000
Brazil	428	23,000	12,000
India	129	8,100	5,200
Russia	112	25,000	14,000
South Africa	80	1,000	650
Ukraine	68	6,500	2,300
United States	43	11,500	3,500
Canada	39	6,300	2,300
Sweden	37	3,500	2,200
Iran	33	2,700	1,500
Kazakhstan	25	2,500	900
Other countries	125	18,000	9,500
Total	**~3,320**	**190,000**	**85,000**

Source: USGS 2016, 91.

Developing countries' share of iron ore production: 62.5 percent; without China, 21 percent.

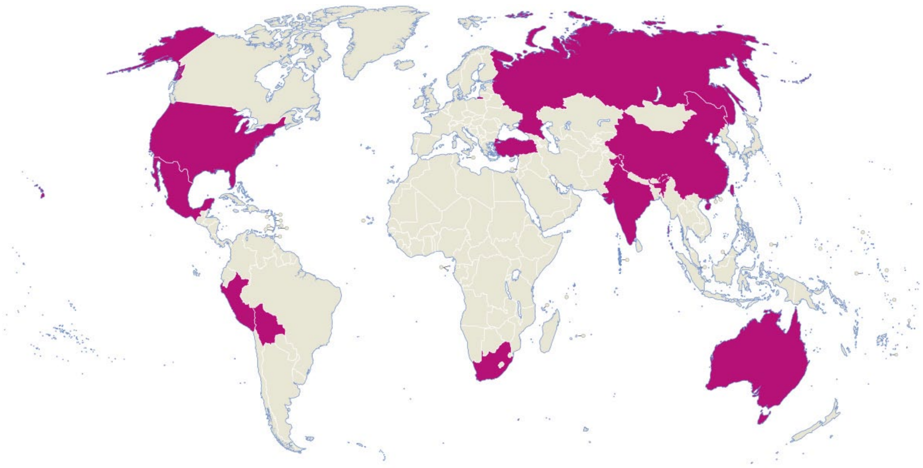
Developing countries' share of crude ore reserves: 32 percent; without China, 20 percent.

Developing countries' share of iron content reserves: 32 percent; without China, 23 percent.

World resources: World resources are estimated to be more than 800 billion tons of crude ore containing more than 230 billion tons of iron.

Substitutes: The only source of primary iron is iron ore, used directly as direct-shipping ore or converted to briquettes, concentrates, iron nuggets, pellets, or sinter. At some blast furnace operations, ferrous scrap may constitute as much as 7 percent of the blast furnace feedstock, iron nuggets, and scrap are extensively used for steelmaking in electric arc furnaces and in iron and steel foundries, but scrap availability can be limited. Technological advancements have been made that allow hematite to be recovered from tailings basins and pelletized.

FIGURE 3.11 Lead Production and Reserves



Source: USGS 2016, 97.
Calculation of developing-countries' share does not include "Other countries" row in table 3.11.

TABLE 3.11 Lead Production and Reserves, 2015 (*thousand metric tons*)

	Production	Reserves
Australia	385	35,000
China	2,300	15,800
Russia	90	9,200
Peru	300	6,700
Mexico	240	5,600
United States	385	5,000
India	130	2,200
Poland	40	1,700
Bolivia	82	1,600
South Africa	40	300
Turkey	54	860
Other countries	225	3,000
Total	**4,271**	**86,960**

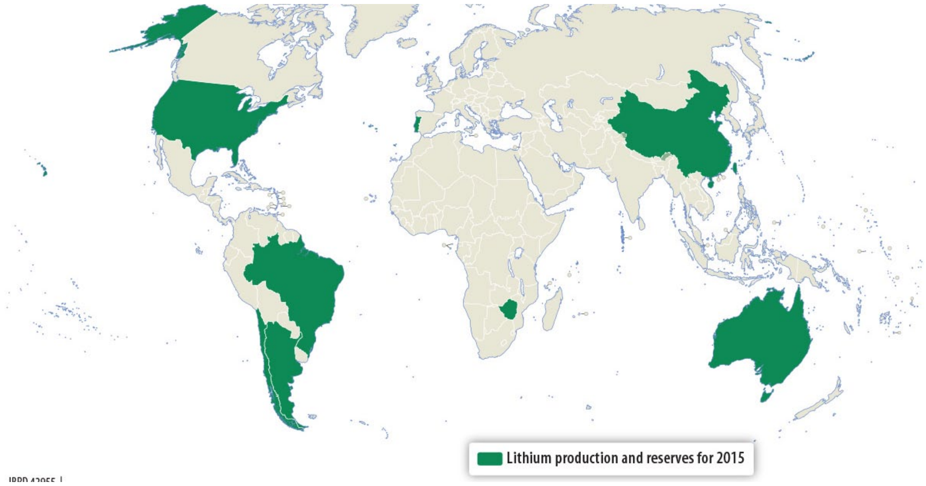
Developing countries' share of lead production: 71 percent; without China, 14 percent.

Developing countries' share of lead reserves: 66 percent; without China, 47 percent.

World Resources: Identified world lead resources total more than 2 billion tons. In recent years, significant lead resources have been identified in association with zinc and/or silver or copper deposits in Australia, China, Ireland, Mexico, Peru, Portugal, Russia, and the United States (Alaska).

Substitutes: Substitution of plastics has reduced the use of lead in cable covering and cans. Tin has replaced lead in solder for potable water systems.

FIGURE 3.12 Lithium Production and Reserves



Source: USGS 2016, 101.
Calculation of developing-countries' share does not include "Other countries" row in table 3.12.

TABLE 3.12 Lithium Production and Reserves, 2015 (*metric tons)*

	Production	Reserves
Chile	11,700	7,500,000
China	2,200	3,200,000
Argentina	3,800	2,000,000
Australia	13,400	1,500,000
Portugal	300	60,000
Zimbabwe	900	23,000
Brazil	160	48,000
United States	N/A	N/A
Total	**~ 32,500**	**~ 14,000,000**

Source: USGS 2016, 101.

Note: N/A = not available.

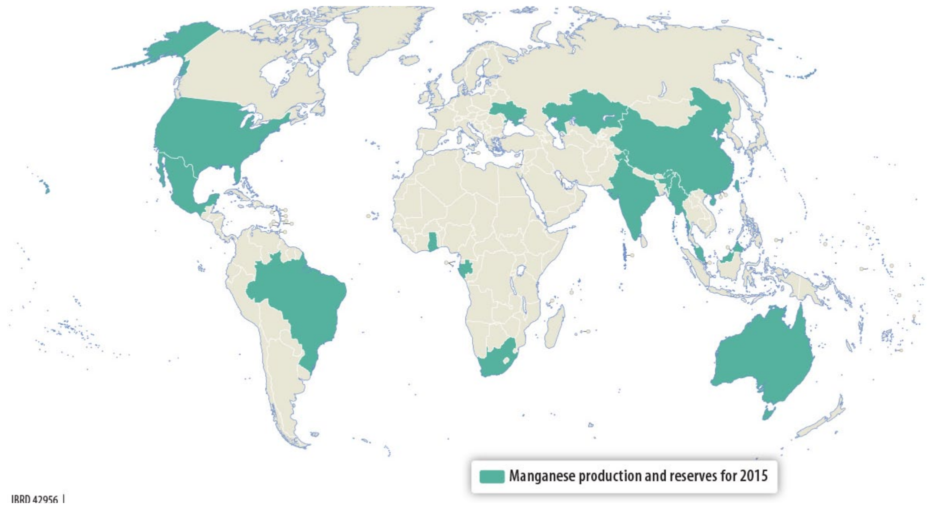
Developing countries' share of lithium production: 52 percent; without China, 45 percent.

Developing countries' share of lithium reserves: 91 percent; without China, 68 percent.

World resources: Identified lithium resources in the United States have been revised to 6.7 million tons and total approximately 34 million tons in other countries. Identified lithium resources in Bolivia and Chile are 9 million tons and more than 7.5 million tons, respectively. Identified lithium resources in major producing countries are Argentina, 6.5 million tons; Australia, 1.7 million tons; and China, 5.1 million tons. In addition, Canada, Congo (Kinshasa), Russia, and Serbia have resources of approximately 1 million tons each. Identified lithium resources in Brazil and Mexico are 180,000 tons each, and Austria has 130,000 tons.

Substitutes: Substitution for lithium compounds is possible in batteries, ceramics, greases, and manufactured glass. Examples are calcium, magnesium, mercury, and zinc as anode material in primary batteries.

FIGURE 3.13 Manganese Production and Reserves



Source: USGS 2016, 107.
Calculation of developing-countries' share does not include "Other countries" row in table 3.13.

TABLE 3.13 Manganese Production and Reserves, 2015 (*thousand metric tons*)

	Production	Reserves
South Africa	6,200	200,000
Ukraine	390	140,000
Australia	2,900	91,000
India	950	52,000
Brazil	1,000	50,000
China	3,000	44,000
Gabon	1,800	22,000
Ghana	390	13,000
Kazakhstan	390	5,000
Mexico	240	5,000
Malaysia	400	N/A
Burma	100	N/A
United States	N/A	N/A
Other countries	740	Small
Total	**18,000**	**620,000**

Source: USGS 2016, 107.

Note: N/A = not available.

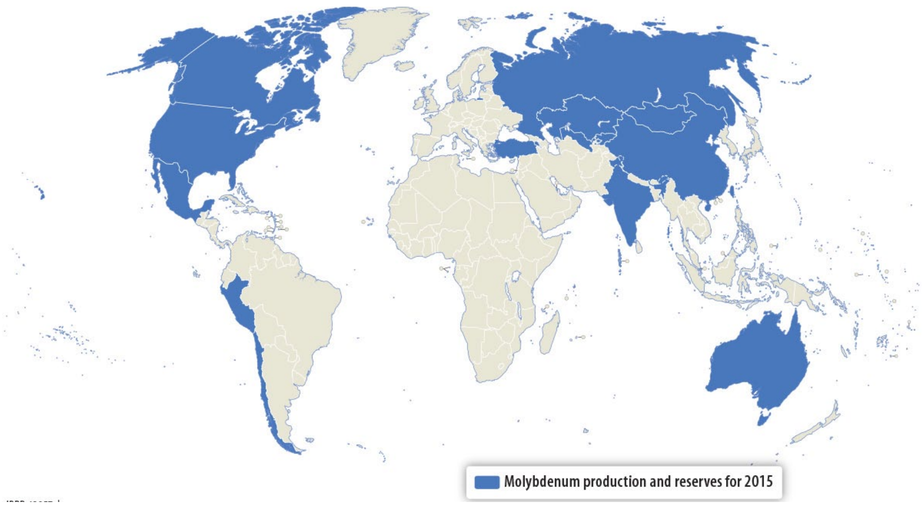
Developing countries' share of manganese production: 79 percent; without China, 63 percent.

Developing countries' share of manganese reserves: 54 percent; without China, 47 percent.

World resources: Land-based manganese resources are large but irregularly distributed. South Africa accounts for about 75 percent of the world's identified manganese resources, and Ukraine accounts for about 10 percent.

Substitutes: Manganese has no satisfactory substitute in its major applications.

FIGURE 3.14 Molybdenum Production and Reserves



Source: USGS 2016, 113.
Calculation of developing-countries' share does not include "Other countries" row in table 3.14.

TABLE 3.14 Molybdenum Production and Reserves, 2015

	Production (metric tons)	Reserves (thousand metric tons)
China	101,000	4,300
United States	56,300	2,700
Chile	49,000	1,800
Peru	18,100	450
Mexico	13,000	130
Canada	9,300	260
Armenia	7,300	150
Russia	4,800	250
Iran	4,000	43
Mongolia	2,000	160
Turkey	1,400	100
Uzbekistan	520	60
Australia	0	190
Kazakhstan	0	130
Kyrgyz Republic	N/A	100
Total	**267,000**	**11,000**

Source: USGS 2016, 113.

Note: N/A = not available.

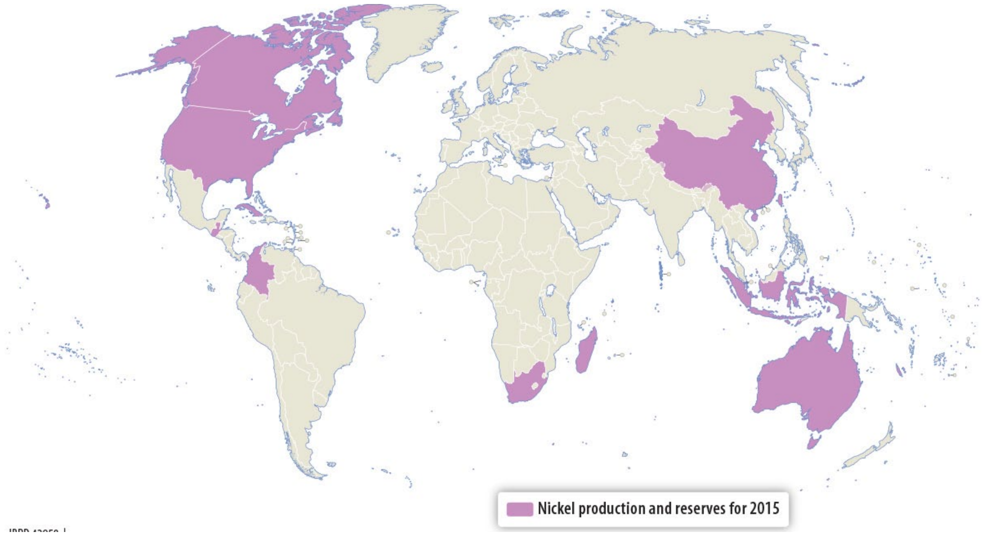
Developing countries' share of molybdenum production: 69 percent; without China, 31 percent.

Developing countries' share of molybdenum reserves: 66 percent; without China, 27 percent.

World resources: Identified resources of molybdenum in the world are 19.4 million tons. Resources of molybdenum are adequate to supply world needs for the foreseeable future.

Substitutes: There is little substitution for molybdenum in its major application as an alloying element in steels and cast irons. In fact, because of the availability and versatility of molybdenum, industry has sought to develop new materials that benefit from the alloying properties of the metal.

FIGURE 3.15 Nickel Production and Reserves



Source: USGS 2016, 115.
Calculation of developing-countries' share does not include "Other countries" row in table 3.15.

TABLE 3.15 Nickel Production and Reserves, 2015 (*metric tons*)

	Production	Reserves
Australia	234,000	19,000,000
New Caledonia	190,000	8,400,000
Cuba	57,000	5,500,000
Indonesia	170,000	4,500,000
South Africa	53,000	3,700,000
China	102,000	3,000,000
Canada	240,000	2,900,000
Guatemala	50,000	1,800,000
Madagascar	49,000	1,600,000
Colombia	73,000	1,100,000
United States	26,500	160,000
Other countries	410,000	6,5000,000
Total	**2,530,000**	**79,000,000**

Source: USGS 2016, 115.

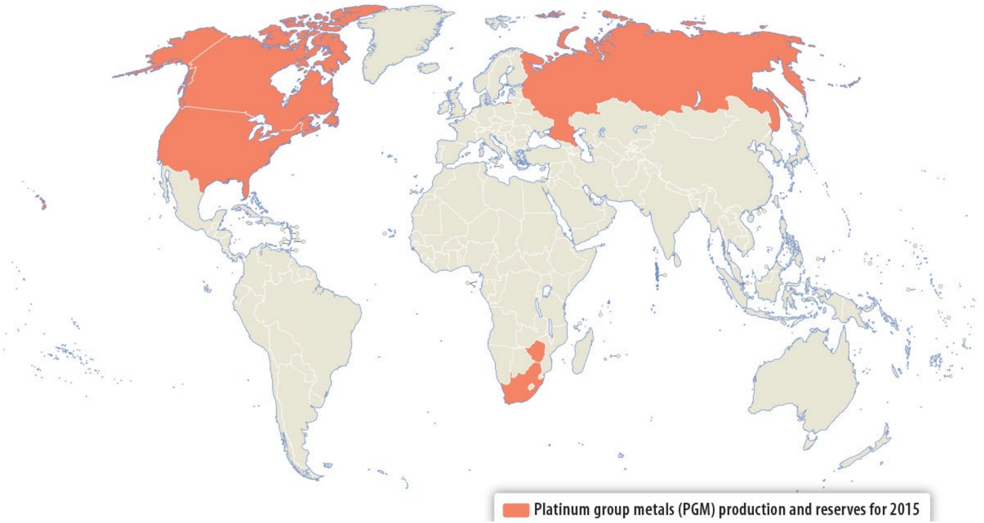
Developing countries' share of nickel production: 29 percent; without China, 25 percent.

Developing countries' share of nickel reserves: 37 percent; without China, 34 percent.

World resources: Identified land-based resources averaging 1 percent nickel or greater contain at least 130 million tons of nickel, with about 60 percent in laterites and 40 percent in sulfide deposits. Extensive nickel resources also are found in manganese crusts and nodules on the ocean floor. The decline in discovery of new sulfide deposits in traditional mining districts has led to exploration in more challenging locations such as east-central Africa and the subarctic.

Substitutes: Low-nickel, duplex, or ultrahigh-chromium stainless steels are being substituted for austenitic grades in construction. Nickel-free specialty steels are sometimes used in place of stainless steel in the power-generating and petrochemical industries. Titanium alloys can substitute for nickel metal or nickel-base alloys in corrosive chemical environments. Lithium-ion batteries instead of nickel-metal hydride may be used in certain applications.

FIGURE 3.16 Platinum Production and Reserves



Source: USGS 2016, 127.
Calculation of developing-countries' share does not include "Other countries" row in table 3.16.

TABLE 3.16 Platinum Group Metals (PGM) Production and Reserves, 2015 (*kilograms*)

	Production		Reserves
	Platinum	Palladium	PGM
South Africa	125,000	73,000	63,000,000 (+)
Russia	23,000	80,000	1,100,000
Zimbabwe	12,500	10,000	N/A
United States	3,700	12,500	900,000
Canada	9,000	24,000	310,000
Other countries	4,800	8,000	800,000
Total	**178,000**	**208,000**	**66,000,000**

Source: USGS 2016, 127.

Note: N/A = not available.

Developing countries' share of platinum production: 77 percent (China has none).

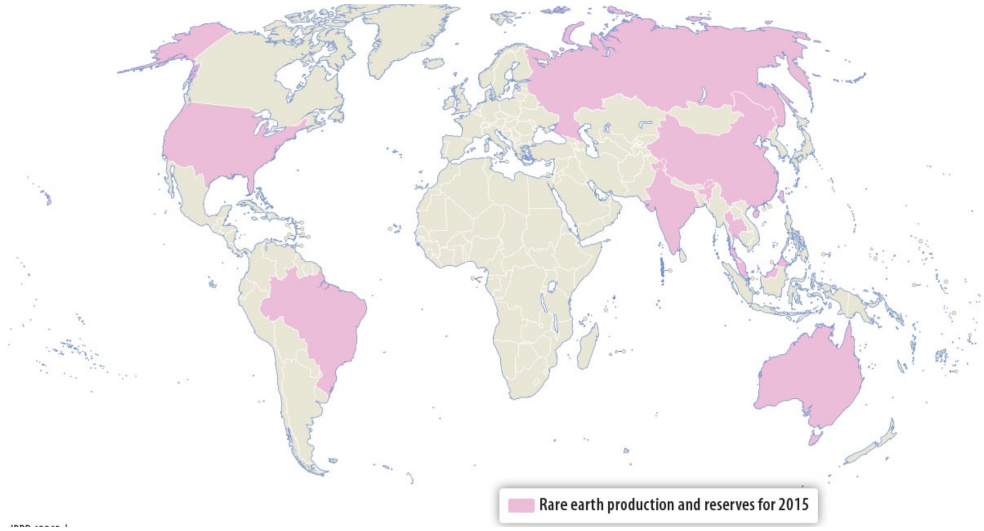
Developing countries' share of palladium production: 40 percent (China has none).

Developing countries' share of PGM reserves: greater than 95 percent (China has none).

World resources: World resources of PGMs are estimated to total more than 100 million kilograms. The largest reserves are in the Bushveld Complex in South Africa.

Substitutes: Less expensive palladium has been substituted for platinum in most gasoline-engine catalytic converters. About 25 percent palladium can routinely be substituted for platinum in diesel catalytic converters; the proportion can be as much as 50 percent in some applications. For some industrial end uses, one PGM can substitute for another, but with losses in efficiency.

FIGURE 3.17 Rare Earth Production and Reserves



Source: USGS 2016, 135.
Calculation of developing-countries' share does not include "Other countries" row in table 3.17.

TABLE 3.17 Rare Earth Production and Reserves, 2015[a] (*metric tons*)

	Production	Reserves
China	105,000	55,000,000
Brazil	0	22,000,000
Australia	10,000	3,200,000
India	N/A	3,100,000
United States	4,100	1,800,000
Malaysia	200	30,000
Russia	2,500	(Listed in other countries)
Thailand	2,000	N/A
Other countries	N/A	41,000,000
Total	**124,000**	**130,000,000**

Source: USGS 2016, 135.

Note: N/A = not available.

[a] Includes key metals necessary for some low carbon technologies, including neodymium.

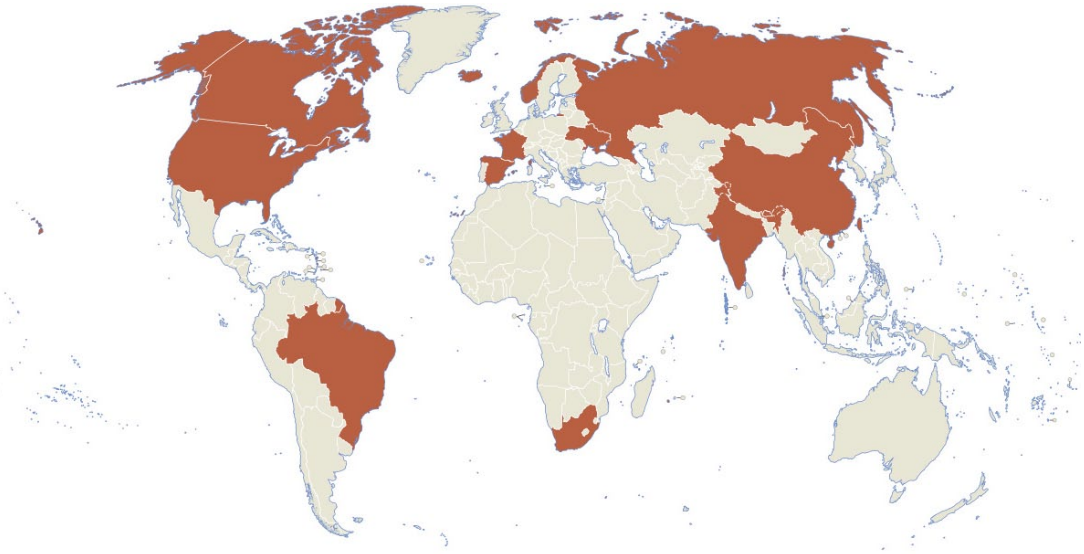
Developing countries’ share of rare earth production: 86 percent; without China, 2 percent.

Developing countries’ share of rare earth reserves: 62 percent; without China, 19 percent.

World resources: Rare earths are relatively abundant in the Earth’s crust, but discovered minable concentrations are less common than for most other ores. World resources are contained primarily in bastnäsite and monazite. Bastnäsite deposits in China and the United States constitute the largest percentage of the world’s rare earth economic resources, and monazite deposits constitute the second largest segment.

Substitutes: Substitutes are available for many applications but generally are less effective.

FIGURE 3.18 Silicon Production



Source: USGS 2016, 151.
Calculation of developing-countries’ share does not include “Other countries” row in table 3.18.

TABLE 3.18 Silicon Production, 2015 (*thousand metric tons*)

	Production
China	5,500
Russia	680
United States	410
Norway	330
Brazil	150
France	130
India	86
South Africa	84
Spain	81
Iceland	75
Bhutan	72
Ukraine	70
Canada	52
Other countries	380
Total	**8,100**

Source: USGS 2016, 151.

Developing countries' share of silicon production: 77 percent; without China, 10 percent.

World resources: Global resources (in the form of silica) for manufacturing silicon metals is abundant and more than adequate to supply world requirements for many decades.

Substitutes: A relatively new crystalline material, perovskites, is being seriously touted as a feasible alternative to silicon in solar panels.

FIGURE 3.19 Silver Production and Reserves

Source: USGS 2016, 153.
Calculation of developing-countries' share does not include "Other countries" row in table 3.19.

TABLE 3.19 Silver Production and Reserves, 2015 (*metric tons*)

	Production	Reserves
Peru	3,800	120,000
Australia	1,700	85,000
Poland	1,300	85,000
Chile	1,600	77,000
China	4,100	43,000
Mexico	5,400	37,000
United States	1,100	25,000
Bolivia	1,300	22,000
Russia	1,500	20,000
Canada	500	7,000
Other countries	5,000	50,000
Total	**27,300**	**570,000**

Source: USGS 2016, 153.

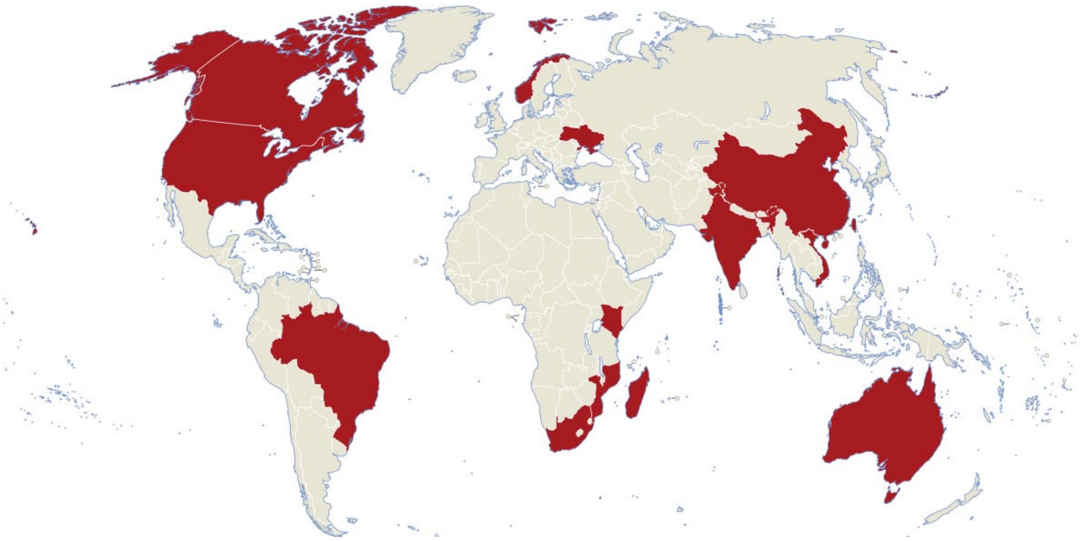
Developing countries' share of silver production: 40 percent; without China, 25 percent.

Developing countries' share of silver reserves: 46 percent; without China, 38 percent.

World resources: Although silver was a principal product at several mines, silver was primarily obtained as a by-product from lead-zinc mines, copper mines, and gold mines, in descending order of production. The polymetallic ore deposits from which silver was recovered account for more than two-thirds of world resources of silver. Most recent silver discoveries have been associated with gold occurrences; however, copper and lead-zinc occurrences that contain by-product silver will continue to account for a significant share of future reserves and resources.

Substitutes: Nonsilver batteries may replace silver batteries in some applications. Silver may be used to replace more costly metals in catalytic converters for off-road vehicles.

FIGURE 3.20 Titanium Mineral Concentrates Production and Reserves



Source: USGS 2016, 179.
Calculation of developing-countries' share does not include "Other countries" row in table 3.20.

TABLE 3.20 Titanium (Ilmenite) Mineral Concentrates Production and Reserves, 2015 (*thousand metric tons*)

	Production	Reserves
China	900	200,000
Australia	720	140,000
India	210	85,000
South Africa	480	63,000
Kenya	430	54,000
Brazil	100	43,000
Madagascar	240	40,000
Norway	420	37,000
Canada	360	31,000
Mozambique	450	14,000
Ukraine	240	5,900
United States	100	2,000
Vietnam	540	1,600
Other countries	90	26,000
Total	**5,610**	**740,000**

Source: USGS 2016, 179.

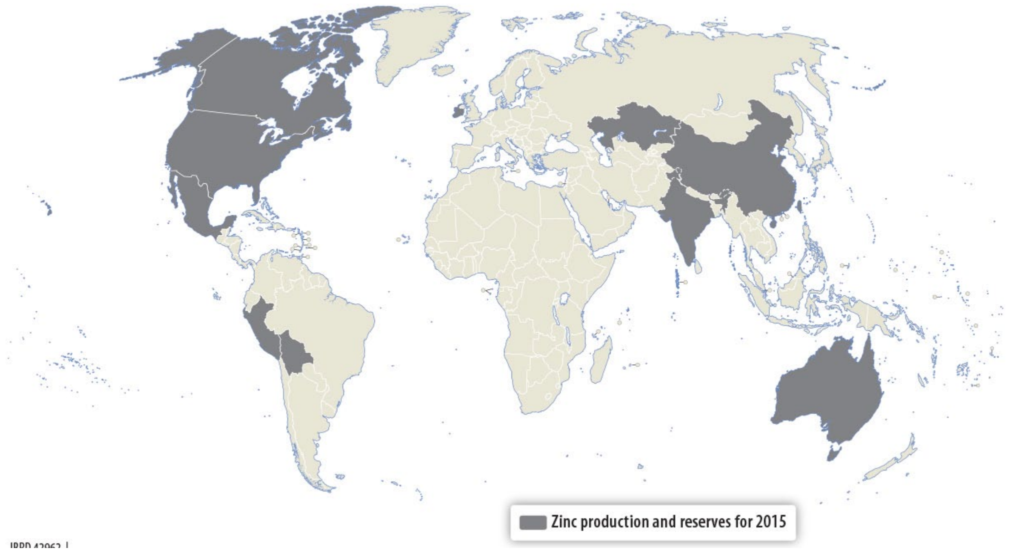
Developing countries’ share of titanium (ilmenite) production: 61 percent; without China, 44 percent.

Developing countries’ share of titanium (ilmenite) reserves: 70 percent; without China, 42 percent.

World Resources: Ilmenite accounts for about 92 percent of the world’s consumption of titanium minerals. World resources of anatase, ilmenite, and rutile total more than 2 billion tons.

Substitutes: Ilmenite, leucoxene, rutile, slag, and synthetic rutile compete as feedstock sources for producing TiO_2 pigment, titanium metal, and welding-rod coatings.

FIGURE 3.21 Zinc Production and Reserves



Source: USGS 2016, 193.
Calculation of developing-countries' share does not include "Other countries" row in table 3.21.

TABLE 3.21 Zinc Production and Reserves, 2015 (*thousand metric tons*)

	Production	Reserves
Australia	1,580	63,000
China	4,900	38,000
Peru	1,370	25,000
Mexico	660	15,000
India	830	10,000
United States	850	11,000
Canada	300	6,200
Bolivia	430	4,600
Kazakhstan	340	4,000
Ireland	230	1,100
Other countries	1,870	26,000
Total	**13,400**	**200,000**

Source: USGS 2016, 193.

Developing countries' share of zinc production: 59 percent; without China, 22 percent.

Developing countries' share of zinc reserves: 41 percent; without China, 22 percent.

World resources: Identified zinc resources of the world are about 1.9 billion metric tons.

Substitutes: Aluminum and plastics substitute for galvanized sheet in automobiles; and aluminum alloy, cadmium, paint, and plastic coatings replace zinc coatings in other applications. Aluminum- and magnesium-based alloys are major competitors for zinc-based die-casting alloys.

Notes

1. http://www.worldbank.org/en/topic/extractiveindustries/overview.
2. All data and statistics are taken from United States Geological Survey (USGS) 2016 Mineral Commodity Summaries.
3. USGS Program 2012, Annex C, Part A, p. 193 (https://minerals.usgs.gov/minerals/pubs/mcs/2012/mcsapp2012.pdf).
4. USGS Program 2012, Annex C, Part A, p. 194 (https://minerals.usgs.gov/minerals/pubs/mcs/2012/mcsapp2012.pdf).

4. Conclusion

This study aims to build awareness of the critical role that mining and metals will need to play in the global zero carbon transition over this century, with a specific focus on the position and capacity of mineral-resource-rich developing countries to supply the carbon-constrained future.

It is clear that meeting the Paris climate target of not exceeding 2 degrees Celsius (2°C) (and making best efforts to reach 1.5°C) global warming over this century will require a radical (that is, to the root) restructuring of energy supply and transmission systems globally.[1] Furthermore, the technologies assumed to populate the clean energy shift (wind, solar, hydrogen and electricity systems) are in fact significantly MORE material intensive in their composition than current traditional fossil-fuel-based energy supply systems (Vidal, Goffé, and Arndt 2013). Our analysis in Chapter 2 indicates a rapid rise in demand for relevant technologies and corollary metals between reaching a 4DS and 2DS climate objective. Relevant metals demand roughly doubles for wind and solar technologies, but the most significant upsurge occurs with energy battery storage technologies—more than a 1000 percent rise for metals required for that particular clean energy option.

Key base metals including copper, silver, aluminum (bauxite), nickel, zinc, and possibly platinum, among others, are expected to benefit from a low carbon energy shift over the century. Key rare earth metals (at least for the three technologies analyzed in depth in this study) are neodymium and indium, among others. However, the actual metals that will experience dramatic increases is unclear and extremely difficult to predict.

Furthermore, the form in which metal demand will increase depends on both inter-technology choices, such as the balance between wind and solar power, and intra-technology choices within particular technologies.

Regarding intra-technology choices,

- For wind technologies, it is a matter of the eventual mix between geared (onshore) or direct-drive (offshore) technologies. To give but one example of the implications for metals, direct-drive systems require neodymium, while geared systems do not.
- For solar, it is a matter of the choice between different types of solar photovoltaic cells. For example, aluminum and copper feed different solar technologies, with real consequences for these metals' prospective markets over the next few decades.
- However, it is in the area of transportation that the impacts on particular metals' future markets is probably most pronounced. The current three options of electric (lithium), hybrid (lead), and hydrogen (platinum) each have their own particular metal needs.

These choices suggest that the world needs to be prepared to not only meet increased overall demand for metals under low carbon scenarios but also to be flexible to meet shifting demand for individual metals as these broad choices between and within technologies start to narrow through economic and technical developments.

Although many of the resources required to supply carbon-constrained technologies are prominent in resource-rich developing countries, it is also clear that the level of geographical data on critical metals, including rare earth metals, is wanting in many developing countries (Brazil, Chile, China, and South Africa being among the exceptions). Second, even when reserves have been identified in developing countries, more often than not, production levels are markedly lower than in more developed countries (for example, Australia). There are also a number of instances in which critical ore lodes (such as lithium in Bolivia and the Democratic Republic of Congo) are not sufficiently developed to enjoy "reserve" status.

Going Forward

This study is a relatively small first step toward identifying future metal trends resulting from a low carbon future and determining the prospects for developing countries.

Areas for further research or investigation can fall into two categories: policy and technological.

Policy-related areas of inquiry include the following:

- **Implications for future environmental and material impact performance.** Studies on commodity implications of a carbon-constrained future typically focus on current reserves and the relative level of availability and access to materials to supply clean technology production scenarios. However, there is also an increasing sensitivity that supplying clean technologies required for a carbon-constrained future could create a new suite of challenges for the sustainable development of minerals and resources. Simply put, a green technology future is materially intensive and, if not properly managed, could bely the efforts and policies of supplying countries to meet their objectives of meeting climate and related Sustainable Development Goals. It also carries potentially significant impacts for local ecosystems, water systems, and communities. A dialogue is required at the national and civil society levels within resource-rich developing countries, between the mining-metals and climate–environmental–clean-energy constituencies, to develop a path forward that aligns a potential growing market for key commodities with a sustainable future.

- **Mapping minerals in developing countries.** There is a significant gap in data and mineral mapping in many developing country regions, particularly Africa. The U.S. Geological Survey provides the most publicly available and sophisticated and updated information on commodity production and reserves, but its primary client, naturally, is the U.S. government. In addition, the United States, the European Union, and Japan have also established nationally funded programs tracking access to and availability of critical and rare earth metals that would also play a role in supplying clean energy technologies. No such institutional capacity is evident in most developing country regions. Capacity in this area is critical for resource-rich developing countries to best benefit from economic growth in their respective countries.

- **Predicting technology choice based on supply constraints and demand patterns.** As documented above, much of the uncertainty relating to the potential demand for many metals arises as much from intra-technology choices as it does from inter-technology choices. One likely driving factor for such choices is the availability, and most crucially the cost, of key metal inputs. Understanding where supply constraints may lie, and where prices are most likely to rise, may help inform the possible direction of some of these choices, which, in turn, can help clarify demand.

- **Developing networks and raising awareness.** One of the outcomes of this analysis is the realization that the implications of this work go far beyond the traditional minerals and metals community. Linkages should be pursued and facilitated among research and social communities, such as
    - Relevant developing country governments and programs supporting resource extraction
    - Climate change and clean energy communities and research organizations.
    - Resource development and Sustainable Development research organizations
    - Critical metals institutes and associations
    - Industrial ecology academic programs

Technology-related areas of inquiry pertain mostly to **expanding the scope of future clean technologies**. Although the literature review in annex A lightly covers additional clean technologies crucial to the low carbon future, more detailed research in each of those areas would be critical. Other technology options and transmission modes (for example, the infrastructure implications of decentralized grids) are also not included in the Literature Review but should be covered. Areas to be covered might include the following:

- **Electrical cabling and high-efficiency electric motors.** Both copper and aluminum have long been used as conductors in electric wire and electric motors. The spread of distributed energy generation and electricity access is likely to increase future demand for more electrical cabling. However, the demand increase for that cabling and the market share of copper versus aluminum cabling are unclear. Similarly, for electric motors, multiple studies indicate that motors with copper rotors and stators are more efficient than those with aluminum rotors (Kirtley et al. 2009; Waide and Brunner 2011). As the need for high efficiency motors increases, the demand for copper for motor applications may correspondingly increase, but quantitative projections on this trend are limited.

- **Light-weighting of vehicles.** Lighter vehicles are more fuel efficient. Creating them might involve changing alloy mixtures, replacing steel with aluminum, or replacing metals in general with carbon fiber. These substitutions may significantly affect metal demand.

- **Energy-efficient technologies and buildings.** A large part of any low carbon transition would be achieved through the implementation of energy-efficiency measures, including new technologies. The metal footprint of such technologies could be substantial, but little or no data exist in this area, save for some studies on light-emitting diode (LED) lighting.

- **Transmission and distribution** is a vital part of the energy system and is an important source of metal demand. Future transmission and distribution systems are also likely to look different from those of today, especially if distributed renewable generation increases significantly. The literature on the metal intensity of electricity grids is very limited, and few scenarios are available for the extent of future investment in grids. Further research in this area would be highly beneficial.

- **Metal intensity of traditional and next-generation fossil fuel plants and nuclear facilities.** Much of the literature focuses on the metal intensity of renewable technologies. However, a credible baseline must be constructed to fully understand the impact of a shift to a low carbon economy. There is a dearth of literature examining the current and potential metal footprint of fossil fuel generation technologies. The inclusion of nuclear plants complicates the picture even more because of the complex technological choices that are available in this area. The potential metal intensity of carbon capture and storage adds even a further layer of complexity because of the lack of commercially operating facilities. Further work is required here to create a good understanding of the current metal footprint of the energy industry, and what a business-as-usual metal footprint might consist of.

- **Metal supply and metal families.** The availability and cost of several critical metals is complicated by the fact that they are secondary metals found in ores such as bauxite or copper for which the primary metal accounts for the main economic value. For example, rare earth metals such as indium and germanium are dependent on zinc production, and the supply and demand balance for these three metals are, as a result, entangled. In short, how will demand for the coproducts drive demand for the base metal?

- Further work would also be useful with respect to key **rare earth metals**, with regard to both disaggregation capacity for these products (rare earth metals are typically not economically or physically retrievable as discrete ores, but often enmeshed with other base metals, as mentioned above for zinc) and their geological location. Currently, very little mapping of available rare earths in key regions of the developing world, particularly Africa, has been undertaken.

- **Recycling rate.** The recycling of metals from end-of-life products can improve the future availability of those metals, but data on both current and future metal recycling rates are often poor. To further this analysis of metal criticality in the energy industry, data on current and future recycling rates should be improved.

Notes

1. Just as a reminder, for the purposes of this exercise, this report does not evaluate the actual prospects for meeting the Paris Agreement's targets. World Bank policy is clear that temperature rise of 2°C or more must be avoided, and this study proceeds on that guidance.

Annex A. Literature Review

Two types of studies assess demand for metals in a future low carbon economy. The first focuses on transforming the energy system and examines metal demand, and sources of supply, for a wide range of low carbon energy technologies. These studies focus on either a regional or a global scale. The second category of literature examines individual low carbon energy technologies in more detail. These studies outline the different options for designing each low carbon energy technology and discuss the metal implications for each option. These two types of studies investigate both energy-generating technologies, renewable and otherwise, and energy-using technologies such as lighting, vehicles, and motors.

System-Wide Approach

The U.S. Department of Energy (2011) examines the role of rare earth metals and other materials in low carbon energy in the U.S. economy for 2025. The report focuses on a number of low carbon technologies, including wind, solar photovoltaics (PV), electric vehicles, and lighting, finding that production of these technologies could be disrupted by short-term supply challenges for five rare earth metals (dysprosium, neodymium, terbium, europium, and yttrium). These metals are critical for producing magnets in wind turbines and electric vehicles and phosphors in energy-efficient lighting.

Similar work in the European Union examines potential supply bottlenecks for abiotic and biotic materials (European Commission 2014) and for critical metals in meeting the European Union's Strategic Energy Technology Plan by 2020 (Moss et al. 2011; Moss et al. 2013). Moss et al. (2011) examine material requirements to produce wind, solar PV and concentrating solar power (CSP), carbon capture and storage, nuclear fission, bioenergy technologies, and an updated electricity grid. The study finds five metals were ranked "critical" for the roll-out of these technologies: tellurium, indium, gallium, neodymium, and dysprosium. The follow-up study (Moss et al. 2013) examines further technologies, including fuel cells, electricity storage, electric vehicles, and lighting. Eight metals were identified as critical for these technologies: dysprosium, europium, terbium, yttrium, praseodymium, neodymium, gallium, and tellurium.

An extensive study by Grandell et al. (2016) examines a number of technologies, including wind, solar, fuel cells, batteries, electrolysis, hydrogen storage, electric vehicles, and energy-efficient lighting, looking for bottlenecks in the global transition to a low carbon economy by 2050. Using a global energy model, the authors find that silver is particularly critical for the energy transition and tellurium, indium, and dysprosium to a lesser extent. They conclude that the Intergovernmental Panel on Climate Change renewable energy scenarios are wanting because they do not consider potential shortages in critical rare earth metals, particularly for solar PV and CSP.

A report by Dawkins et al. (2012) examined the use of five key metals—cobalt, lithium, neodymium, indium, and tellurium—in low carbon technologies. Using scenarios from the International Energy Agency and the World Economic Forum, they find that the solar PV industry is most likely to be affected by metal shortages, with severe risks of cumulative supply deficits of indium and tellurium, moderate risks for neodymium, and limited risks for cobalt and lithium.

Speirs, Gross, et al. (2014) reviewed a range of modeling studies to examine the evidence for future demand for and supply of critical metals in the low carbon transition. They focus their investigation on cobalt, gallium, germanium, indium, lithium, platinum group metals, rare earth metals, selenium, silver, and tellurium, which are used in key technologies such as thin film PV, light-emitting diode (LED) lighting, lithium-ion batteries, hydrogen fuel cells, electric vehicles, CSP, nuclear, and wind turbines. From their review they conclude that demand for these critical metals is expected to grow significantly; there is little evidence to suggest that resource shortages are affecting production growth today or will in the short term, but exponentially rapid rates of production cannot continue indefinitely. The availability and cost of several critical metals are complicated by the fact that they are secondary metals found in ores such as bauxite or copper for which the primary metal accounts for the main economic value. Recycling of critical metals from end-of-life products can assist in helping future availability but is unlikely to be sufficient to satisfy all demand.

Technology-Specific Studies

This section reviews studies that investigate the metal footprints of key energy-supplying and energy-using technologies. Many types of renewable electricity generation technologies could be deployed. Each is at a different stage of maturity. The literature on the use of metals in renewable electricity generation has, however, focused predominantly on two technologies: wind and solar power. Many other renewable options exist, such as hydropower, geothermal, wave and tidal power, biofuels, and hydrogen fuel cells; there is, however, a dearth of technology-specific literature, although these technologies have been covered in much of the system-wide literature discussed above. There is agreement in the literature that there are no anticipated issues for the supply of metals to produce these technologies in future energy systems.

Wind

Wind energy is transformed to electrical energy by spinning wind turbines that drive electrical generators. Wilburn (2011) estimates that meeting 20 percent of U.S. electricity demand from wind by 2030 would require 1.5 million metric tons of steel, 310,000 metric tons of cast iron, 40,000 metric tons of copper, and 380 metric tons of neodymium, but only the supply of neodymium may be an issue.

In an investigation into the criticality of various metals for renewable energy technologies in the European Union, Öhrlund (2012) finds that widespread deployment of wind and solar PV may significantly increase demand for eight metals: gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium, and terbium. Demand for these metals would be met almost exclusively by virgin raw material extraction.

See table A.1 for the metals necessary for wind turbine manufacturing.

TABLE A.1 Metals Used in Wind Turbine Manufacturing

Metal	Range of estimates (kilograms/megawatt)	Notes
Aluminum (Al)	Unknown	—
Boron (B)	0.8–7.0	Lower estimate is for high–medium speed turbines; higher estimate is for low-speed turbines.
Chromium (Cr)	789–902	—
Copper (Cu)	1,140–3,000	—
Dysprosium (Dy)	2.8–25.0	Lower estimate is for high–medium speed turbines; higher estimate is for low-speed turbines.
Iron (in magnet)	52–455	Lower estimate is for high–medium speed turbines; higher estimate is for low-speed turbines.
Iron (cast)	20,000–23,900	—
Lead (Pb)	Unknown	—
Manganese (Mn)	32.5–80.5	—
Molybdenum (Mo)	116–136	—
Neodymium (Nd)	0–186	Lower estimate is for current-generation onshore turbine; higher estimate is for 2025 mix of direct-drive and hybrid-drive turbines.
Nickel (Ni)	557–663	—
Praseodymium (Pr)	4–35	Lower estimate is for high–medium speed turbines; higher estimate is for low-speed turbines
Steel	103,000–115,000	—
Terbium (Tb)	0.8–7.0	Lower estimate is for high–medium speed turbines; higher estimate is for low-speed turbines
Zinc (Zn)	5,150–5,750	Estimated based on the amount of zinc used for galvanizing engineering steel.

Solar Photovoltaics

Solar PV transforms light energy into electrical energy through the use of semiconductor materials. Candelise, Speirs, and Gross (2011) examine the evidence for future potential constraints on the production of thin film PV due to limited availability of tellurium and indium. Although the authors find little evidence that the supply of either material could constrain production, they conclude it may constrain future cost reductions for PV. This finding is supported by Houari et al. (2014) who, using a systems dynamic model, find that the maximum growth of thin film PV is less constrained by tellurium availability than had been estimated by previous studies, such as Andersson (2000).

The potential for large-scale manufacture of PV and the metal requirements for such manufacture are estimated by Keshner and Arya (2004). In response to the possibility that metal availability could limit PV production, Wadia, Alivisatos, and Kammen (2009) examine extraction costs and supply constraints for 23 potential semiconductor materials, finding large differences in material extraction costs between them.

Fthenakis (2009) highlights that the supply of minor metals used in thin film PV production may be constrained by the annual production of base metals, but this is unlikely to halt the most aggressive scenarios for renewable energy deployment. Enhanced recovery during primary production, recycling of modules at the end of life, and reducing the thickness of semiconductor layers are anticipated to mitigate increases in demand.

See table A.2 for the metals necessary for solar PV.

TABLE A.2 Metals Used in Solar Photovoltaic Installations

Metal	Range of estimates (kilograms/megawatt)	Notes
Aluminum (Al)	102	—
Boron (B)	0.0008	—
Cadmium (Cd)	0.93–83.51	Lower estimate is for CIGS solar cells; higher estimate is for CdTe photovoltaics.
Copper (Cu)	16.97–2194.1	Lower estimate is for CIGS solar cells; higher estimate is for a mix of 80 percent c-Si, 10 percent a-Si, 5 percent CdTe, 5 percent CIGS.
Gallium (Ga)	0.12–6.17	Range is for CIGS but from the two different sources.
Germanium (Ge)	Unknown	—
Indium (In)	4.5–83.79	Range is for CIGS but from the two different sources.
Lead (Pb)	72.38–269.3	Lower estimate is for c-Si; higher estimate is for mix of 80 percent c-Si, 10 percent a-Si, 5 percent CdTe, 5 percent CIGS.
Molybdenum (Mo)	0–unknown	Thin film technologies may use a back electrode composed partially or completely of molybdenum. Information on the use of molybdenum per unit of installed capacity is limited.
Nickel (Ni)	Unknown	—
Selenium (Se)	0.5–84.41	Range is for CIGS but from the two different sources.
Silicon (Si)	0–18.4	Lower estimate is for c-Si; higher estimate is for a-Si.
Silver (Ag)	5.17–19.2	—
Steel	Unknown	Used for solar panel structures.
Tellurium (Te)	4.7–90.38	Lower estimate is for CIGS; higher estimate is for CdTe.
Tin (Sn)	5.95–463.1	Lower estimate is for CIGS; higher estimate is for mix of 80 percent c-Si, 10 percent a-Si, 5 percent CdTe, 5 percent CIGS.
Zinc (Zn)	29.99	—

Sources: Data primarily from Moss, et al. (2011) and Ohrlund (2012).

Note: a-Si = amorphous silicon; CdTe = cadmium telluride; CIGS = copper indium gallium selenide; c-Si = crystalline silicon.

TABLE A.3 Metals Used in Concentrating Solar Power (CSP) Installations

Metal	Range of estimates (kilograms/megawatt)	Notes
Aluminum (Al)	Unknown	Used for CSP structures.
Silver (Ag)	3.75–13.75	Lower estimates are for parabolic troughs; the higher end is for Fresnel reflectors.
Steel	Unknown	Used for CSP structures.

Source: Data primarily from Moss, et al. (2011).

Concentrating Solar Power

CSP uses a much smaller range of metals than PV because of the relative simplicity of the technology. Light is concentrated with reflectors onto a small area to heat a working fluid, which is then used to generate steam to drive an electric generator. The technology has been covered in the system-wide approach in both Grandell et al. (2016) and Moss, Gross, et al. (2011); both studies highlight the critical use of silver in the reflecting mirrors in CSP. See table A.3 for the metals necessary for CSP.

Carbon Capture and Storage

Kleijn et al. (2011) highlight that carbon capture and storage (CCS) technologies make a low carbon energy system more metal intensive. They demonstrate that CCS for both gas- and coal-fired power stations are substantially more metal intensive than conventional generation, and that a significant expansion of current mining activity would be required to make the transition to a low carbon–based power generation system with significant CCS capacity. See table A.4 for the metals necessary for CCS.

Nuclear Electricity Generation

Peterson et al. (2005) examine the scale of steel and concrete inputs for various types of nuclear plant designs. They find that although recently constructed sites show considerable increases in steel and concrete inputs compared with designs from the 1970s, next-generation reactors show major reductions in steel and concrete intensity compared with both designs of the 1970s and current designs. See table A.5 for the metals necessary for nuclear generation.

LED Lighting

Wilburn (2012) completed a report on behalf of the U.S. Geological Survey examining the dependence of LED production on rare earth metals and on metals that are the by-product of the mining of more common metals. The report identifies arsenic, gallium, indium, and the rare earth metals cerium, europium, gadolinium, lanthanum, terbium, and yttrium as being crucial to the production of semiconductors for LED. Because most production of these metals is currently in China and there is little to no recycling of LEDs, there is potential

TABLE A.4 Metals Used in Carbon Capture and Storage Installations

Metal	Range of estimates (kilograms/megawatt)	Notes
Aluminum (Al)	Unknown	—
Chromium (Cr)	326	—
Cobalt (Co)	7.5	—
Copper (Cu)	692	—
Manganese (Mn)	3,761	—
Molybdenum (Mo)	7.5	—
Nickel (Ni)	1,145	—
Niobium (Nb)	100	—
Steel	Unknown	Steel is used to construct structures and pipelines for carbon capture and storage.
Vanadium (V)	100	—

Source: Data primarily from Moss, et al. (2011).

TABLE A.5 Metals Used in Nuclear Electricity Generation Installations

Metal	Range of estimates (kilograms/megawatt)	Notes
Cadmium (Cd)	0.5	—
Chromium (Cr)	427	—
Cobalt (Co)	0	—
Copper (Cu)	59.6	—
Hafnium (Hf)	0.5	Used in reactor control rods.
Indium (In)	1.6	Used in reactor control rods.
Lead (Pb)	4.3	—
Molybdenum (Mo)	20–71	Lower value is for small modular reactors.
Nickel (Ni)	256	—
Niobium (Nb)	2	—
Silver (Ag)	8.3	—
Steel	Unknown	—
Tin (Sn)	4.6	—
Titanium (Ti)	1.5	—
Tungsten (W)	5	—
Vanadium (V)	0.6	—
Yttrium (Y)	0.5	—
Zirconium (Zr)	30.5	—

Source: Data primarily from Moss, et al. (2011).

TABLE A.6 Metals Used in LED Manufacturing

Metal	Range of estimates (milligrams/ 100 candela)	Notes
Aluminum (Al)	0.026	—
Antimony (Sb)	0.008	—
Cerium (Ce)	Unknown	—
Chromium (Cr)	0.020	—
Copper (Cu)	0.010	—
Europium (Eu)	Unknown	—
Gallium (Ga)	0.001	—
Gold (Au)	0.036	—
Indium (In)	Unknown	—
Iron (Fe)	95.52	—
Lanthanum (La)	Unknown	—
Lead (Pb)	Unknown	—
Molybdenum (Mo)	Unknown	Used in the crucibles to make the sapphire substrate and in the heat sink of LED chips.
Nickel (Ni)	1.253	—
Silver (Ag)	0.160	—
Terbium (Tb)	Unknown	—
Yttrium (Y)	Unknown	—
Zinc (Zn)	0.015	—

Sources: Data primarily from Lim et al. (2011) and Wilburn (2012).

Note: LED = light-emitting diode. Values in this table are for the LED chip and phosphor, but do not include values for other electronics that may be present within the LED bulb.

for short-term dependence on China for supply of materials to facilitate LED production. See table A.6 for the metals necessary for LED lighting.

Hybrid and Electric Vehicles

A variety of different types of hybrid and electric vehicles could become dominant in future transportation systems. These include micro-hybrids, full hybrids, plug-in hybrids, electric vehicles, and fuel cell vehicles. Most of the research on the metal content of electric vehicles is included in the system-wide studies reviewed above. Sullivan, Kelly, and Elgowainy (2015) estimate the material composition for the power trains for a plug-in hybrid, a fuel cell vehicle, and an internal combustion engine, finding that fuel cell vehicles use less metal content than plug-in hybrids, which in turn use less than standard internal combustion engines. These vehicles can use a range of battery technologies, with lithium- or nickel-based batteries providing propulsion functionality in full hybrids, plug-in hybrids, and full electric vehicles.

Micro-hybrids are also used widely, especially in Europe, and use lead batteries to provide start-stop functionality and to store energy from regenerative braking. Full hybrids, plug-in hybrids, and full electric vehicles also all use a lead battery to power vehicle electronics (for example, safety and comfort features).

Gruber et al. (2011) focus on one critical metal, lithium, and estimate future supply and demand through 2100. They focus on the demand for lithium for batteries in electric vehicles and examine the impact of the creation of a global electric vehicle fleet. Using data from the Intergovernmental Panel on Climate Change's growth scenarios and projections of market penetration from Credit Suisse, they conclude that, even factoring in nonvehicle demand for lithium batteries, identified reserves are sufficient to meet future demand until the end of the century. In a later study, Speirs et al. (2014) conduct a similar analysis, highlighting the wide range of both demand and supply estimates based on uncertainty regarding material intensity, size of market, and market share. The authors conclude that lithium demand is likely to grow sharply by 2050 but that existing reserves would be sufficient to meet demand.

With regard to the availability of materials used in lead, lithium, and nickel batteries, EUROBAT et al. (2014) conducted a study of the long-term availability of materials used in battery technologies. This study concludes that there are no current or future resource availability issues with the materials used to manufacture lead- and nickel-based batteries. The high end-of-life recycling rates (99 percent in Europe and North American) and the high recycled content of lead batteries (more than 85 percent) drive this result for lead. The report highlights some future resource availability issues for battery technologies such as lithium-ion batteries because of low end-of-life recycling.

See table A.7 for the metals necessary for electric vehicle manufacturing.

Energy Storage Batteries

Batteries are used to store electrical energy not only for electric vehicles, but also in mobile electronics (mobile phones and laptops), and for decentralized energy storage for electricity produced with decentralized, intermittent low carbon–generation technologies like solar PV and wind.[1] Although a number of battery chemistries are available, this review focuses on lithium-ion batteries because they are likely to be a key player in the energy storage market at sizes relevant for automobiles, mobile electronics, and small domestic energy storage installations (Kempener and Borden 2015). However, it can be expected that a range of battery technologies will be used, including lead, nickel, and newer batteries such as flow batteries. See table A.8 for the metals used in lithium-ion batteries.

TABLE A.7 Metals Used in Electric Vehicle Manufacturing

Metal	Range of estimates (kilograms/ vehicle)	Notes
Boron (B)	0.01–0.09	—
Cerium (Ce)	0–1.03	—
Cobalt (Co)	0–13.91	Lower estimate is for hybrid electric vehicles; higher estimate is for battery electric vehicles (70 kilowatt motor).
Copper (Cu)	0–71.08	—
Dysprosium (Dy)	0.0005–0.43	—
Gallium (Ga)	0.004–0.001	—
Germanium (Ge)	0.00003–0.00005	—
Gold (Au)	0.00016–0.0002	—
Indium (In)	0.00003–0.00005	—
Lanthanum (La)	0–1.16	—
Lead (Pd)	8–12	Lower estimate for use in electric vehicles; higher end for micro-hybrids.
Lithium (Li)	0.09–12.7	Lower estimate is for hybrid electric vehicles; higher estimate is for battery electric vehicles.
Manganese (Mn)	0–91.5	Lower estimate is for low-intensity battery electric vehicles; high estimate is for high-intensity battery electric vehicles.
Neodymium (Nd)	0.0062–2.91	Lower estimate is for battery electric vehicles; higher estimate is for fuel cell 90 kilowatt motor vehicle.
Nickel (Ni)	0–46.5	Lower estimate is for hybrid electric vehicle; higher estimate is for all-electric vehicle with lithium-ion battery.
Palladium (Pd)	0.00064–0.0008	—
Praseodymium (Pr)	0–0.08	—
Samarium (Sm)	0–0.08	—
Silver (Ag)	0.005–0.007	—
Terbium (Tb)	0.009–0.021	—
Titanium (Ti)	0–38.78	—

Note: These values include metals used in the vehicle structure, electronics, motors, and battery.

TABLE A.8 Metals Used in Lithium-Ion Batteries

Metal	Range of estimates (kilograms/kilowatt-hour of energy storage)	Notes
Aluminum (Al)	0–0.05	—
Cobalt (Co)	0.2–0.25	—
Iron (Fe)	0–1.2	—
Lithium (Li)	0.1–0.4	Lithium-sulfur technology has the highest lithium usage, while lithium-air has the lowest.
Manganese (Mn)	0–0.4	—
Nickel (Ni)	0–0.4	—

Source: Simon, Ziemann, and Weil 2015.

Gas Turbine Electricity Generation

Advances in gas turbine efficiency require higher temperature steam, which will change metal requirements so that the turbine can endure these higher temperatures. Moss et al. (2013) estimate that increasing efficiency through the use of advanced ultra-supercritical designs will increase the demand for nickel-based alloys. Table A.9 shows their estimate of the metal requirements for the nickel-based components of the turbine only. Unfortunately, comparable data for the turbine composition of the current best available technology is not available. Moss et al. (2013) also use life-cycle analysis data to estimate the metal content of the balance of the plant, as seen in table A.10.

TABLE A.9 Metals Used in the Nickel-Based Components of an Advanced Ultra-Supercritical Gas-Fired Turbine

Metal	Advanced ultra-supercritical plants (kilograms/megawatt)	Notes
Aluminum (Al)	0	—
Chromium (Cr)	26.25	—
Cobalt (Co)	13.96	—
Iron (Fe)	2.38	—
Manganese (Mn)	0.88	—
Molybdenum (Mo)	10	—
Nickel (Ni)	64.79	—
Titanium (Ti)	1.42	—

Source: Moss et al. 2013.

TABLE A.10 Metals Used in a Combined Cycle Gas Turbine Power Station

Metal	Current best technology (kilograms/ megawatt)	Advanced ultra-supercritical plants (kilograms/megawatt)	Notes
Aluminum (Al)	1,100	1,100	Assumes that metal demand for the balance of the plant is similar for current best available technology and advanced ultra-supercritical technology.
Chromium (Cr)	2.44	2.44	
Cobalt (Co)	1.8	1.8	
Copper (Cu)	1,100	1,100	
Nickel (Ni)	15.75	15.75	
Steel (Chromium)	4,500	4,500	

Source: Moss et al. 2013.

TABLE A.11 Metals Used in the Boilers and Pipework of Current State-of-the-Art and Future Advanced Ultra-Supercritical Coal-Fired Power Stations

Metal	Current estimate (kilograms/ megawatt)	Estimate for advanced ultra-supercritical plants (kilograms/megawatt)	Applies to	Notes
Chromium (Cr)	111.25	281.25	Boilers and pipework	—
Cobalt (Co)	0	187.5	Boilers and pipework	—
Iron (Fe)	1,091.25	0	Boilers and pipework	—
Manganese (Mn)	6.25	3.75	Boilers and pipework	—
Molybdenum (Mo)	5	56.25	Boilers and pipework	—
Nickel (Ni)	2.5	656.25	Boilers and pipework	—
Niobium (Nb)	0.75	9.38	Boilers and pipework	—
Titanium (Ti)	0	21.56	Boilers and pipework	—
Tungsten (W)	18.75	0	Boilers and pipework	—
Vanadium	2.5	0	Boilers and pipework	—

Source: Moss et al. 2013.

Clean Coal-Fired Electricity Generation

As with gas-fired electricity generation, more efficient coal-fired power plant designs are likely to be more metal intensive for chromium, cobalt, molybdenum, titanium, and particularly nickel, as shown in table A.11. These metals are important for constructing components that are resistant to higher temperatures and more corrosive environments compared with current designs.

Conclusions on Technologies and Metals to Examine

The purpose of this literature review is to produce lists of energy technologies and metals to be examined in this project. Table A.12 lists the energy technologies that this literature review identified as important.

Credible data were found for the energy-generation technologies in the initial list included in the project proposal: wind, solar PV, CSP, nuclear electricity generation, and CCS. The ranges for metal use for each of these technologies provide good evidence for different technology choices within each category.[2] For combined heat and power technology, existing data indicate that metal use will not be substantially different from today's systems.

For energy-demanding technologies, good evidence of metal use was found for electric vehicles. Natural gas vehicles and light-weight vehicles were excluded from the study. For the former, metal use per vehicle is not likely to change significantly from today's vehicles, and there is an absence of robust data for the latter. Changes in construction materials were found to have little effect on metal use.

Lithium-ion and lead-acid battery energy storage technologies were investigated—they are likely to be the energy storage technology that achieves wide deployment in the study timeframe, and they have significant metal use implications. Table A.13 lists the metals that this literature review identified as important for inclusion in this study.

Of the metals that the consultants initially identified for inclusion in the study in consultation with the International Council on Mining and Metals, iridium, osmium, rhodium, and ruthenium were not found to have significant use in the energy technologies investigated. Uranium and thorium, while significant for nuclear technologies, were not included because of their role as fuel rather than in capital equipment.

TABLE A.12 Energy Technologies Covered by the Literature Review

#	Technology
1a	Wind electricity generation—onshore
1b	Wind electricity generation—offshore
2a	Solar photovoltaics—crystalline silicon
2b	Solar photovoltaics—CdTe
2c	Solar photovoltaics—CIGS
2d	Solar photovoltaics—amorphous silicon
3	Coal-fired electricity generation
4	Gas-fired electricity generation
5	Nuclear power
6a	Energy storage—lead acid
6b	Energy storage—lithium ion

Note: CdTe = cadmium telluride; CIGS = copper indium gallium selenide.

TABLE A.13 Metals Key for This Study

Metal	Metal	Metal
Aluminum	Iron	Silicon
Chromium	Lead	Silver
Cobalt	Lithium	Steel
Copper	Manganese	Zinc
Indium	Molybdenum	

Table A.14 summarizes the metals and technologies covered in this annex.

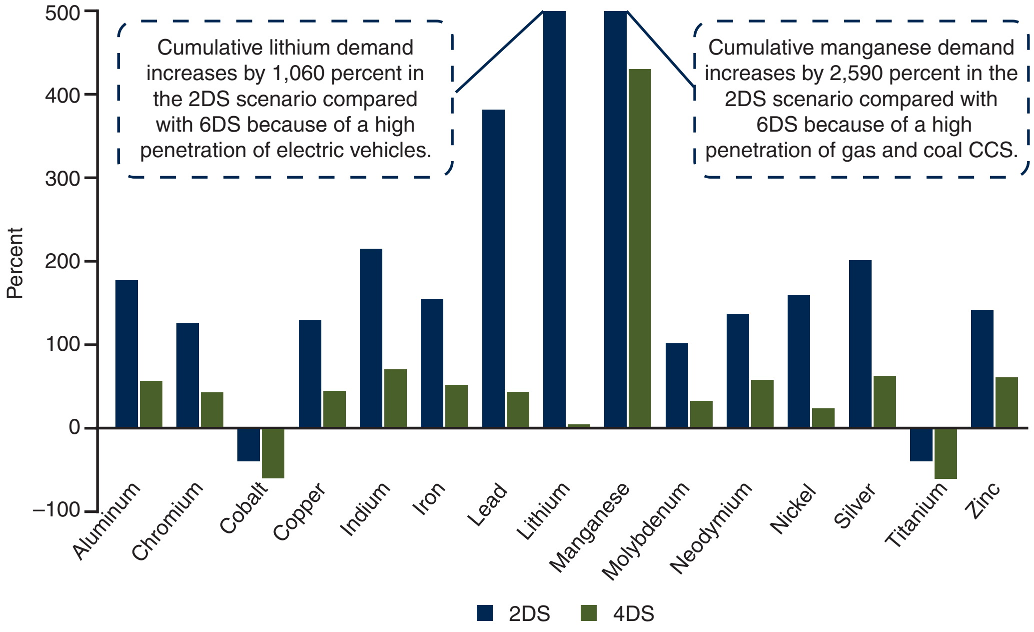
Taking into account all of these technologies, figure A.1 lays out a "median" level scenario for key metals that could benefit from a low carbon transition.

The results of this study were compared with the results of two similar studies, Vidal, Goffé, and Arndt (2013) and Kleijn et al. 2011. This comparison confirmed this study's most basic conclusion, that increased penetration of renewable energy supply technologies, carbon capture and storage, and energy storage technologies will generally lead to greater demand for metal.[3]

TABLE A.14 Matrix of Metals and Energy Technologies Explored in This Scenario Study

	Wind	Solar photovoltaic	Concentrating solar power	Carbon capture and storage	Nuclear power	Light-emitting diodes	Electric vehicles	Energy storage	Electric motors
Aluminum	X	X	X	X		X		X	X
Chromium	X			X	X	X			
Cobalt				X	X		X	X	
Copper	X	X		X	X	X	X		X
Indium		X			X	X	X		
Iron (cast)	X		X			X		X	
Iron (magnet)	X								X
Lead	X	X			X	X			
Lithium							X	X	
Manganese	X			X			X	X	
Molybdenum	X	X		X	X	X			
Neodymium (proxy for rare earths)	X						X		
Nickel	X	X		X	X	X	X	X	
Silver		X	X		X	X	X		
Steel (Engineering)	X								
Zinc		X				X			

FIGURE A.1 Change in Cumulative Metal Demand Compared with the 6 Degree Scenario for All Technologies Examined in This Study, 2013–50



Note: 2DS = 2 degree scenario; 4DS = 4 degree scenario; 6DS = 6 degree scenario; CSS = carbon capture and storage.

Notes

1. For example, Tesla's Powerwall (https://www.tesla.com/en_CA/powerwall?redirect=no) is a lithium-ion battery home energy storage pack.
2. For example, different generator choices in wind turbines will result in different amounts of demand for metal.
3. However, both Vidal, Goffé, and Arndt (2013) and Kleijn et al. (2011) predict that there will be significantly more impact on metal demand from the deployment of renewable energy and related technologies. Vidal, Goffé, and Arndt (2013) conclude that a 5–18 percent annual increase in the production of aluminum, copper, and steel would be needed to generate 25,000 terawatt-hours of electricity from solar and wind technologies in 2050. Kleijn et al. (2011) assume that, in a 2050 scenario in which all primary energy comes from renewables, and where hydrogen and electricity are the two primary energy carriers, total global metal demand would increase dramatically. In addition to their extreme energy scenario, it includes estimates of metal use in hydrogen pipelines and electricity transmission infrastructure; these technologies are not included in this study.

Annex B: Elaboration of Calculation of Energy Storage Battery Scenarios

For the automotive battery energy storage sector, a single scenario was taken from Pillot's (2015) projections through 2025. These projections were then extrapolated to 2050. Pillot's projection stipulates that lithium-ion batteries will increasingly penetrate the electric vehicle and hybrid vehicle markets. At the same time, lead-acid batteries will continue to be used for starting and ignition functions in combustion engine vehicles, and will be increasingly used in start-stop technology and light-hybrid vehicles. Other automotive battery technologies, including nickel metal hydride, are projected to lose market share to lithium-ion and lead-acid chemistries.

Approximately 100 GW of grid-scale energy storage was online worldwide in 2015. Some 99.3 percent of this is pumped-hydro storage, with the remainder, outside of compressed air energy storage, being almost exclusively sodium-sulfur batteries. The projections for grid-scale energy storage are based on Inage (2009). Inage's analysis states that because of increasing penetration of renewables, ". . . simulations undertaken suggest that worldwide energy storage ranging from 189 GW to 305 GW would be required." Furthermore, the 2014 IEA Energy Technology Perspectives (IEA 2014) indicate that up to 500 GW may be needed by 2050. These figures were converted into GWh of energy storage capacity by assuming that grid-scale energy storage operates for 12 hours per day before being recharged for 12 hours. This assumption of a 12-hour run time is supported by data on current energy storage technologies. As seen in table B.1, the average energy-to-power ratio of current grid-scale energy storage installations is approximately 12. However, this ratio varies considerably between storage types. If the technology mix were to change in the future, the energy-to-power ratio might change as well; this user input can be changed in the model.

The figures in table B.1 were used to construct three energy storage scenarios to correspond to the 2DS, 4DS, and 6DS ETP scenarios. These scenarios, 6DS-ES, 4DS-ES, and 2DS-ES, assume, respectively, that 189 GW, 305 GW, and 500 GW[1] of grid-scale energy storage output are needed. Decentralized ("behind the meter") energy storage was assumed to be 10 percent of grid-scale energy storage in any given year. This is an approximate projection.

TABLE B.1 The Current Grid-Scale Energy Storage Landscape

Technology	Power capacity (GW)	Energy capacity (GWh)	Energy-to-power ratio
Pumped hydro	127	1,500	11.81
Compressed air energy storage	0.44	3.73	8.48
Sodium sulfur battery	0.316	1.9	6.01
Lithium-ion battery	0.07	0.017	0.24
Lead-acid battery	0.035	0.07	2.00
Nickel cadmium battery	0.027	0.00675	0.25
Flywheels	0.025	0.004	0.16
Redox flow battery	0.003	0.012	4.00
Total	**128**	**1,506**	**11.77***

Source: International Electrotechnical Commission 2009.

*This number is not a total, but a weighted average.

Note

1. The 500 GW figure for the 2DS-ES scenario corresponds to the maximum grid-scale energy storage output needs projected by the IEA.

Annex C. Deep GHG Reduction Scenarios

Other scenarios examined beyond the International Energy Agency's (IEA's) Technology Perspectives Scenarios comprise the following:

- Carbon Mitigation Initiative and Stabilization Wedges (Princeton Environmental Institute)[1]
- Pathways to Deep Decarbonization (Deep Decarbonization Pathways Project)
- "100% Clean and Renewable Wind, Water and Sunlight (WWS) All Sector Energy Roadmaps for 139 Countries" (Stanford University and University of California, at Berkeley; Jacobsen et al. 2014)
- World Energy Outlook Special Report 2015: 450 Scenario (IEA 2015c)[2]
- Summary for Policymakers of the Contribution of Working Group 3 to the Fifth Assessment Report (IPCC 2014).

Carbon Mitigation Initiative (CMI) and Stabilization Wedges (Princeton Environmental Institute)[3]

CMI is a project of Princeton University, supported by British Petroleum and Ford Motor Company, that bases its work on the concept of "sectoral wedges," first developed by Robert Socolow in 2004. Socolow proposes a discrete set of wedges that would each work to avoid (at a minimum) 1 billion tons of emissions per year by 2060. His team proposes that some 9 billion tons of emissions per year would need to be avoided, calling for nine wedges. The result would be to keep global emissions flat for the next 50 years, with continued and significant reductions thereafter. Wedge strategies identified include the following:

- Energy efficiency and conservation
  - Increased transport efficiency*
  - Reduced miles traveled
  - Increased building efficiency*
  - Increased efficiency of electricity production*
- Nuclear energy
  - Nuclear electricity*
- Fossil-fuel-based strategies
  - Fuel switching (coal to gas)*
  - Fossil-based electricity with carbon capture and storage (CCS)*
  - Coal synthesis with CCS*
  - Fossil-based hydrogen fuel with CCS*

- Renewables and biostorage
    - Wind-generated electricity*
    - Solar electricity*
    - Wind-generated hydrogen fuel*
    - Biofuels*
    - Forest storage
    - Soil storage

Strategies listed with an asterisk are those that would require a shift or new technologies with implications for minerals and metals. It is clear that the vast majority of wedge strategies would require mineral or metal inputs. As with most scenarios, CMI provides no analysis on the material implications of its wedge strategies for the commodities market.

Pathways to Deep Decarbonization (Deep Decarbonization Pathways Project [DDPP] 2015)

The DDPP is a "bottom up" analysis that identifies deep decarbonization pathways for 16 national economies, currently accounting for 74 percent of global emissions. It is bottom up in that each country's deep decarbonization pathway is developed by "at home" experts and research institutes. Countries covered include Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, the United Kingdom, and the United States. It also works within a "back cast" framework, setting GHG emission reduction targets for 2050, consistent with the 2°C global warming scenario, and then examining what each country can do to help meet them. The DDPP's current work establishes potential reductions of 9.8–11 gigatons or 48–57 percent below 2010 levels, while still assuming a GDP growth rate of 250 percent between 2010 and 2050.

Specific technology change is emphasized for decarbonizing electricity, decarbonizing fuel production, and alternative vehicle deployment. It is estimated that successfully implementing these three measures would result in 3,800 gigawatts (GW) of solar electricity generation (at an estimate cost of US$844 billion; 4,100 GW of wind (at an estimated cost of US$127 billion); along with 1.2 billion electric, hybrid, and fuel cell passenger vehicles and 250 million alternative fuel freight vehicles (at an estimated cost of US$911 billion).

"100% Clean and Renewable Wind, Water and Sunlight (WWS) All Sector Energy Roadmaps for 139 Countries of the World" (Stanford University and University of California at Berkeley; Jacobson et al. 2017)

The scenario with the most extensive breakdown of countries' potential and capacity to transform to a net zero carbon future, this analysis develops roadmaps for converting the all-purpose energy infrastructures (for electricity, transportation, heating and cooling, industry, and agriculture/forestry/fishing) of 139 countries to ones powered by wind, water, and sunlight (WWS) with a conversion to WWS systems of 80 percent by 2030 and 100 percent by 2050. While many will legitimately dispute the claims in the study that such an abrupt shift—by far the largest such transformation of any peer-reviewed scenario—is technically and economically feasible, the point of using this scenario is to examine its consistency with other scenarios in identifying the critical sectors and technologies required to deliver a net zero carbon future.

In that respect, at a cumulative level, the study estimates that reaching a full WWS transformation by 2050 would be met mostly through the following major technologies: onshore wind (19.8 percent or 1.2 million 5 megawatt units), offshore wind (12.7 percent or 761,000 5 megawatt units), photovoltaics at the utility level (40.4 percent or 503,000 50 megawatt utility-scale units), rooftop photovoltaics (6.5 percent or 779 million 5 kilowatt units for residences and 42.2 million 100 kilowatt systems), hydropower (4 percent or 0 new systems), and geothermal (0.8 percent or 840 100 megawatt geothermal plants).

In addition, specific measures with clear implications for technology change and the minerals and metals that make up those technologies include the following:

- Development of super and smart grids
- No new fossil fuel power plants constructed by 2020 (including no nuclear or CCS)
- All new house and office ware appliances
- Full electrification and use of hydrogen in all transportation modes including ships, rail, and all road vehicles. Small aircraft to be electrified by 2040.

World Energy Outlook Special Report 2015: 450 Scenario (IEA 2015c)

Peer reviewed by the Organization for Economic Cooperation and Development (OECD) and major developing country national governments, the fourth chapter in this document lays out a path for the globe to have a 50 percent probability to meet the 2 degrees Celsius (2°C) global warming target of 450 parts per million by volume (ppmv) of GHG emissions. In particular, it proposes three key measures to reach a net zero carbon future:

- Widespread deployment of low carbon technologies in the power sector
- Technological advances in industrial efficiency to sharply reduce the GHG emissions
- Achieving low carbon road transport.

Reforms in the power sector make up more than half of the emissions reductions required to meet the 450 ppmv target, followed by industry sector reforms (26 percent), transportation (16 percent), and buildings (6 percent). More specifically, the report identifies three sets of technologies that will be absolutely necessary for a net zero carbon future to have any prospects of success:

- Variable renewables: Increase their contribution to power supply from 3 percent today to 20 percent by 2040 (installed capacity from 450 gigawatts today to 3,300 gigawatts in 2040)
- Carbon capture and storage: Rapid expansion required by, at latest, 2025 (looking to capture, cumulatively, 52 gigatons of carbon dioxide [CO_2] emissions by 2040 with 60 percent targeting the power sector, and the remainder heavy industry, including cement, iron and steel, and chemicals)
- Alternative fuel vehicles: By 2040, sales of electric vehicles exceed 40 percent of total passenger car sales globally. The report also allows for fuel cell vehicles but is not as optimistic about their impact in reducing emissions.

A critical hurdle for renewables to take hold is energy storage, particularly for wind and solar energy installations, which is currently, as a technology, at a very nascent stage. Technology deployment in this area would need to increase to 400 gigawatts by 2050, which would also carry significant implications for metals required to build those batteries.

Summary for Policy Makers of the Contribution of Working Group 3 to the Fifth Assessment Report (Intergovernmental Panel on Climate Change (IPCC 2014)

Working Group 3 of the IPCC is responsible for addressing the mitigation piece of the climate change puzzle. As such, it provides a summary of all relevant peer-reviewed literature addressing net zero carbon future scenarios and extensive analysis, with discrete chapters, of all sectors contributing to GHG emissions and their reduction. The Summary for Policy Makers attempts to synthesize the status of the extensive range of research on all issues related to mitigation.

Regarding the 450 ppmv, 2°C scenario, it concludes that substantial reductions in anthropogenic emissions will be required by mid-century through large-scale changes in energy systems, amounting to 90 percent global reductions from 2010 levels by 2040–70 and net zero levels by the end of the 21st century.

Specific sectors identified that will be crucial to achieving reductions cover energy supply and energy end-use activities. With regard to the former, electricity is considered to be the first key step: the most rapid rate of decarbonization occurs with power supply, with low carbon sources (including renewables, CCS, and nuclear) comprising 80 percent of power supply by 2050, from the current share of 30 percent. This approach would include continuation of renewables as the majority of new installations (a milestone first achieved in 2012). Natural gas and bioenergy can play a “bridging role” in this scenario, but only if they are accompanied by CCS technologies. Although nuclear can potentially make a large contribution, the same degree of confidence in its use is not forthcoming because of a number of issues that have contributed to growing adverse public opinion.

On the energy end-use side, transportation is regarded as a key sector for bending the GHG emissions trend. Reversing GHGs will be particularly challenging given baseline projections of a doubling of CO_2 emissions from all sources by 2050. At best, the Summary for Policymakers concludes that emissions from this sector could be reduced by 40 percent from the baseline projection (still representing absolute growth in GHG emissions). From a technology perspective, this reduction would be achieved through fuel efficiency and vehicle performance. Although electric-based power is mentioned, most confidence is found in its use for trains and public buses over the short term. Electric vehicles and hydrogen-powered passenger vehicles are constrained by issues relating to energy storage and the relative low energy density of low carbon transport fuels.

Potential for emission reductions in the building sector can be found in the adoption of low-energy codes and in the reduction of GHGs through improved technologies in buildings' heating and cooling systems. Finally, for industry, emissions reductions can be achieved through energy-intensity improvements via upgrades, replacement, and deployment of best available technologies.

Summary of Findings

A comparative analysis of these deep GHG reduction scenarios is complicated by the fact that each scenario uses its own set of matrices to measure what would be required to meet the intended decarbonized goal. Nevertheless, a number of critical messages common to all scenarios can help us identify the critical sectors and technologies needed to achieve a climate-friendly future.

- **The first and most critical sector to address is electricity, or power.** All scenarios are in strong agreement that the sector most critical to beginning to meet the 450 ppmv target, and where the most potential lies for GHG reductions over the most immediate term, is the power and electricity sector. All scenarios agree that traditional renewable installations (particularly wind and solar) will need to grow by factors of 5 to 10 over their current levels by 2050. CCS is identified as a key component in the majority of scenarios, contributing GHG emissions reductions comparable to renewables. There is considerably less consensus on the potential contribution of nuclear in the power sector, with significant concerns raised about its costs, safety, waste disposal issues, and overall negative public view.

- **The scenarios exhibit considerably less coherence on the potential of various energy end-use categories (transportation, buildings, and industry):**

    - Transportation is a challenge on two fronts: Expected growth in the sector is so strong that the most robust scenarios only envision a reduction *in the growth* of GHG emissions, and not absolute reductions, by 2050. Some posit that absolute reductions are possible but only toward the end of the century. Second, confidence in the capacity of zero emission vehicles (whether electric vehicles or hydrogen-based vehicles) to successfully penetrate the market is moderate, mostly because of continued concerns about supporting infrastructure and the battery storage capacity issue.

  - The vast majority of reductions related to buildings are intimately linked to retrogrades, clean electricity provided to power heating and cooling systems, and the advent of "zero emissions" buildings.
  - Opportunities for reductions in industry are typically related to energy efficiency and use of best available technologies, but interestingly, CCS is regarded as key as well, particularly for the cement, iron, steel, and chemical industries.
- **Implications and impacts of scenarios do not account for elements required to manufacture relevant technologies.** The described scenarios typically address issues related to economic impacts (for example, GDP), employment, equity, or related environmental and social issues. What none address is the potential availability of the materials required to service and supply a carbon-limited future—the very point of this report.

Notes

1. Stabilization Wedges: Carbon Mitigation Initiative, Princeton University (http://cmi.princeton.edu).
2. Achieving the Transition: Long Term Energy Sector Transformation (chapter 4 in IEA [2015c]).
3. Stabilization Wedges: Carbon Mitigation Initiative, Princeton University (http://cmi.princeton.edu).

Glossary

2DS 4DS, 6DS: Refers to global warming scenarios over the 21st century of 2 degrees, 4 degrees, and 6 degrees Celsius. In this study, used as reference for determining potential technology and metal demands until mid-century.

Base Metals: Metals that oxidize, tarnish, or corrode relatively easily when exposed to air or moisture. Base metals are widely used in commercial and industrial applications. They are more abundant in nature and therefore far cheaper than precious metals such as gold, silver, and platinum. Base metals include aluminum, copper, lead, nickel, tin, and zinc.

Bioenergy: Renewable energy from biological sources.

Carbon Capture and Storage (CCS): Technology that seeks to redirect GHG emissions, especially carbon, from the atmosphere into Earth's geological structures. Often regarded as a key technology in "decarbonizing" fossil fuels such as coal, oil, and gas.

Carbon Neutrality: See Net Zero Carbon.

Concentrating Solar Power (CSP): Solar power technology that uses mirrors to generate energy.

Critical Materials Initiative (CMI): Based within the U.S. Department of Energy, the CMI is managed by a number of university-based research facilities focusing on technologies that can diversify the sources of critical materials (nearly exclusively rare earth metals) required for supporting key modern technologies, provide substitutes for materials that are in short supply, or improve the utilization of existing resources through enhanced efficiency in manufacturing and improved recycling.

Electric Vehicles: Road vehicles that use electricity, in the form of battery storage, as power source.

Energy Storage Batteries: A primary technology in energy storage systems intended to manage power supply to create a more resilient and cost-effective energy infrastructure. For the purposes of this study, batteries in support of promoting a carbon-constrained future can be divided into two categories:

> **Lead-Acid Batteries** are the more mature technology, and have traditionally had a cost advantage over lithium-ion batteries. They have poor power-to-weight and energy-to-weight ratios.
>
> **Lithium-Ion Batteries** have an excellent energy-to-weight ratio, and prices have decreased drastically in the past decade. Typically regarded as crucial for electric vehicles to have any prospect of future growth.

Energy Technology Perspectives (see International Energy Agency's Energy Technology Perspectives)

Gigawatt-hours (GWh): A unit of energy representing 1 billion (1,000,000,000) watt hours, equivalent to 1 million kilowatt hours. Gigawatt hours are often used as a measure of the output of large electricity power stations.

Greenhouse Gases (GHGs): In the context of this report, refers to the major global warming contributions as a result of human activities, covering carbon dioxide, methane, nitrous oxide, and a number of more complex gases with high global warming potential but relatively low production levels.

Hybrid Vehicles: In the context of this study, refers to road vehicles that use two distinct types of power: the internal combustion engine and the electric motor.

Intergovernmental Panel on Climate Change (IPCC): Comprising recognized experts nominated by national governments, the IPCC assesses the scientific, technical, and socioeconomic information relevant for the understanding of the risk of human-induced climate change.

International Council on Mining and Metals (ICMM): Comprising 23 mining and metals companies and 34 regional and commodities associations, ICMM's mandate focuses on a safe, fair, and sustainable mining industry.

International Energy Agency's Energy Technology Perspective (IEA's ETP): Provides an annual update on the relative uptake of clean energy technologies in support of climate and sustainable energy goals. In 2015, the IEA ETP developed three power technology scenarios for reaching 2°C, 4°C, and 6°C temperature increases over the century.

Light-Emitting Diodes (LEDs): Technology that emanates light with much less required energy than more traditional modes of lighting.

Micro Hybrid Vehicle: Road vehicles that use regenerative braking technology to stop a combustion engine when the vehicle pulls to a stop, and to restart it when the driver accelerates.

Net Zero Carbon, or **Carbon Neutrality:** Refers to a measured amount of GHGs released into the atmosphere balanced by an equivalent amount sequestered or offset, so that the net impact of the emissions in the global atmosphere is zero. There is strong consensus among experts that achieving the Paris goal of keeping the increase in global temperature to well below 2°C, would require the globe to become carbon neutral within this century, possibly by 2050.

Paris Agreement: Global agreement negotiated under the UN Framework Convention on Climate Change in 2015 in which, for the first time in 25 years of negotiations, all countries agreed to undertake efforts to combat climate change. As such, it charts a new course in the global climate effort. The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping the global temperature rise this century well below 2° Celsius above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5° Celsius.

Photovoltaic (PV): Solar energy technology that produces energy typically through the use of solar panels as conduction materials.

Precious Metals: Metals considered to be rare or that have a high economic value. The higher relative values of these metals are driven by various factors, including their rarity, uses in industrial processes, and as investment vehicles. The most popular precious metals with investors are gold, platinum, and silver, and precious metals used in industrial processes include iridium, which is used in specialty alloys, and palladium, which is used in electronics and chemical applications.

Rare Earth Metals: A set of 17 chemical elements in the periodic table, typically associated with elements that play a key role in supporting technologies associated with the modern economy—from the miniaturization of electronics, to the enabling of green energy and medical technologies, to supporting a myriad of essential telecommunications and defense systems. While named "rare earths," they are in fact not that rare and are relatively abundant in the Earth's crust and tend to occur together in nature and are difficult to separate from one another and other base metals. However, because of their geochemical properties, rare earth elements are typically dispersed and are not often found concentrated as rare earth minerals in economically exploitable ore deposits.

Reserves and Resources: In the context of this study refers to status of mineral deposits in geological formations. Resources typically cover a broader estimate of potential mineral outlays, while reserves are more formally defined and carry more detailed data. For more information, please refer to chapter 3 of this report.

Solar Technologies: Technologies providing power supply through the use of energy from the sun that can be divided into four subcategories:

> **Crystalline Silicon** cells make up about 85 percent of the current market. They can either be manufactured as single crystalline, polycrystalline, or amorphous silicon.

Copper Indium Gallium Selenide (CIGS) is a "thin film" solar technology. It can be made into cells that are thinner than crystalline silicon, and thereby may reduce material and manufacturing costs while allowing for flexible cells.

Cadmium Telluride (CdTe) is another thin film technology. It is cost competitive with crystalline silicon and has good efficiency. However, the toxicity of cadmium and the future supply of tellurium make the future of this technology uncertain.

Amorphous Silicon or Amorphous Silicon-Germanium solar cells are the final thin film technology considered here. These cells suffer from lower performance than crystalline silicon, but are able to be printed on flexible materials.

Start-Stop Vehicles: Motor road vehicles which systems automatically shut off the **engine** when the vehicle is at rest and the restarts the **engine** automatically when the driver lifts off the **brake** or puts in the clutch to select 1st gear.

Terawatt-Hour (TWh): A metric measurement unit of power. The terawatt is equal to 1 trillion watts (10^{12}W).

United Nations Framework on Climate Change (UNFCC): The multinational negotiating body for addressing climate change.

United States Geological Survey (USGS): An agency within the U.S. Department of Interior, the USGS's main responsibilities are to map public lands in the United States, examine geological structures, and evaluate mineral resources both within the United States and globally. The USGS's mandate has expanded over the past few decades to cover research related to groundwater, ecosystems, environmental health, natural hazards, and climate and land-use change. In 2012, it established an Energy and Minerals Mission Area with a mandate to conduct research and assessments on the location, quantity, and quality of mineral and energy resources, including the economic and environmental effects of resource extraction and use.

Wind Technologies: Refers to technologies providing power supply through the use of wind. Wind technologies are divided into two broad categories:

Geared Turbines, which are typically found on land-based wind turbines and use a system of gears to convert the relatively low rotation speed of the turbine to a much higher speed (thousands of revolutions per minute) for the generator. Geared turbines use coil-driven generators that use significant amounts of copper, but do not have permanent magnets.

Direct-Drive Wind Turbines are typically offshore installations and do not have a gearbox, so they generally feature greater reliability than geared models. However, they do use a more complicated and expensive low-speed generator, which is generally constructed with permanent magnets containing rare earth metals.

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