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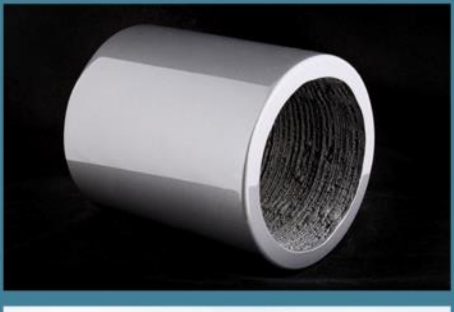
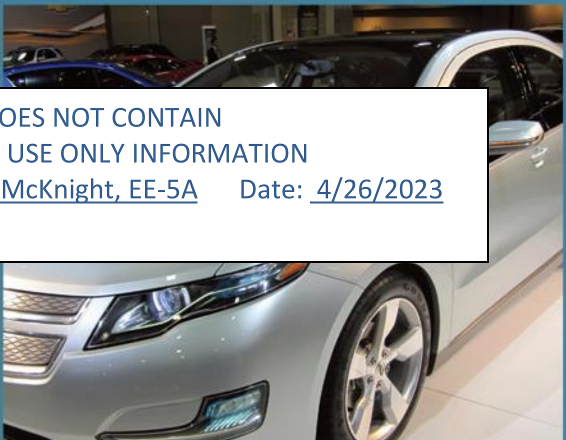
U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

February 2019





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List of Acronyms

AEV	all-electric vehicle
Ah	ampere-hours
BatPaC	Battery Performance and Cost model
CdTe	cadmium telluride
CFRP	carbon fiber reinforced polymers
CIGS	copper-indium-gallium-selenide
CMI	Critical Materials Institute
c-Si	crystalline silicon
DOE	U.S. Department of Energy
DRC	Democratic Republic of the Congo
EV	electric vehicle
g/cm^3	grams per cubic centimeter
GW	gigawatt
HEV	hybrid electric vehicle
ICE	internal combustion engine
IEA	International Energy Agency
kg	kilogram
kWh	kilowatt-hour
LED	light-emitting diode
Li-ion	lithium-ion
lm/W	lumen per watt
μμ	micrometers
MW	megawatt
NAICS	North American Industry Classification System
NAS	National Academy of Sciences
NdFeB	neodymium-iron-boron
NiCd	nickel-cadmium
NIiMH	nickel-metal hydride
PGMs	platinum group metals
PHEV	plug-in hybrid electric vehicle
PV	photovoltaics
R&D	research and development
REO	rare earth oxide

ROW	rest of world
TRIP	transformation-induced plasticity
USGS	U.S. Geological Survey
VRB	vanadium redox flow battery
W/m^2	watts per square meter
WEO	World Energy Outlook
WTO	World Trade Organization

Executive Summary

This report examines the role raw materials play in the manufacturing of energy technologies. The global markets for various energy technologies have been growing rapidly in recent years, which can place stress on the markets for raw materials. In addition, there is significant interplay between materials production and global supply chains that has implications for domestic manufacturing and its associated economic activity, including jobs, competitiveness, and innovation. This report includes updates to the technology analyses and criticality assessments contained in the U.S. Department of Energy's (DOE's) 2010 and 2011 *Critical Materials Strategy* reports.

Highlights of findings from this 2019 *Critical Materials Strategy* report include:

- Since the publication of the 2010 and 2011 reports, a combination of market forces, shifts in energy policy, and other factors have significantly changed the market outlook for some energy technologies and materials.
- Factors such as dramatic increases in demand, increasing geographical concentration of production, and market complexity of coproduction contribute to increased supply risk. In turn, material criticality can impact downstream manufacturing.
- Wind turbines, electric vehicles (EVs), vehicle lightweighting, catalytic converters, grid storage batteries, solar PV cells, and light emitting diodes (LEDs) use materials that are at risk of supply disruption. These risks generally increase in the medium term.
- Supply challenges for gallium, neodymium, lithium, cobalt, magnesium, dysprosium, and rhodium may affect domestic manufacturing and supply chains of energy technologies with high growth potential in the years ahead.
- Addressing these issues will require continued research and development (R&D), education and workforce training, and policy engagement.

Market Evolution since the 2011 *Critical Materials Strategy* Report

In the 2011 *Critical Materials Strategy* report, five rare earth elements—neodymium, dysprosium, terbium, europium, and yttrium were found to be critical. These materials are used in magnets and lighting phosphors. Lithium and tellurium were found to be near critical. Since 2011, there have been significant market developments that have shifted the picture for material criticality. The following are the highlights:

In rare earth markets, demand side response to price signals has been more rapid and robust than supply side response, and as a result new production has struggled to stay on line. Back in 2011, with rare earth prices more than ten times their current level, there was an abundance of proposed new mining projects. However, getting production online took several years, and some producers underestimated the cost of technically complex rare earth separations. For example, U.S. producer Molycorp re-opened Mountain Pass Mine in 2012, but filed for bankruptcy in 2015.

Prices drove wind turbines and electric vehicles away from rare earth magnets, but as the market softened, performance has brought them back. When the prices for rare earth elements were at or near their dramatic peak in 2011, both wind turbine and electric vehicle manufacturers turned to lower performance technologies that did not rely on rare earth magnets. However, more recently, both sets of manufacturers have been returning to rare earth magnets, and prices have seen an uptick. The cyclic nature of these dynamics also contributes to the supply risks described above.

Rare earth elements in phosphors for fluorescent lighting are no longer critical. At the time of the 2011 *Critical Materials Strategy* report, the global market for high efficiency compact fluorescent lamps (CFLs) and linear fluorescent lamps (LFLs) was growing due to strengthening global energy efficiency standards. At the same time, supply for rare earth elements used in lighting phosphors--including terbium, europium, and yttrium--was constrained. Since 2011, the market share for LED lighting has grown more rapidly than anticipated, edging out fluorescent lighting. LED lighting requires roughly an order of magnitude less rare earth phosphor.

The market share for solar PV thin films has reduced relative to crystalline silicon. Back in 2011, the trend in solar PV market share for cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) thin films relative to crystalline silicon was unclear. Since that time, the market dominance of crystalline silicon has increased, which in turn has reduced the importance of tellurium for energy applications.

2019 Criticality Assessment

For this report, fifteen materials were assessed for criticality in wind turbines, solar PV cells, grid storage batteries, EVs, vehicle lightweighting, catalytic converters, and LEDs. This set of materials and energy technologies were selected based on current and anticipated global trends in the supply of the materials and the demand for the energy technologies through 2030.

This report complements other U.S. government criticality assessments such as those produced by the National Science and Technology Council's Subcommittee on Critical and Strategic Minerals Supply Chains, and by the U.S. Department of the Interior in response to Executive Order No. 13,817, *A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals*. Such assessments differ in scope, approach, and purpose from this 2019 *Critical Materials Strategy* report, which provides important in-depth analysis into the potential growth in demand for these materials in energy technologies. Consequently, this report covers a smaller set of key materials where energy technologies with high growth potential constitute (or could constitute) a significant share of global consumption. Nonetheless, complementary assessments across the U.S. government played an important role in scoping this report and providing crucial input data.

As with the 2010 and 2011 *Critical Materials Strategy* reports, this report frames criticality in two dimensions: importance to energy and supply risk. Four materials—dysprosium, neodymium, gallium, and rhodium—were found to be critical in the short term (<5 years) (Figure 4-1). These critical materials are used in magnets, batteries, LEDs, solar PV coatings, and catalytic converters. Cobalt, lithium, magnesium, palladium, and platinum were found to be near critical in the short term. Between the short term and medium term (5-10 years), the importance to energy and supply risk scores shift for some materials (Figure 4-2). Lithium, cobalt, and magnesium become critical in the medium term. These materials are used in batteries and vehicle lightweighting. In the medium term, platinum shifts from near critical to not critical.

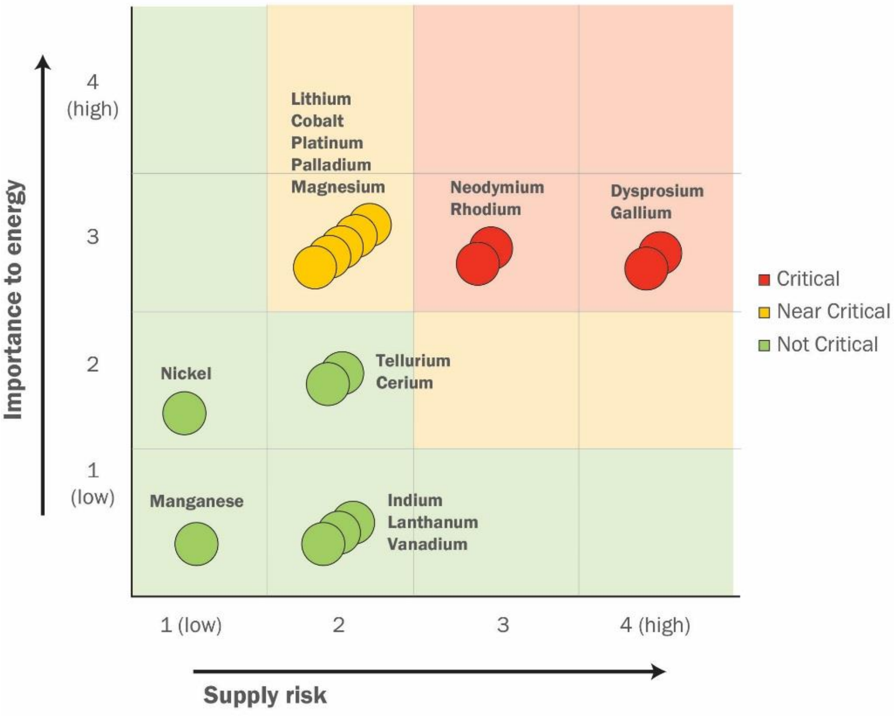

Figure ES-1. Short-term (2015–2020) criticality matrix

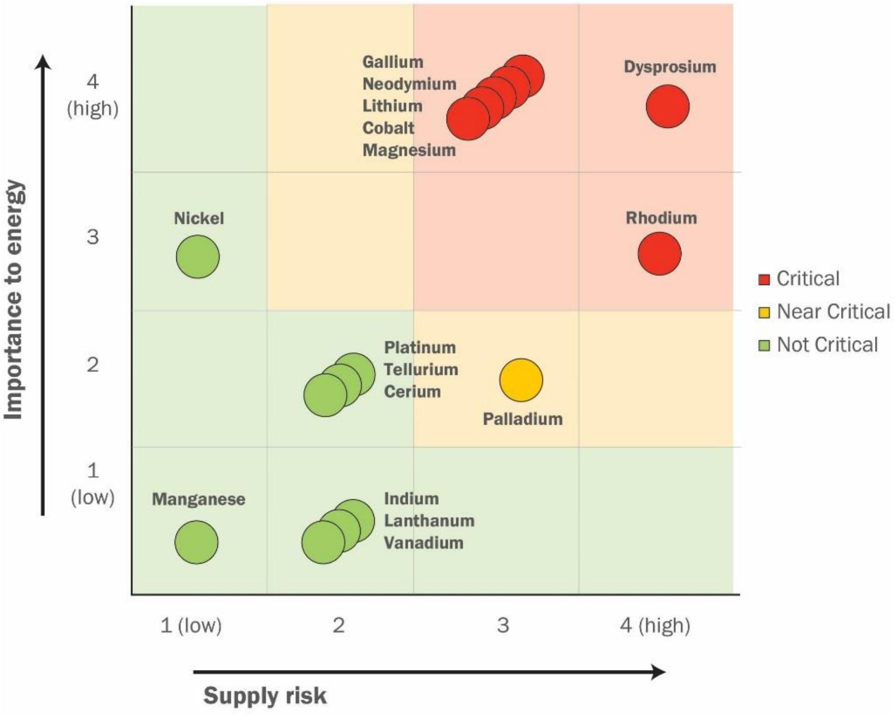

Figure ES-2. Medium-term (2020–2030) criticality matrix

The following are the highlights from the assessment:

Future LED growth may be constrained by gallium supply. LED lighting uses quantities of gallium that are significant relative to global production. The use of gallium in communication technologies is also growing. In response to this increase in demand, global production has increased by more than a factor of three since 2000, but the new production is concentrated in China. In addition, gallium is co-produced with aluminum, which could affect the ability of gallium production to respond to demand in the future.

Future growth of batteries in vehicles and for grid storage may be constrained by lithium and cobalt supply. Both lithium and cobalt are in a period of increasing prices and/or price volatility. With increases in global demand for batteries and limitations in substitutability, both lithium and cobalt could experience increasing supply constraints, particularly in the medium term. The market response for cobalt in particular may be limited because of complex market dynamics in the Democratic Republic of the Congo (DRC) – the largest global supplier. In addition, cobalt is co-produced with zinc and copper, which are both currently seeing a decline in global demand.

Magnesium availability may constrain vehicle lightweighting. Magnesium alloys and aluminum alloys containing magnesium are both important for vehicle lightweighting. The amount of these materials in domestic vehicles has increased steadily since the 1990s. Global magnesium production has increased dramatically in the past several years, particularly in China. The resulting rise in production concentration contributes to supply risk.

Of the platinum group metals (PGMs) used in catalytic converters, rhodium is most constrained. Catalytic converters are a dominant use of PGMs. On a global basis, technological advances (such as reduced engine sizes) are reducing PGM requirements for catalytic converters, while more stringent environmental requirements are increasing PGM requirements. Of the PGMs (platinum, palladium, and rhodium), rhodium is the most constrained, as its production is more geographically concentrated, and platinum and palladium are somewhat substitutable for one another.

Criticality in the Context of Dynamic Global Supply Chains and Innovation

There is a dynamic interplay between supply and demand at various stages of global energy technology supply chains, which both impacts and is impacted by material criticality. Understanding these dynamics can inform a proactive approach to developing national priorities in materials production, manufacturing, jobs, and trade. While domestic mining, mineral processing, and primary metal manufacturing are small in economic terms relative to U.S. manufacturing as a whole, they can play a critical role in innovation and economic security—by providing a base for further downstream activities, potentially drawing manufacturing to the United States by reducing supply risk for specialized raw materials. Ensuring economic security through raw material supply also enhances national security.

Innovation can catalyze the establishment of entire industries that shift global materials markets and contribute to material criticality --as illustrated by recent developments in LEDs and gallium markets. Innovation across the full supply chain can also provide a response to material criticality. This includes enabling supply diversification through advanced separation techniques and material recovery from conventional and unconventional sources, component and material substitution, and recycling and more efficient use. Understanding and addressing permitting and other policy barriers can help these innovations to succeed in the market.

Next Steps

The landscape of critical materials used in energy technologies brings risks and opportunities. The strategy to address the issues broadly covers: 1) Diversification of global supply chains; 2) Pursuit of substitutes; and 3) More efficient use and recycling. In addition, addressing broader issues in materials production, manufacturing, jobs, and trade can support the ability of the economy to be more resilient and responsive to changes in the landscape, which has important national security implications. There are a number of next steps that the U.S. Department of Energy and its partners can pursue to address specific issues and enhance longer term capabilities and resilience, including the following:

- Sustained and integrated R&D
- Understanding and addressing policy barriers for conventional and unconventional domestic production
- Understanding environmental risks across the supply chain and the relation to U.S. competitiveness
- Education and workforce training
- Understanding risk and opportunities in trade, intellectual property, and other policies
- Enhanced data quality and availability
- Interagency and international collaboration.

Focused and coordinated effort in these areas can help the United States in achieving economic and national security goals.

1 Introduction

Raw materials are essential for domestic manufacturing, which promotes jobs, sparks innovation, strengthens U.S. competitiveness, and provides a foundation for broader economic activity. Ensuring economic security through raw material supply also enhances national security. Furthermore, many technologies that are vital to national security rely on a secure supply of raw materials.

This report focuses on energy technologies and examines the market implications of trends in supply and demand for materials. The demand for many energy technologies—including wind turbines, solar photovoltaic (PV) panels, electric vehicles (EVs), vehicle lightweighting, grid storage, and energy-efficient lighting—have been growing rapidly in recent years. These trends have implications for the global use of materials with unique chemical and physical properties, which can further impact the materials' availability for energy uses. The situation can intensify if there is supply risk deriving from raw material availability or other market phenomena such as concentration of material production in a small number of countries, or co-dependence on other material markets.

The U.S. Department of Energy (DOE) defines a critical material as a material showing both a high importance to energy and a high supply risk. DOE began analyzing issues surrounding critical materials eight years ago when it issued two *Critical Materials Strategy* reports in 2010 and 2011. These reports illuminated potential issues in supply and demand of key materials and highlighted opportunities for proactive response, including in research and development (R&D), data and information, and interagency coordination on trade and other policies. The *Critical Materials Strategy* reports recommended proactively addressing material criticality based on three pillars: 1) diversifying global supply chains to mitigate supply risk; 2) developing material and technology substitutes; and 3) promoting recycling, reuse, and more efficient use to significantly lower global demand.

Much has changed since the 2010 and 2011 *Critical Materials Strategy* reports—in the market, in governmental response, and in our understanding of market dynamics. This 2019 *Critical Materials Strategy* report is an update of the 2010 and 2011 reports and was developed to reassess material criticality for energy technologies and revisit the DOE strategy to inform activities by DOE and others moving forward.

This analysis, like those in the previous reports, bounds a range of possibilities for future global demand of specific key materials in energy technologies with high growth potential under different assumptions for technology deployment, market share, and material intensity. The analysis compares the magnitude of these material demand trajectories to global material production levels. The goal of the analysis is to lay out the issues to inform understanding of potential material demand and supply risk interactions in both the short term (2015–2020) and medium term (2020–2030) to help inform R&D investments and policy engagement, rather than to predict the future. In general, DOE's most central role in proactively addressing material criticality is to support research that eventually increases the range of options to reduce supply risk in the medium to long term. DOE can also provide data and analysis to inform decisions in policy areas in the short term, including trade, technology standards, and intellectual property.

1.1 Market Developments since the 2011 *Critical Materials Strategy* Report

Of the 16 materials analyzed in 2011, 5 rare earth elements—dysprosium, europium, terbium, yttrium, and neodymium—were assessed as critical in the medium term (2015–2025), and 2 non-rare earth elements—lithium and tellurium—were assessed as near critical. Over the past several years, a combination of market forces, shifts in energy policy, and other factors have significantly changed the market outlook for rare earth elements, as well as for lithium and tellurium.

1.1.1 Rare Earths in Phosphors, Motors, and Generators

Back in 2011, the 17 elements known as rare earths commanded global attention. These elements have unique magnetic, luminescent, and other properties that make them valuable for energy applications. Of the five rare earths assessed as critical in 2011, europium, terbium, and yttrium are used in phosphors for efficient fluorescent lighting; the other two—neodymium and dysprosium—are used in magnets, including for EV motors and wind turbine generators.

When DOE issued the 2011 *Critical Materials Strategy* report, rare earth demand was projected to increase, and China, the largest producer of rare earths, had tightened export quotas to a level that had the potential to constrain supply. In addition, in late 2010, China temporarily stopped exporting rare earths to Japan following a collision between a Chinese fishing trawler and a Japanese coastguard vessel.[1] With concerns that supply would be unable to meet demand, spot market prices for rare earths rapidly increased and were near their peak when the 2011 *Critical Materials Strategy* report was issued (Figure 1-1). This trend was partly fueled by some rare earth consumers building up their inventories, which further inflated demand, albeit temporarily.

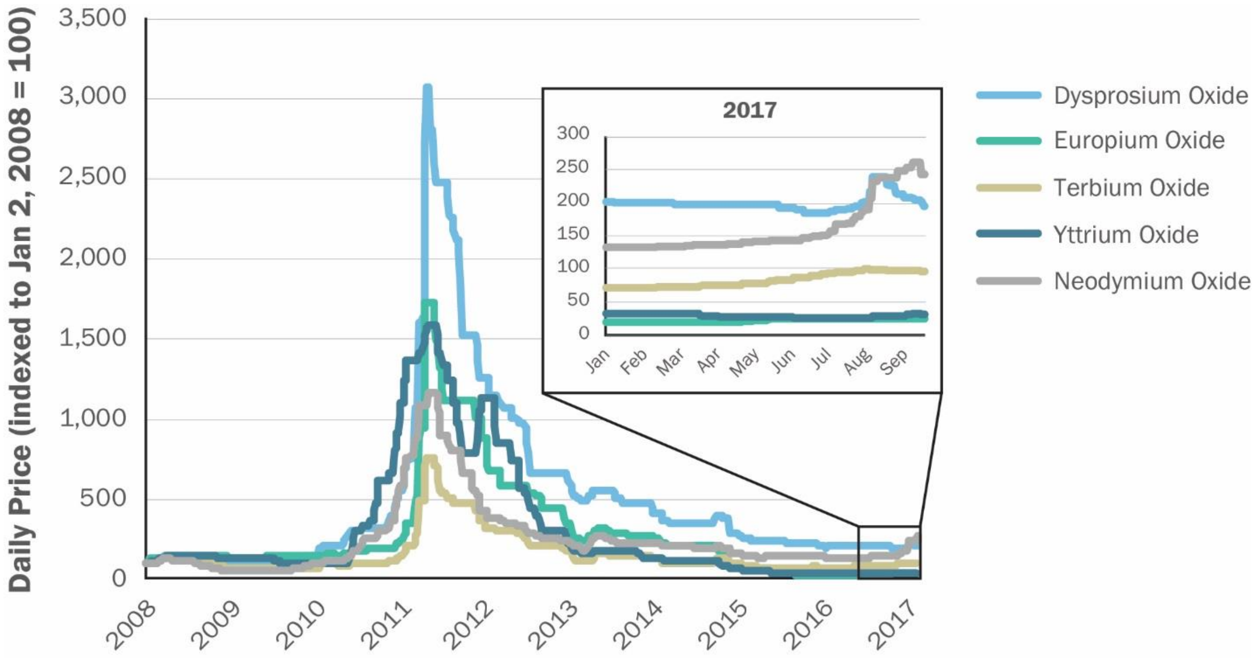

Figure 1-1. Relative free on board China prices of select rare earth oxides (January 2008–September 2017)[2]

In 2011 and 2012, lighting manufacturers using terbium, europium, and yttrium for phosphors in high-efficiency fluorescent lamps were particularly affected. Multiple lighting manufacturers petitioned for an exception from a DOE efficiency standard for general service (linear) fluorescent lamps that was set to come into effect in mid-2012. DOE's Office of Hearings and Appeals granted a 2-year exception from conservation standards for 700-series general service fluorescent lamps.[3] Since 2013, demand for rare earths in lighting has softened due to a relatively rapid uptake of LEDs,[4] which require much lower rare earth content than fluorescent lamps.

Though less dramatic, there were also developments in magnet markets for both wind turbines and EVs that were responsive to constraints on rare earth supply. In 2011, there were indications that some wind turbine manufacturers were avoiding designs that used rare earth magnets entirely, particularly for onshore wind turbines. Faced with particularly acute constraints in dysprosium supply, vehicle manufacturers were able to engineer some of the required dysprosium content out of their rare earth magnets. In addition, some EV manufacturers—most notably Tesla—moved from permanent magnet motors to induction motors, which do not require neodymium or dysprosium, but have efficiency and performance drawbacks. Tesla's designs have recently shifted—the 2017 Model 3 is using rare earth permanent magnet motors.[5]

The softening of demand and easing of supply constraints led to a reduction in rare earth prices. Some existing and potential suppliers of rare earths have found it difficult to weather these rapid price fluctuations. As prices rose, many suppliers were proposing to open or reopen rare earth production facilities. However, supply was unable to come online fast enough, and prices decreased as manufacturers found substitutes for rare earths in their products. Now, lower rare earth prices have brought the profitability of previously proposed rare earth supply projects into question. For example, Molycorp Inc.—the lone U.S. producer of rare earths—reopened its Mountain Pass mine in California in late 2012 as prices were declining but had not yet bottomed out. The company ramped up rare earth production through 2015; however, due to low rare earth prices and technical challenges in processing and separation, the mine never reached its projected production capacity. In 2015, Molycorp filed for Chapter 11 bankruptcy protection to restructure $1.7 billion in debt,[6] and the Mountain Pass mine closed and did not produce in 2016.[7] Then, in 2017, MP Mine Operations LLC—an American-led consortium—purchased the mine.[8] Leshan Shenghe Rare Earth Co. Ltd., a rare earth company in China, holds a non-voting minority interest in MP Mine Operations LLC.[9] Mountain Pass began producing again in 2018. Lynas Corporation—the operator of Mount Weld Mine in Australia—has fared better, but as of the company's fiscal year ending on June 30, 2017, it was still operating at a loss.[10]

The demand side of the rare earth market was able to respond relatively quickly to rapidly increasing prices by reducing or eliminating rare earth needs, which brought the market back into balance. Nonetheless, the supply side of the market is still in a state where it will be difficult to respond to any lasting increases in demand. In the second half of 2017, prices for dysprosium, terbium, and particularly neodymium rose.

Since 2011, several developments in rare earth trade have affected the accessibility of Chinese sources. In 2012, the United States, European Union, and Japan filed requests with the World Trade Organization (WTO) to consult on Chinese measures (duties and quotas) related to rare earth exports.[11] In 2014, the WTO Appellate Body agreed that China's export measures were illegal, and in 2015, China reported to WTO that its export duties and quotas had been removed,[12] making Chinese rare earths more accessible. On the other hand, beginning in 2011 and continuing following the WTO ruling, China has pursued consolidation of rare earth mining and processing companies in an effort to reduce black market production and sales, as well as to protect the environment,[13] reducing Chinese production capacity.

1.1.2 Lithium in EV Batteries

Global growth of electric drive vehicles (including hybrid, plug-in hybrid, and all-electric vehicles) has been significantly slower than the most optimistic 2011 projections, and global lithium production has been fairly flat.[14] Therefore, new lithium production has had difficulty gaining a market foothold. For example, Simbol Materials—which developed technology to recover lithium from geothermal brines in California's Salton Sea—has taken some time to find a path to scale up production, initially projecting to open a commercial lithium production plant in 2012.[15] In 2016, Alger Alternative Energy—who acquired Simbol's technology in 2015—signed contracts for significant delivery of lithium to Asia.[16]

1.1.3 Tellurium in Solar PV

Despite dramatic growth in global solar PV deployment, global growth of tellurium use in thin-film solar PVs has also been slower than the highest 2011 projections. This has been driven mainly by the increased market share of competing crystalline silicon solar PVs.

1.2 Governmental Response since the 2011 *Critical Materials Strategy* Report

Informed by insights from the 2010 and 2011 *Critical Materials Strategy* reports and follow-on analysis, DOE has pursued a wide range of activities, including R&D investment and collaboration with other federal agencies and international partners. These efforts have been responsive to congressional interest while also helping to shape the scope and themes of this 2019 *Critical Materials Strategy* report.

1.2.1 DOE R&D Investment Response

Following the 2010 and 2011 *Critical Materials Strategy* reports, DOE invested about $400 million in R&D to address all three pillars of its strategy: 1) diversifying global supply chains to mitigate supply risk; 2) developing material and technology substitutes; and 3) promoting recycling, reuse, and more efficient use to significantly lower global demand. The Advanced Research Projects Agency-Energy invested more than $30 million through the Rare Earth Alternative Critical Technologies program to address alternatives to rare earth magnets. The Geothermal Technologies Office funded projects addressing extraction of critical materials from geothermal brines, and the Office of Fossil Energy and National Energy Technology Laboratory invested in separation process innovation for recovery of rare earth elements from coal resources. The Office of Science invested in fundamental research involving theory, computation, synthesis, and characterization to understand the properties of critical materials, which enables their more efficient use in functional materials as well as the discovery and development of substitutes for critical materials. Most significantly, DOE invested $115-million over five years to establish the Critical Materials Institute (CMI) led by Ames Laboratory. DOE has been appropriated $75M total in FY17-19 to continue CMI. CMI addresses all three pillars, with particular focus areas including magnets with reduced neodymium and dysprosium content, lighting phosphors with reduced rare earth content, and rare earth element production process innovation.

1.2.2 Interagency Agenda and Collaboration

In 2010, the National Science and Technology Council established the Subcommittee on Critical and Strategic Minerals Supply Chains. Since 2013, the White House's Office of Science and Technology Policy, the U.S. Geological Survey, and DOE have co-chaired the Subcommittee. The Subcommittee is tasked with coordinating critical materials policy development across the federal government and recommending any risk-mitigation actions needed. The group has pursued work in R&D, data and information, and criticality assessment. The Subcommittee also provided input into the WTO rare earth case filed by the United States, Japan, and Europe.

In 2016, the Subcommittee issued a report entitled *Assessment of Critical Minerals: Screening Methodology and Initial Application* that presented a two-stage methodology to continually screen and analyze potentially critical minerals.[17] The first stage of the methodology is an early-warning screening tool that uses regularly-reported, publicly-available data to identify emerging critical minerals on an ongoing basis. This tool has been instrumental in highlighting new materials for DOE and its partner agencies to examine. A report and an associated journal article highlighting the most recent results from the early warning screening tool were recently published.[18,19]

In addition, over the course of several years, DOE has shared investment with the U.S. Department of Defense on agent-based models of rare earth supply chains. These models have informed thinking on potential mismatches between supply and demand responses to price signals, the role of inventories, and other phenomena.[20]

1.2.3 Congressional Interest

Since 2010, Congress has shown a sustained interest in critical materials, holding multiple hearings in both the House and Senate; in addition, there have been well over a dozen bills proposed addressing critical materials, though none have passed. In 2016, the U.S. Government Accountability Office issued a report entitled *Strengthened Federal Approach Needed to Help Identify and Mitigate Supply Risks for Critical Raw Materials*, which recognized the work of DOE, the U.S. Geological Survey, and the interagency Subcommittee and urged federal agencies to strengthen their collaboration on critical materials. The report also recommended additional engagement with industry and international partners, as well as an expansion of the raw materials screened by the Subcommittee.

1.2.4 International Actions

Back in 2010 and 2011, the United States began working with Japan and the European Union, launching a series of Trilateral Critical Materials Conferences that provided a forum for sharing analysis and R&D. This conference has continued on an annual basis, with the eighth held in December 2018.[a]

In 2013, Ames Laboratory, a U.S. Department of Energy Office of Science national laboratory operated by Iowa State University, signed a memorandum to collaborate on rare-earth scientific efforts with New Energy and Industrial Technology Development Organization (NEDO), a Japanese energy and industrial technology R&D organization.[21] This has resulted in five bilateral meetings to date.

In addition, as described above, the United States, European Union, and Japan jointly filed for a WTO consultation on China's rare earth export measures.[22]

1.3 Scope of this 2019 *Critical Materials Strategy* Report

Informed by market developments and governmental responses since the 2011 *Critical Materials Strategy* report, this report begins by exploring material criticality in the context of dynamic global supply chains (Chapter 2: Criticality in the Context of Dynamic Global Supply Chains and Implications for the U.S. Economy). This chapter also reviews the implications of material supply risk for domestic manufacturing and its associated economic activity, including jobs, competitiveness, and innovation.

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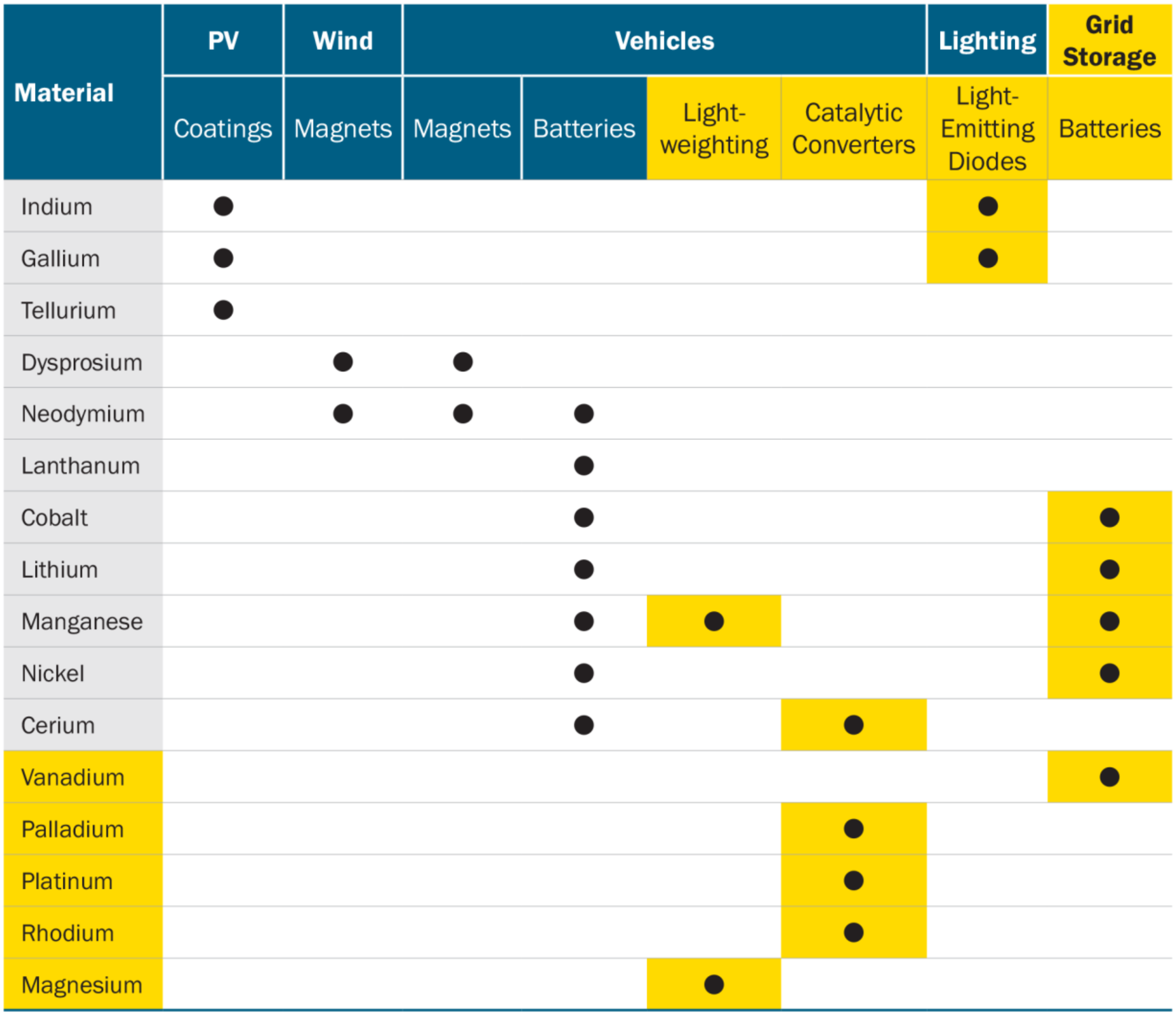
[a] Trilateral conference agendas are available at https://energy.gov/policy/initiatives/department-energy-s-critical-materials-strategy.

This report then details the global supply and demand trends for key materials in select energy technologies (Chapter 3: Use of Key Materials in Energy Technologies). Table 1-1 shows the technologies, components, and materials selected for this in-depth analysis. Although a larger set of energy technologies and associated materials were considered, final selection was based on a number of factors, including 1) a technology's expected global growth potential, 2) a technology's dependence on and significant demand for a material 3) a material's recent global production trends; and 4) availability of global technology deployment scenarios. Chapter 3 ends with a largely qualitative discussion of notable energy technologies and materials that were not selected.

Given the market development since the 2010 and 2011 *Critical Materials Strategy* reports, this report examines a slightly different set of energy technologies. In addition to the technologies covered in the previous reports, this 2019 *Critical Materials Strategy* report covers vehicle lightweighting, catalytic converters, and grid storage batteries. Notably with the rapid shift in the market for efficient lighting, this report examines LEDs rather than fluorescent lighting. Given this set of energy technologies, this report includes an assessment of materials that were not covered in the previous reports: vanadium, the platinum group metals (palladium, platinum, and rhodium), and magnesium. This report does not examine the rare earth elements yttrium, terbium, and europium—which were covered in the previous reports—because they were primarily used in phosphors for fluorescent lighting, which this report does not consider. This is a significant shift in market circumstances, as these materials were determined to be critical in 2011.

Table 1-1. Technologies, Components, and Materials Covered in this Report (highlighted cells are new to 2019)



Material	PV	Wind	Vehicles				Lighting	Grid Storage
	Coatings	Magnets	Magnets	Batteries	Light-weighting	Catalytic Converters	Light-Emitting Diodes	Batteries
Indium	●						●	
Gallium	●						●	
Tellurium	●							
Dysprosium		●	●					
Neodymium		●	●	●				
Lanthanum				●				
Cobalt				●				●
Lithium				●				●
Manganese				●	●			●
Nickel				●				●
Cerium				●		●		
Vanadium								●
Palladium						●		
Platinum						●		
Rhodium						●		
Magnesium					●			

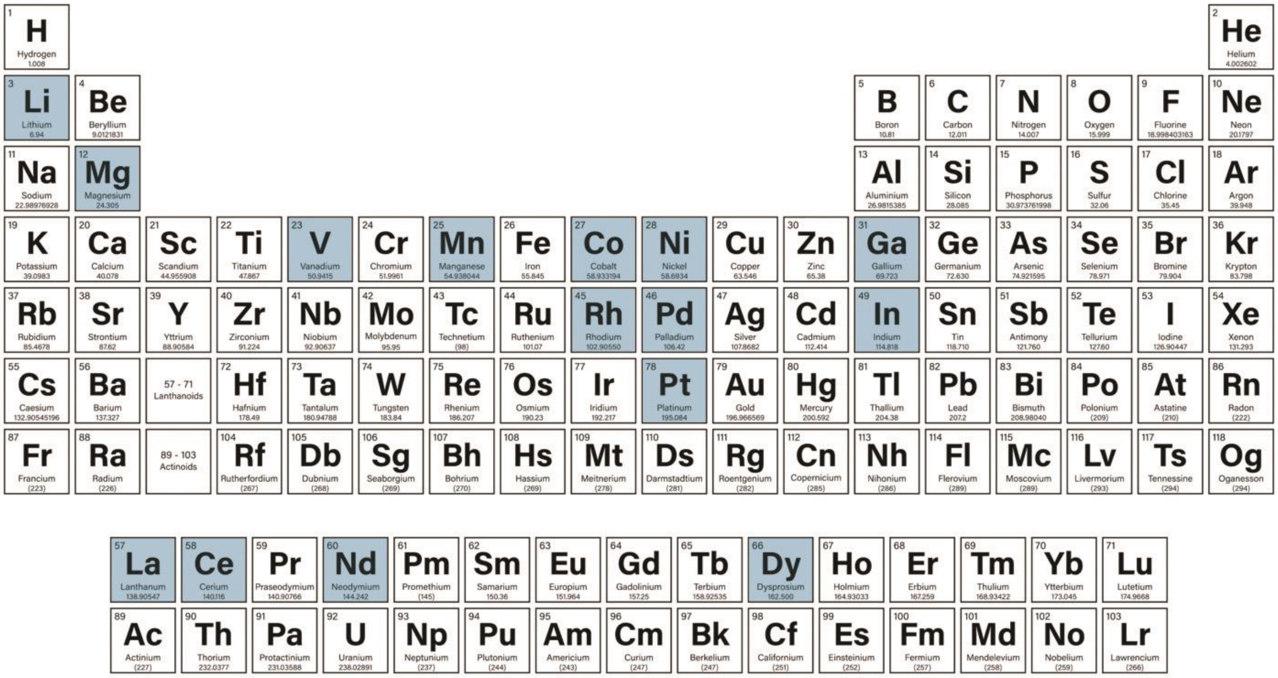


Figure 1-2. Key materials for energy within the Periodic Table of Elements

Informed by the quantitative analysis presented in Chapter 3 (Use of Key Materials in Energy Technologies), Chapter 4 (Criticality Assessment) summarizes short- and medium-term criticality assessments of the various key materials along two dimensions—importance to energy and supply risk. The collection of assessments is valuable to inform policy priorities and R&D investment, which Chapter 5 (Next Steps) discusses.

1.4 Other Relevant Material Criticality Assessments

As previously mentioned, the National Science and Technology Council Subcommittee on Critical and Strategic Mineral Supply Chains developed an early warning screening tool for mineral criticality.[23,24] Derived from publicly available, regularly reported data from the U.S. Geological Survey, this tool uses a set of three indicators – supply risk, production growth, and price volatility – to screen a large list of minerals for indications of potential criticality across the global economy on an ongoing basis. The minerals identified by the early warning screening tool are not necessarily critical, but observed market dynamics suggest that further analysis may be warranted. This tool is meant to proactively identify emerging critical minerals to help federal agencies prioritize which minerals to target with their relevant efforts.

On December 20, 2017, Executive Order No. 13,817, *A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals*, directed the Secretary of the Interior to publish a list of critical minerals within 60 days.[25] Through the U.S. Geological Survey, the Secretary of the Interior published the list on May 18, 2018, using a methodology adapted from the early warning screening tool described above.[26] However, the methodology for the 2018 critical minerals list differs from the screening tool methodology in that it does not assess criticality from a global perspective, but in terms of a mineral's domestic availability and importance to the U.S. economy and national security. As such, net import reliance is a key indicator.

Finally, just before Executive Order No. 13,817 was issued, the U.S. Geological Survey also published a report entitled *Critical Mineral Resources of the United States*.[27] Rather than assessing mineral criticality, it presents in-depth information on the global and national distribution and availability of minerals determined to be critical and/or strategic by a number of recent studies, emphasizing a broad range of existing and emerging technologies, as well as national security.

The assessments described above differ in scope, approach, and purpose from this 2019 *Critical Materials Strategy* report, which provides an important sector-specific perspective by performing in-depth analysis into the potential global growth in demand for materials in energy technologies. Consequently, this report covers a smaller set of key materials where energy technologies with high growth potential constitute (or could constitute) a significant share of global consumption. Nonetheless, complementary assessments across the U.S. government played an important role in scoping this report and providing crucial input data.

1.5 Endnotes

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[1] The Economist, “Bare anger: Chinese anger with Japan over a fishing-boat incident is both unexpectedly persistent and uncalibrated,” November 4, 2010, http://www.economist.com/node/17416850.

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2 Criticality in the Context of Dynamic Global Supply Chains and Implications for the U.S. Economy

The U.S. Department of Energy's 2011 *Critical Materials Strategy* report examined the markets for materials in energy technologies, including demand drivers, material supply characteristics, and price trends. This updated report is informed by a more interconnected and dynamic perspective on the interplay between supply and demand at various stages along energy supply chains, which both impact and are impacted by material criticality. This chapter explores the interactions between materials production and global supply chains and considers the implications for domestic manufacturing and its associated economic activity, including jobs, competitiveness, and innovation.

2.1 Dynamics of Materials Production

Supply risk is an important facet of material criticality and is driven by a number of dynamic factors, including rapid production growth, price volatility, geographic concentration of production, and codependence on other materials markets. In general, these factors can make it difficult for supply to respond to market signals, or they can present sources of potential supply disruption. Other characteristics of materials production, including source flexibility and recycling, can provide opportunities for supply to better respond to market signals and reduce supply risk. While these aspects of materials production are broadly consistent with the 2011 *Critical Materials Strategy* report, this section presents recent trends and new insights into the dynamics of materials production.

2.1.1 Production Growth and Price Volatility

As illustrated in Figure 2-1, from 2000 to 2014, some key materials markets showed stronger production growth than commodity materials, such as steel, while others experienced weaker growth. Over this 15-year period, iron and steel production doubled, while global production of both gallium and cobalt increased by more than a factor of three. Gallium's rise is in large part due to dramatic global increases in the use of communication and information technologies, including smartphones. Cobalt's increase is in large part due to growth in battery markets. On the other hand, growth in both rare earths and platinum group metals (PGMs) was weaker than growth in steel over this period.

Price volatility is often exhibited in small growing markets when supply has difficulty responding to market signals. Some materials—such as vanadium, indium, manganese, and rare earths—had significant price volatility between 2000 and 2014 (Figure 2-2). Production can be slow to respond to price signals and can contribute to price volatility for several reasons. First, production can be plagued with high barriers to entry due to capital requirements and technical complexity, which can prevent supply from adequately responding to increases in price. Second, many of these materials are produced as by-products, which makes it difficult to respond to price changes because production is driven by production of the primary source material. Third, there may be some geopolitical factors—such as the trade policies of other nations—that contribute to market constraints and price volatility.

One of the challenges in examining market change is obtaining credible, timely production data. The data for Figure 2-1 and Figure 2-2 are taken from the dataset underlying the work of the National Science and Technology Council's Subcommittee on Critical and Strategic Mineral Supply Chains.[1]

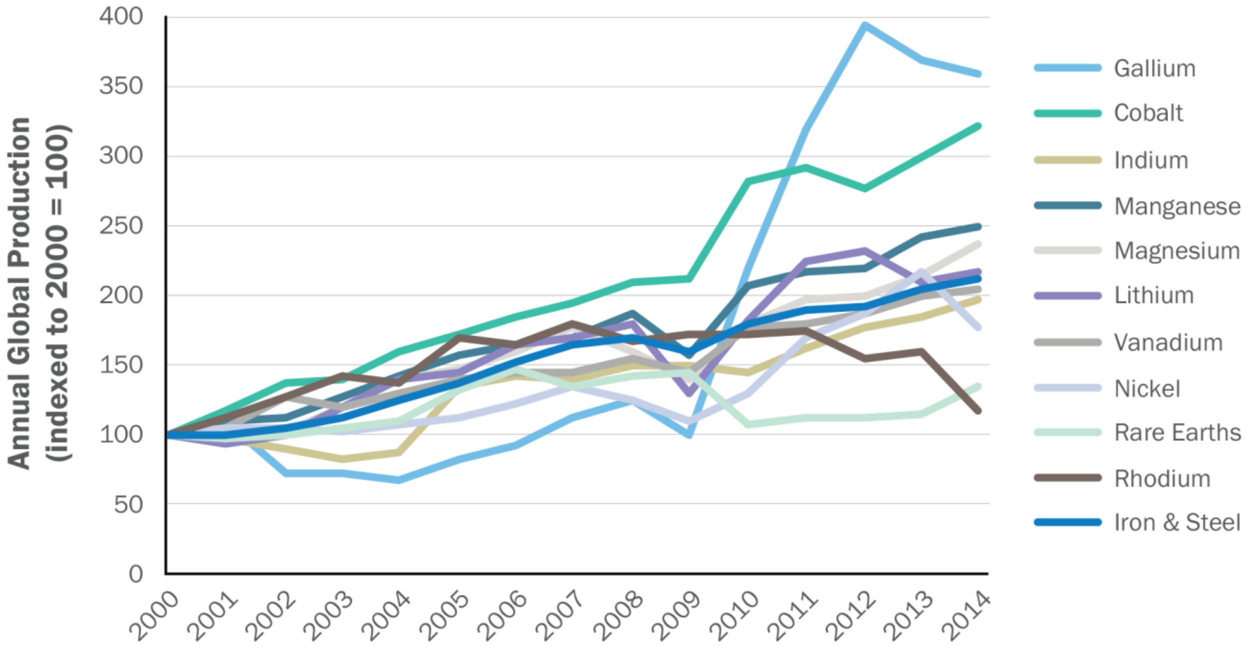

Figure 2-1. Comparison of annual global production for select materials (2000–2014)[2]

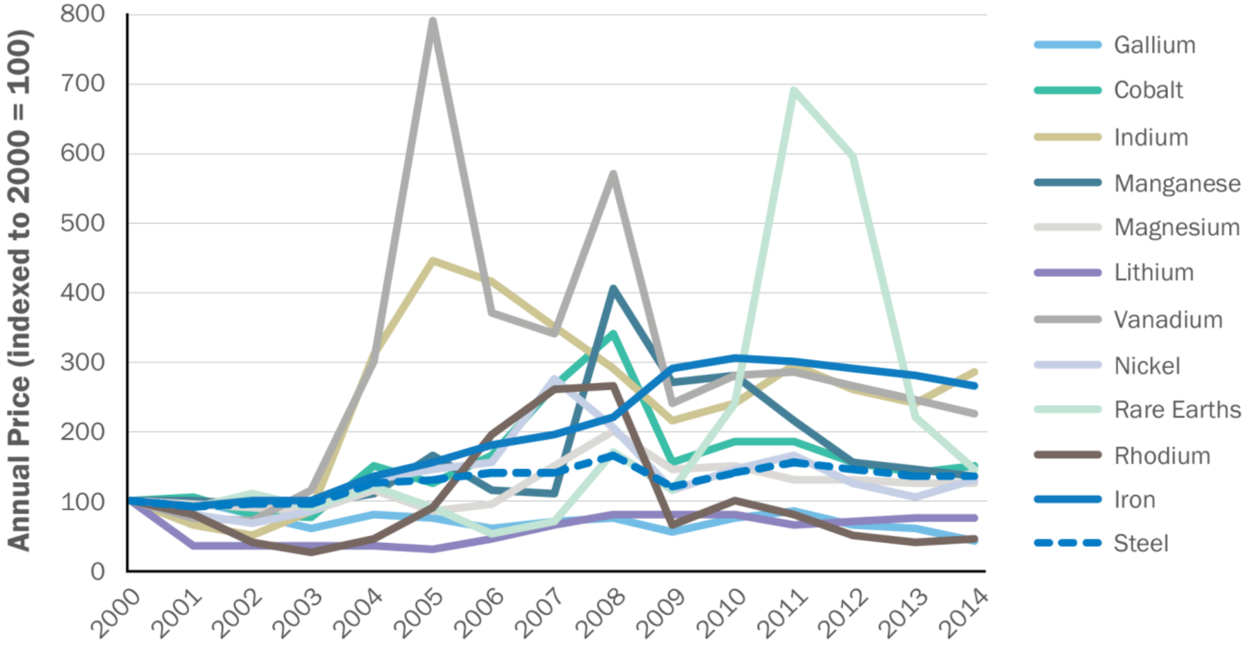

Figure 2-2. Comparison of price for select materials (2000–2014)[3]

2.1.2 Supply Concentration

For some materials, a significant portion of global production is concentrated in a small group of countries. This lack of supplier diversity can threaten adequate and consistent access to raw materials because a large share of global supply is at risk of disruption due to often unforeseen incidents, such as natural disasters, labor strikes, or shifting industrial or trade policies. Figure 2-3 shows that, on average, across all materials, supplier diversity decreased over the 15-year period (2000–2014), but each individual material has experienced different trends. For example, the production of magnesium, gallium, and lithium are becoming more concentrated. This is further illustrated in Figure 2-4, which shows that much of the increase in gallium production concentration is coming from a dramatic increase in global production met almost exclusively by China.

At the time of the 2011 *Critical Materials Strategy* report, tightening Chinese export quotas for rare earths sparked concerns over supply concentration in China, which was responsible for 90% of global production in 2010.[4] Supply concentration for rare earths has decreased somewhat as production outside of China has expanded, but China still produced 84% of the global rare earth supply in 2014.[5]

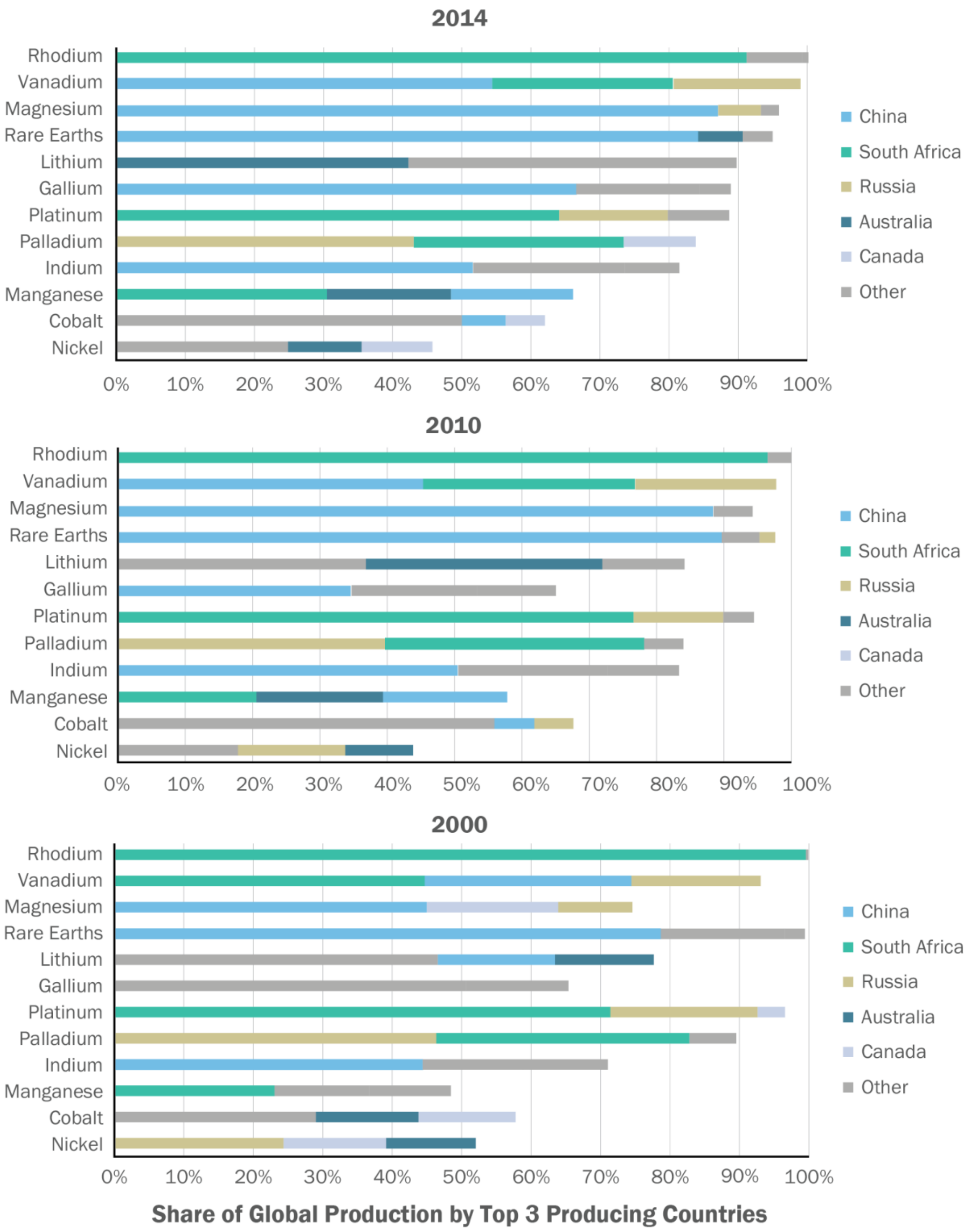

Figure 2-3. Comparison of share of the three largest global producers of select materials (2000, 2010, and 2014)[a,6]

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[a] Tellurium data not available.

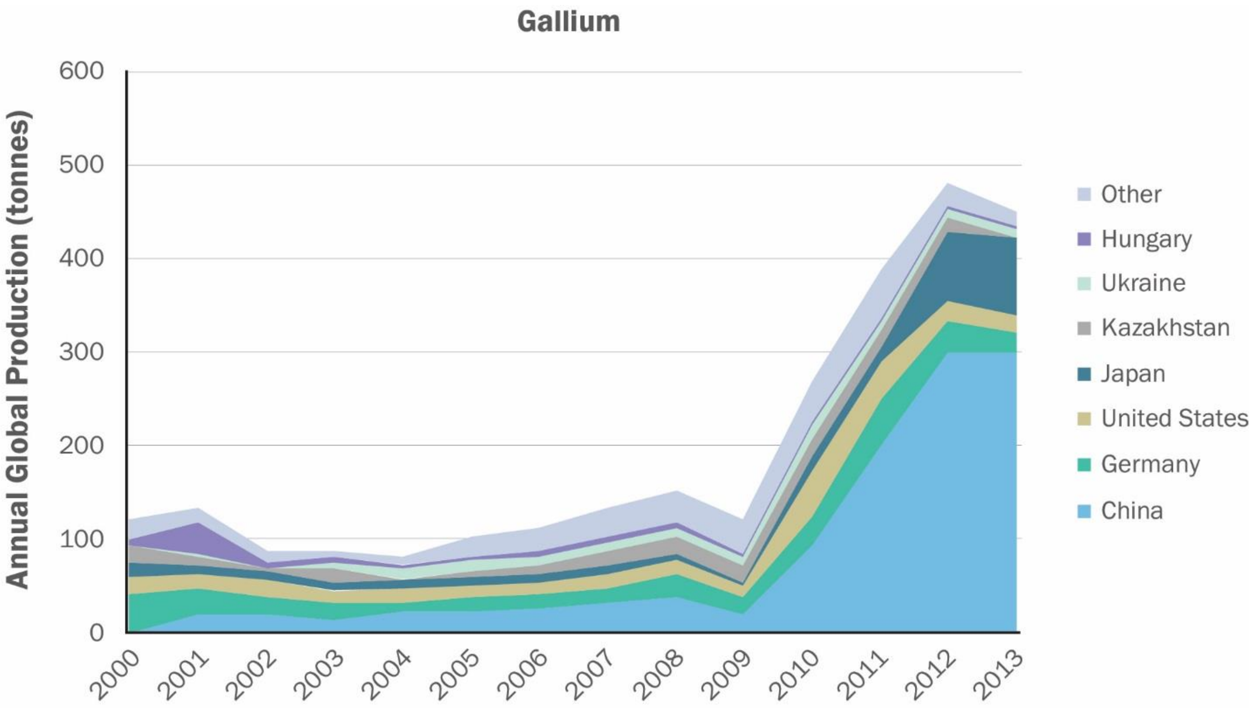

Figure 2-4. Annual global production of gallium by country (2000–2013)[7]

2.1.3 Coproduction and By-production

In many cases, a variety of materials are supplied from a single source; therefore, the supply of a given material, whether a primary product or a by-product, is often interconnected with other materials. Generally, by-production is beneficial and necessary to meet demand for less profitable materials, but it also introduces complex dynamics between their markets. These dynamics can lead to over- and under-supply and price volatility. Analyzing these dynamics is critical to understanding global energy supply chains.

Materials produced together are either primary products or by-products (coproducts are a special situation relevant mostly to rare earths and will be discussed later in this section). Generally, primary products are materials that bring producers the largest share of revenue. By-products are produced along with primary products and contribute less revenue. In some instances, by-products have very little market value and must be managed at a cost. In other instances, by-products have strong market value and can be sold for additional revenue.

Producers will optimize output of by-products as a function of concentration, production costs, and market price. For example, trace amounts of gallium are found in most aluminum-producing bauxite deposits, but gallium is only produced when found in a high enough concentration. The original concentration in the feed bauxite determines the achievable extraction efficiency. At a typical feed concentration of 50 parts per million, about 15% of the contained gallium is extractable.[8] This suggests that technical process improvements could improve yield.

Figure 2-5 shows more examples of primary products and commonly associated by-products. The primary product is in the center of the figure. By-products are shown in the concentric rings. Higher percentages of the respective by-product are shown closer to the center of the figure. For example, the figure illustrates that roughly 50% of cobalt is produced as a by-product of nickel; between 25% and 50%

as a by-product of copper; and some small, non-zero amount as a by-product of platinum. Many of the materials examined in this report (marked with color-coded circles) tend to be produced as by-products. Some materials are produced almost exclusively as a by-product of one primary product (*e.g.*, gallium). Others are produced as a by-product of a number of primary products. For example, indium is produced as a by-product of zinc, copper, tin, lead, and iron production.

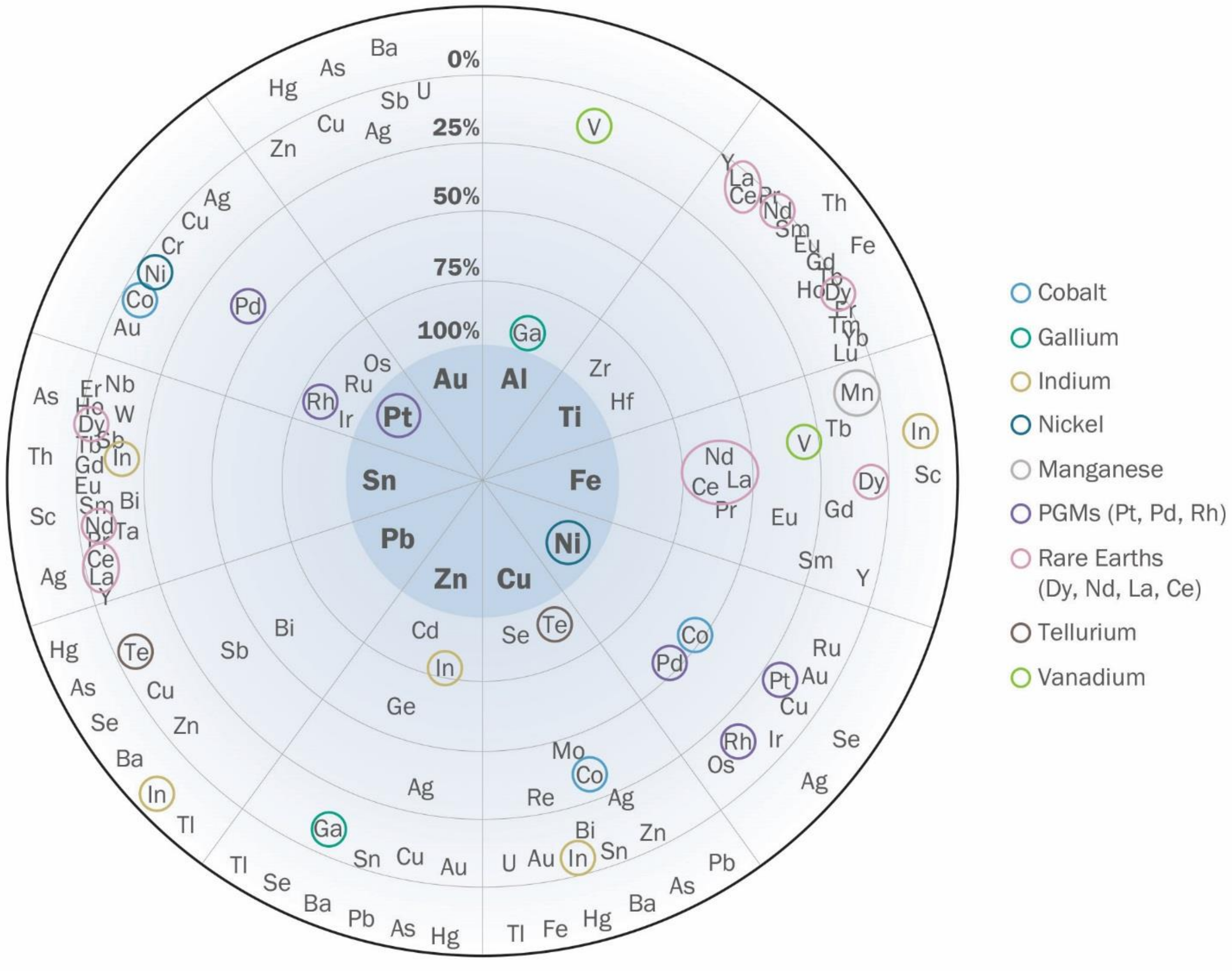

Figure 2-5. Primary products and by-products[b,9]

For many materials, the quantities produced as by-products can be large enough to meet global needs;[10] however, market interconnectedness can inhibit supply response and lead to price volatility. Examining nickel, copper, and cobalt illustrates these dynamics. As a by-product of nickel and copper production, cobalt does not drive mine production; rather, it helps provide additional revenue to the mining operation. In 2014, 20.3 million tons of copper and 2.5 million tons of nickel were produced, while only 0.1 million tons of cobalt was produced.[11] Nonetheless, the supply of cobalt is deeply connected with the supply of copper and nickel. In 2011, prices for all three materials decreased by 20%–30%. Over the next 5 years, cobalt prices stabilized, while prices for copper and nickel continued to decrease. Since

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[b] PGMs: Pt = platinum; Pd = palladium; Rh = rhodium. Rare Earths: Dy = dysprosium; Nd = neodymium; La = lanthanum; Ce = cerium.

2016, cobalt prices have increased significantly while copper and nickel prices have remained relatively flat (Figure 2-6). This suggests that cobalt demand is strengthening, but supply is struggling to respond because of weak nickel and copper prices. These market developments could be exacerbated by recent trade policies instituted by the world's leading supplier of cobalt—the Democratic Republic of the Congo (DRC).[12]

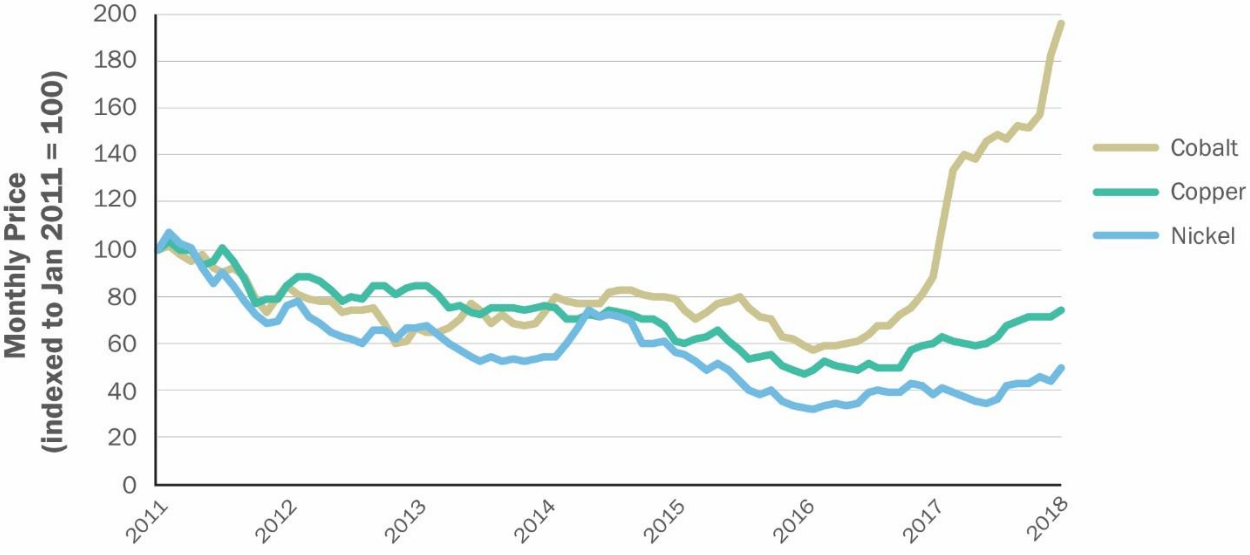

Figure 2-6. Average monthly cobalt, copper, and nickel prices (January 2011–January 2018)[13]

Examining rare earths illustrates the effects of changing prices of by-products, specifically a special type of by-product—a coproduct. Coproduction refers to cases where many materials are produced together, each bringing in similar revenues rather than one material accounting for an overwhelming majority of revenue. Rare earth-containing ores (*e.g.*, bastnäsite, xenotime, and monazite) are often composed of more than 10 different rare earth elements. Figure 2-7 illustrates the different ore compositions at four different mines. This blend, along with the market prices and overall production, determines the mine's revenue. For example, based on current prices and the ore blend at the Bayan Obo mine in China, neodymium currently accounts for about 60% of the mine's revenue; however, other elements—such as praseodymium—are also important contributors.

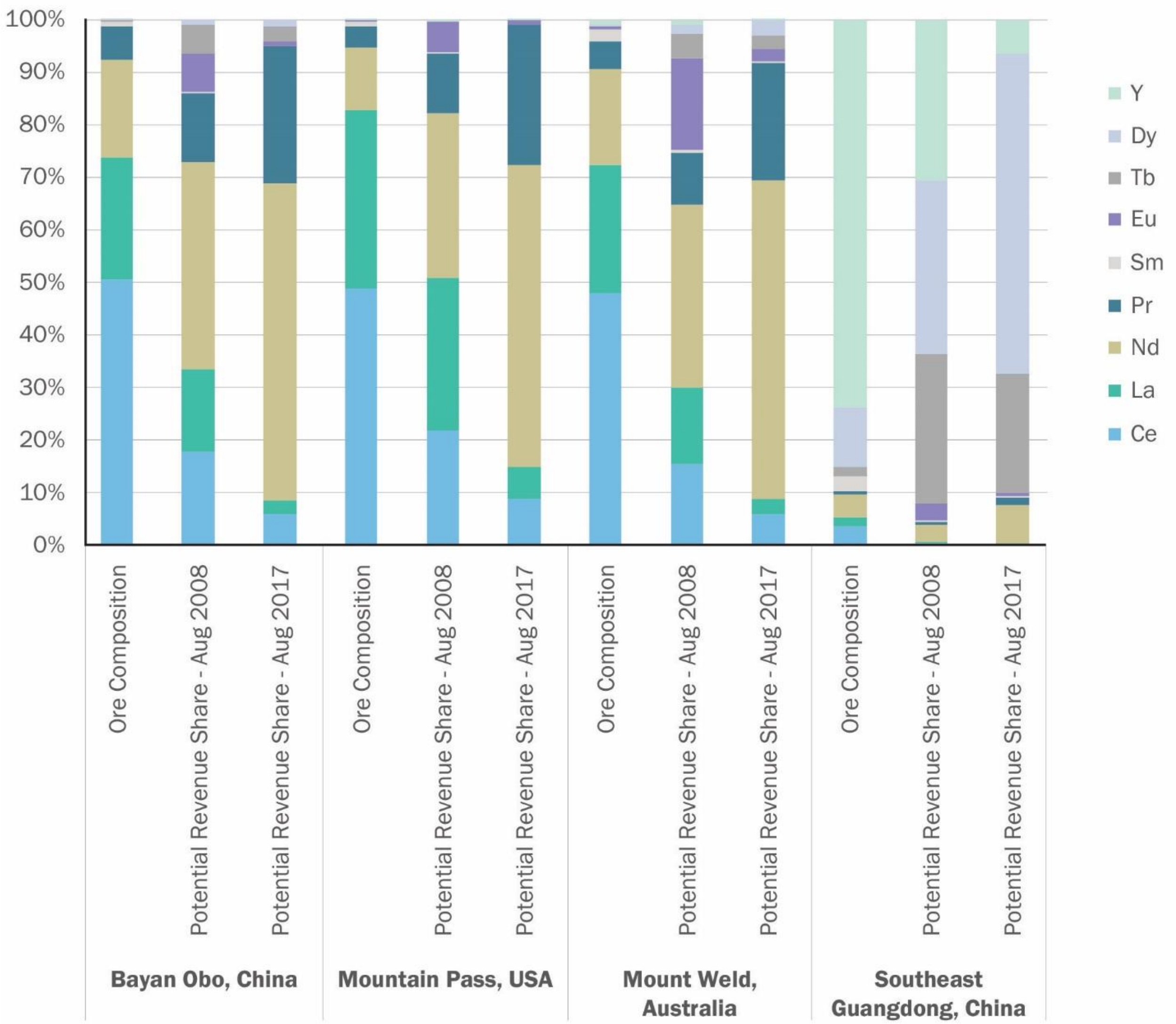

Figure 2-7. Composition of rare earth ore compared to potential revenue shares based on August 2008 and August 2017 prices at four different mines[c,d,e,14,15]

Fluctuations in relative prices can change each material's share of mine revenue, sometimes resulting in different materials driving production. For example, in August 2008, large portions of Bayan Obo's, Mountain Pass', and Mount Weld's revenue was generated from lanthanum, cerium, and neodymium, with praseodymium and europium making smaller but significant contributions (Figure 2-7). Today,

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[c] Gadolinium also appears in relevant quantities within these ores, especially in Southeast Guangdong, China, where it constitutes 5% of the rare earth ore. However, lack of price data for August 2008 precluded it from being included in this figure.

[d] Note that Mountain Pass mine temporarily closed in 2016 and began reproducing in 2018. This figure is for illustration only.

[e] Acronyms: Ce = cerium; La = lanthanum; Nd = neodymium; Pr = praseodymium; Sm = samarium; Eu = europium; Tb = terbium; Dy = dysprosium; Y = yttrium.

more than 80% of those same mines' potential revenue is generated from neodymium and praseodymium, with the share of revenue from cerium, europium, and lanthanum dropping significantly. The figure also shows that the composition of the rare earth resource in Southeast Guangdong is such that the mine's revenue stream in 2008 was mostly dependent on yttrium and dysprosium. At current prices, yttrium accounts for a smaller portion of revenue while dysprosium and terbium are larger contributors.

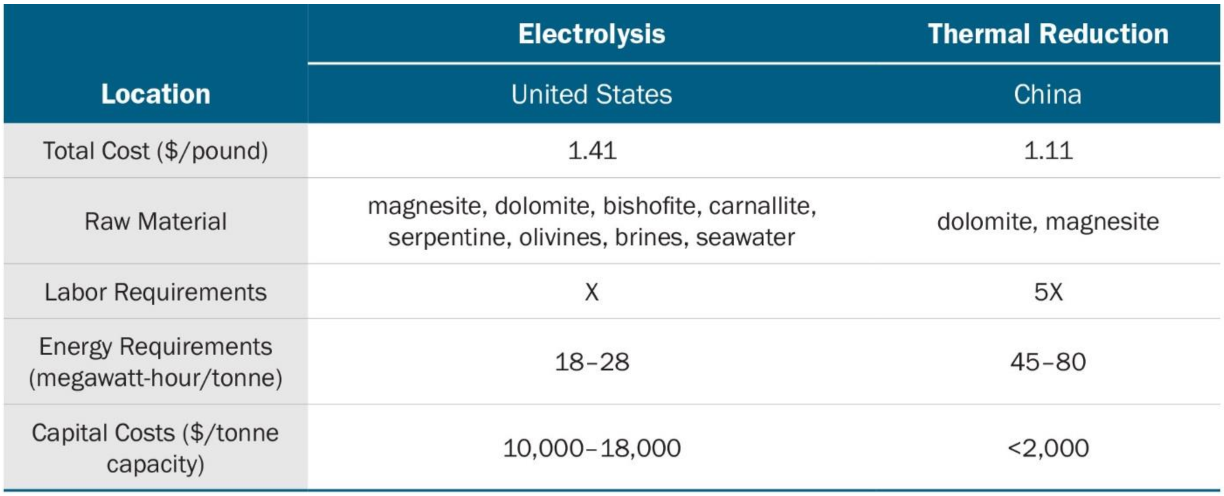
While cerium often makes up large portions of rare earth-containing ores, such as bastnäsite and monazite, prices are such that cerium's share of mine revenue is relatively small. In some cases, cerium is thought of more as a waste product because its low price does not outweigh the cost of separation and purification.[16] Furthermore, with production being driven by less abundant but higher-value products, such as neodymium, cerium's relative abundance within rare earth-containing ores often leads to excess supply, which further suppresses prices. The U.S. Department of Energy's Critical Materials Institute is currently researching new uses for cerium to take advantage of its abundant supply. One example is a cerium-aluminum alloy co-developed by Oak Ridge National Laboratory and Eck Industries that is lightweight, corrosion resistant, and can withstand temperatures up to 500°C; the technology has been licensed by Eck Industries[17].

2.1.4 Source Flexibility and Recycling

For some of the materials examined in this report, there are multiple pathways to production—including recycling—that can add flexibility to the early stages of a supply chain. Such flexibility can make supply chains more resilient and responsive to changing market conditions. While there are frequently multiple possible production paths, one can dominate due to lower overall costs and other factors. Decisions on production pathways are typically based on tradeoffs between capital costs and operational costs—such as labor, energy, and environmental compliance—which can differ by location. Price volatility can introduce significant uncertainty, which can make it challenging to plan for additional supply, particularly for new processes with uncertain costs and permitting requirements.

An example of a material with multiple pathways to production is magnesium. Magnesium is produced from dolomite, magnesite ore, and olivine resources, as well as salt brines and seawater. Furthermore, there are two common methods for refining magnesium: thermal reduction and electrolysis. Each refining method is suited for certain raw magnesium materials and presents tradeoffs between capital costs and operating costs (Table 2-1). A number of alternative processes are under development, but more R&D is necessary before they can be competitive.[18]

Table 2-1. Comparison of Electrolysis and Thermal Reduction Magnesium Processing[19,20]



	Electrolysis	**Thermal Reduction**
Location	United States	China
Total Cost ($/pound)	1.41	1.11
Raw Material	magnesite, dolomite, bishofite, carnallite, serpentine, olivines, brines, seawater	dolomite, magnesite
Labor Requirements	X	5X
Energy Requirements (megawatt-hour/tonne)	18–28	45–80
Capital Costs ($/tonne capacity)	10,000–18,000	<2,000

Magnesium refining through thermal reduction typically has the lowest capital cost, but it has high energy and labor requirements, as well as high environmental management needs. With low energy prices, low labor costs, and low environmental standards, thermal reduction is the favored magnesium refining method in China, which accounts for a large and growing majority of magnesium production (Figure 2-8). Electrolysis is an alternative to thermal reduction; it is favored by the west (*e.g.*, United States, Canada) but is generally associated with higher production costs. While the raw material inputs for thermal reduction are commonly limited to dolomite and magnesite, the raw material inputs that can be used for electrolysis are more varied, including magnesite, dolomite, olivine, seawater, and brines. Though thermal reduction currently dominates production, rising labor costs and environmental standards in China could make electrolysis or other processes more cost competitive. However, volatility in the price of magnesium can make it difficult to sustain investment in alternative processes currently under development.

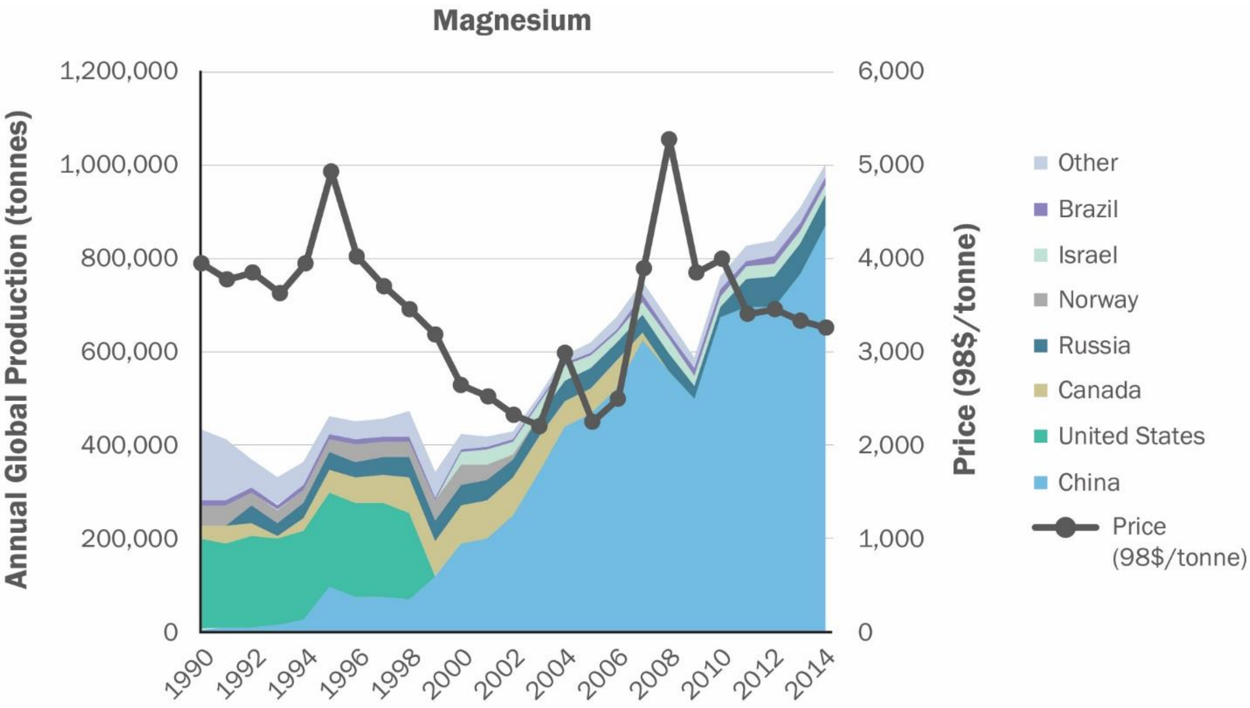


Figure 2-8. Annual global production of magnesium by country and price (1990–2014)[21]

One potential additional source of raw materials is end-of-life recycling, which, in some cases, can alleviate supply constraints by providing access to materials faster than from a new mine.[22] For some specialty materials like PGMs, an established recycling infrastructure already exists and makes up more than 30% of available supply.[23] In developed countries, 95% of PGM content can be recovered from spent automotive catalysts.[24] As such, the R&D trend is toward achieving higher efficiencies in current processes and expanding the suite of recycling opportunities.[25]

In some cases, new recycling processes are developed in response to supply constraints. For example, when export restrictions in China threatened access to rare earth supplies, research into rare earth recycling boomed at corporate and national levels.[26] However, rare earths are difficult to recycle because they are used in minute amounts, with a suite of other materials, and across a wide range of products. In addition, the products they are embedded in are globally distributed.[27] In 2012, Mitsubishi established an organizational framework via a network of subsidiaries, as well as a technical process to extract neodymium and dysprosium from consumer air conditioners and other large appliances.[28] In 2015, the U.S. Department of Energy's Critical Materials Institute licensed a membrane solvent extraction system to Momentum Technologies that had the potential to extract more than 90% of neodymium, dysprosium, and praseodymium from magnets.[29] In 2018, the U.S. Department of Energy's Critical Materials Institute was awarded an R&D 100 Award, with special recognition of a Gold Award for Green Technology, for acid-free dissolution recycling of rare earths and cobalt from e-waste.[30]

Pursuing recycling pathways within the United States rather than exporting end-of-life wastes for recycling gives more domestic access to the materials that are recycled from domestic products. In addition, pursuing domestic recycling avoids the extraordinary environmental impacts associated with dumping E-waste in Africa and other regions.[31]

2.2 Dynamic Global Supply Chains

Individually, characteristics of materials production discussed in Section 2.1 can impact supply risk. In concert with each other and with downstream global supply chains, however, the outcome is more complex. Actors within global supply chains respond to changing conditions, including shifts in production, pricing, inventories, regulations, and deposit developments. These responses interact with one another, often in unanticipated ways. In addition, mismatches in the response time of various actors within supply chains to market signals can drive market conditions. For example, as factors like demand or export restrictions drive up price, consumers of raw materials may shift to substitutes or increase use efficiency more rapidly than new sources can be developed. These dynamics contribute to a shift in material criticality over time, as well as shifts in market opportunity and consequences for raw material industries and manufacturers of technology.

An example of global supply chains responding to supply risk was recently born out in the rare earth magnet market. In 2011, a mismatch of supply and demand for rare earths led to a large price spike across all rare earths, including neodymium and dysprosium, which are utilized for permanent magnets in wind turbines and electric vehicles, among other applications. The price spike led to a set of market responses across the supply chain, including pursuit of new rare earth production, accumulation of inventories, and strategies to substitute for or avoid the use of rare earth magnets. Electric vehicle and wind turbine manufacturers were able to deftly pivot to reduce their reliance on neodymium and dysprosium by introducing product lines that use little or no rare earths, which sometimes came at a cost to performance. However, rare earth producers faced stronger structural barriers and longer time lags to open or reopen production facilities. Market conditions resulting from the interactions among these factors have been illustrated in scholarly articles.[32]

2.3 Implications of Material Criticality for the Domestic Economy

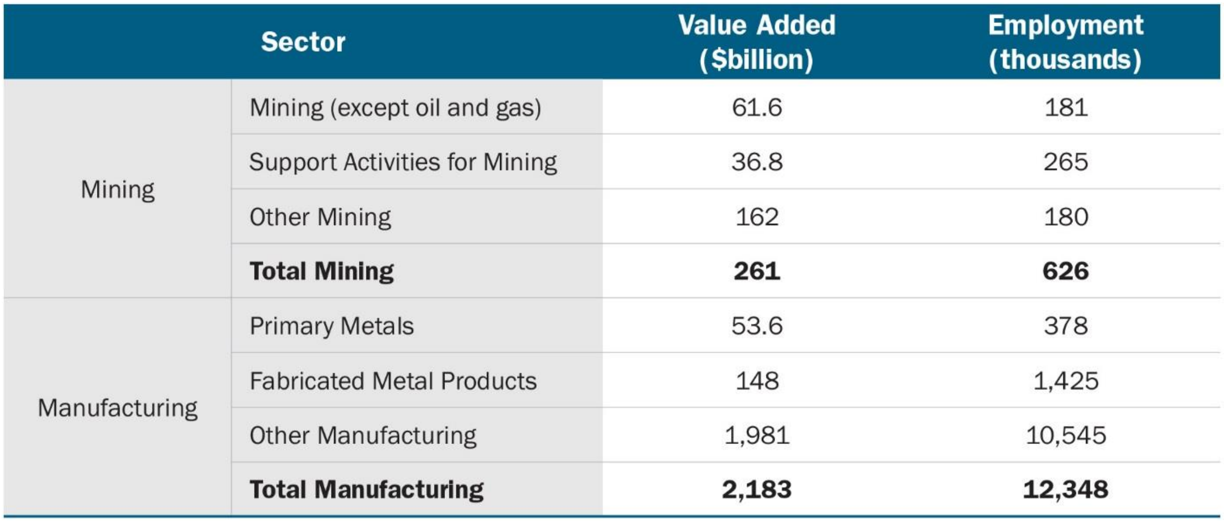
Stable access to raw materials, whether from domestic sources or trade partners, is vital for domestic manufacturing, which accounts for a significant number of jobs as well as economic value added. Although domestic materials production has been declining in recent years, domestic manufacturing output has continued to grow. This suggests an increased reliance on material imports, which introduces risks for domestic manufacturing and associated downstream economic activity that relies on advanced technologies and other manufactured products. Further, the loss in domestic materials production can have implications for innovation at multiple stages along the supply chain.

2.3.1 Materials Production as a Base for Broader Economic Activity

Mining and early-stage metals manufacturing, while small relative to all other domestic manufacturing, play a critical role by providing a base for downstream economic activity. These industries contribute billions of dollars to the economy and employ millions of people, but they also provide important inputs for domestic manufacturing, which contributes trillions of dollars to the economy and employs tens of millions of people (Table 2-2).

Despite the mining sector's comparatively small size, domestic production of raw materials can strengthen domestic manufacturing by reducing risk and increasing collaboration.[33] Contracts with domestic materials production companies can be more secure and help reduce the risk of supply disruptions and ensure price stability. It may also be easier for domestic manufacturers to collaborate with domestic materials production companies in the pursuit of new materials or new products and technologies.

Table 2-2. 2016 Value Added and Direct Employment of U.S. Mining and Manufacturing[f,34,35]



Sector		Value Added ($billion)	Employment (thousands)
Mining	Mining (except oil and gas)	61.6	181
	Support Activities for Mining	36.8	265
	Other Mining	162	180
	Total Mining	**261**	**626**
Manufacturing	Primary Metals	53.6	378
	Fabricated Metal Products	148	1,425
	Other Manufacturing	1,981	10,545
	Total Manufacturing	**2,183**	**12,348**

In some instances, the United States has ceded leadership in lower-end manufacturing sectors to emerging economies and has offset the losses with high-end, high-value goods.[36] In 1990, the United States was the world's largest metallic and industrial minerals producing country, but it has since dropped to the seventh-largest producing country.[37] During this time, other countries have expanded output while U.S. mineral production has decreased by roughly 17% (Figure 2-9). However, a significant amount of primary metals production and metals fabrication still occurs domestically, benefiting downstream economic activity in the United States. These benefits can trickle back upstream into materials production by increasing demand for new materials and introducing new sources of raw materials and new refining solutions. Continuous investment in R&D is critical because once those capabilities are gone, reestablishing them is difficult.[38]

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[f] Mining data refers to North American Industry Classification System (NAICS) code 21: Mining. Manufacturing data refers to NAICS codes 31–33: Manufacturing.

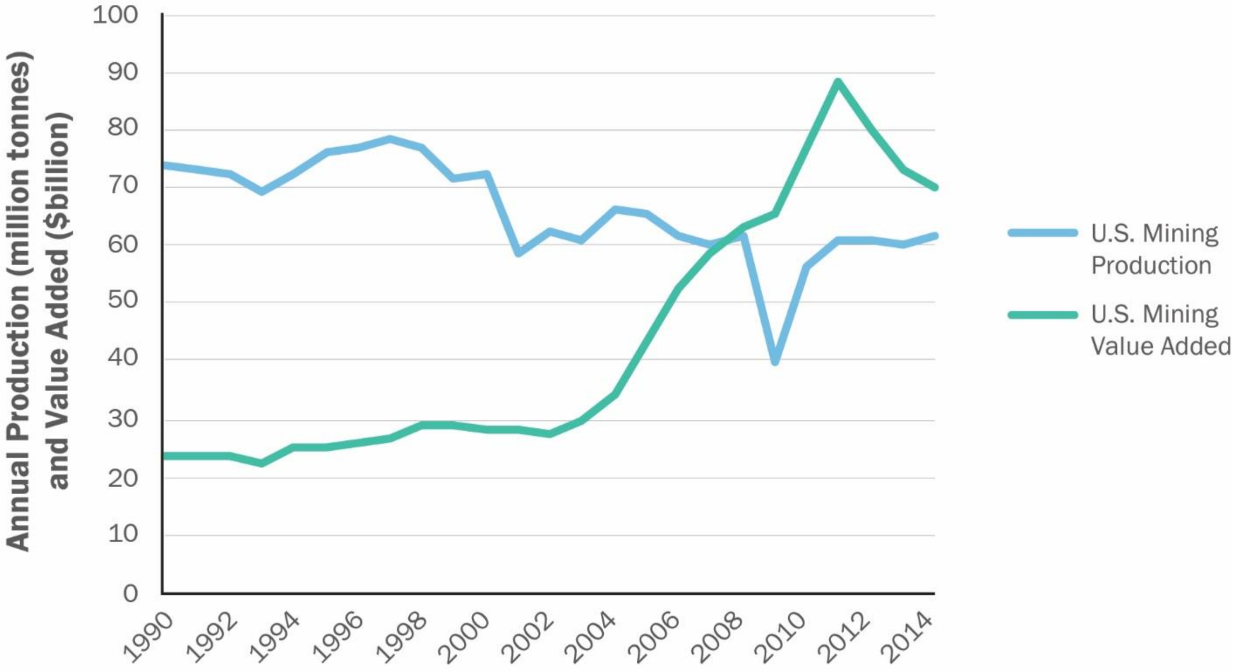

Figure 2-9. U.S. mining production and value added (1990–2014)[g,39,40]

The decrease in U.S. mineral production is not because of a small resource endowment, but is likely due to a complex array of other factors, including uncertainty in permitting, cost competitiveness (financial, labor, and energy costs), lack of technical capabilities, and competition for investment dollars. Developing a new mine from discovery to first output can take in excess of 10 years and cost several billion dollars.[41]

Several of the countries that are scaling production to meet increasing global demand for minor metals and minerals have been able to produce at low cost, in part because of lax health and environmental protections. For example, there have been significant worker health issues and impact to waterways in the DRC from cobalt production.[42] Pollution from extensive rare earth mining tailings in Batou, China has seeped into groundwater.[43] These issues are both a challenge and an opportunity for U.S. mining. Given the U.S.'s strong track record in mining productivity, sustainability, and safety,[44] increasing domestic production of these metals and minerals could contribute to a global reduction in associated health and environmental impacts.

While domestic mineral production has dropped, gross output and value added from domestic manufacturing has more than doubled since 1990 (Figure 2-10). The United States is the second-largest manufacturer in the world, generating $2.2 trillion in value in 2015. This is behind only China, which generated $3 trillion in value, but ahead of Japan, which generated $0.8 trillion.[45] The strong growth in U.S. manufacturing, paired with the decrease in mineral production, suggests a growing reliance on material supply imports, which can increase supply risk.

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[g] Mining production excludes smelted and refined minerals, as well as primary metals manufacturing. Value added refers to NAICS code 212: Mining (except Oil and Gas).

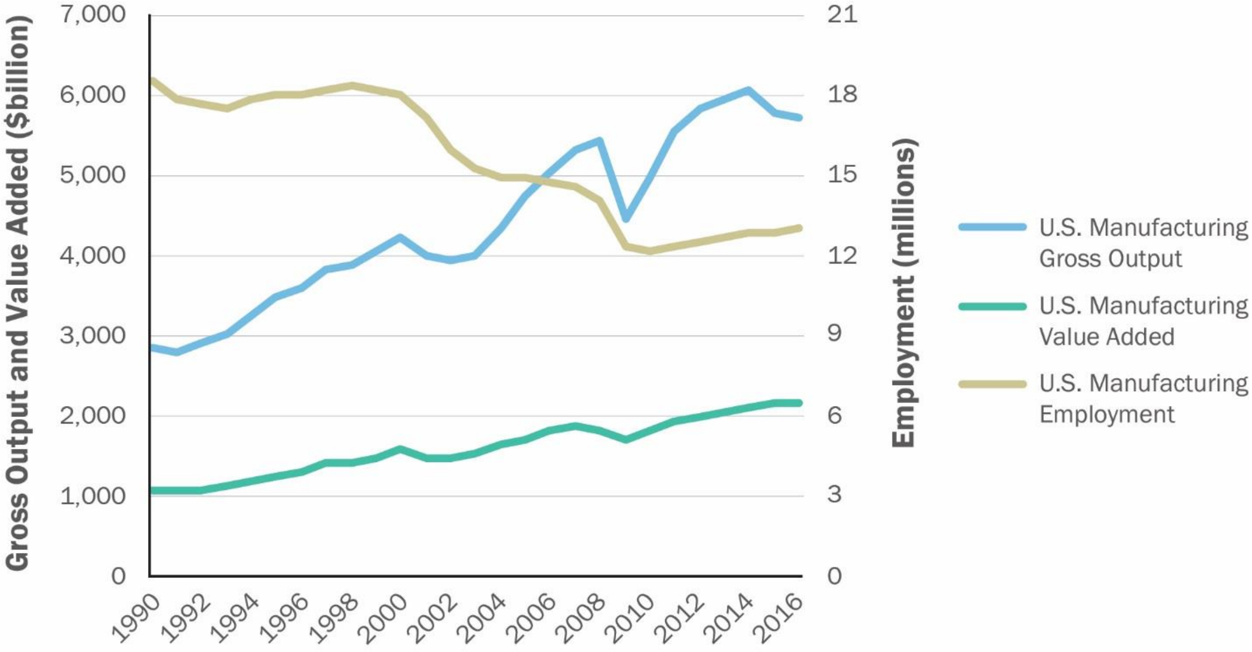

Figure 2-10. U.S. manufacturing gross output, value added, and employment (1990–2016)[h,46,47,48]

An example of the connections between materials production, manufacturing, and broader economic activity is the U.S. wind industry. Today, wind turbine manufacturing in the United States employs 88,000 people[49] and generates roughly $33 billion[50] in value added. In 2014, the United States was a global leader in manufacturing nacelles, blades, towers, and generators for wind turbines. The large size of wind components (blades can be greater than 50 meters) makes transporting the components difficult. Domestic component manufacturing has sprung up in response. A significant amount of manufacturing is located in the Midwest close to many of the best wind resources (Figure 2-11).

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[h] Refers to NAICS codes 31–33: Manufacturing.

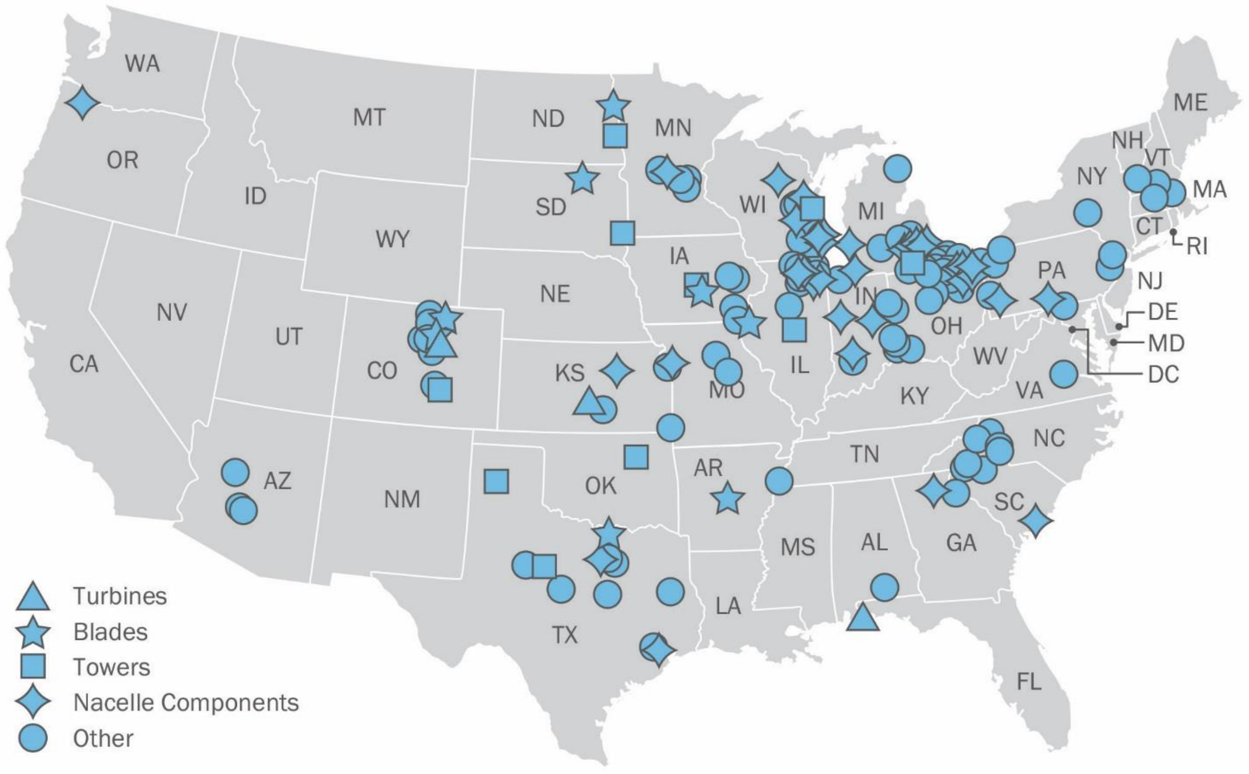

Figure 2-11. Wind final component manufacturing sites[51]

The domestic wind manufacturing sector relies on a large supply chain. Figure 2-12 illustrates the various stages of the wind supply chain and shows examples within each segment of the manufacturing stage (note: this figure is only illustrative and not exhaustive). The manufacturing stage of the supply chain starts with mining of raw materials, which are then processed into primary metals or materials. The metals and materials are then used to fabricate products and assembled into subcomponents. Finally, subcomponents are assembled into the final component.

There are many raw materials used to make a wind turbine: neodymium and dysprosium, which are refined into alloys and then used in magnets in the generator; iron, which is refined into steel and used in the generator, the hub, and the tower; silica, which is used in concrete for the tower and fiberglass for the blades; and graphite, natural gas, and petroleum, which are inputs into carbon fiber manufacturing, which is used in the blades.

These materials are the base for all downstream economic activity in the wind turbine supply chain. Although many of these materials are produced in the United States—with the exception of neodymium, dysprosium, and graphite—they participate in a global market, and downstream domestic manufacturing activities may opt for international sources of raw materials. Similarly, domestic component and subcomponent assembly rely on a global market for primary metals and materials even though the United States has significant production capacity for carbon fiber, fiberglass, concrete, aluminum, and steel. Sourcing material and subcomponent internationally can provide competitive advantages, but it can also introduce vulnerabilities into the wind supply chain.

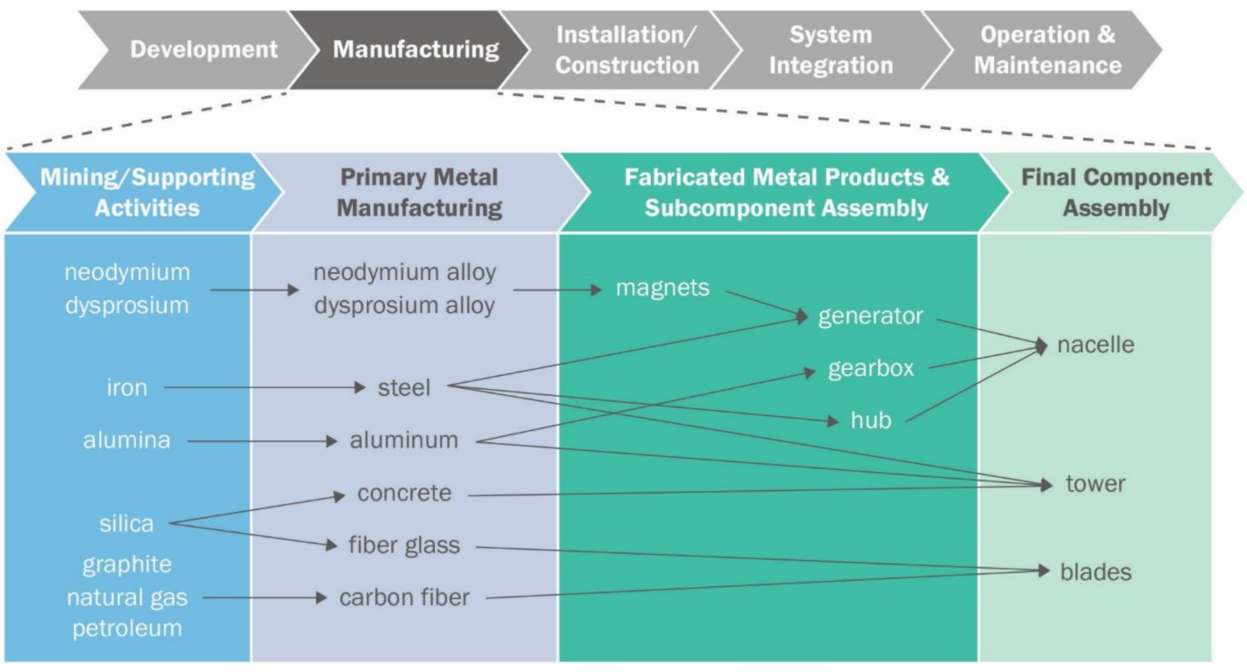

Figure 2-12. Illustrative supply chain for wind turbines[i,52,53]

2.3.2 The Role of Innovation in Material Criticality

Changes in materials markets can impede or spur innovation at multiple stages along the supply chain, which has repercussions for domestic manufacturing and associated economic activity. There also exists a strong feedback loop where innovation can have large impacts on material markets.

The history of the U.S. rare earths market demonstrates how changing domestic production can impact innovation and broader economic activity. From the mid-1960s to the 1980s, the United States was the dominant producer of rare earths, as well as the "world leader in rare-earth technology innovation."[54] Driven in large part by R&D of the high-grade rare earth deposit at Mountain Pass mine in California, a strong system of rare earth innovation emerged in the United States. However, in the early 1990s, rare earth mining production dominance shifted from the United States to China, and rare earth manufacturing and engineering jobs and notably NdFeB magnet manufacturing capability soon followed. The repercussions did not stop there; as shown in Figure 2-13, U.S. innovation in rare earth technologies, as reflected in patents filed, also moved offshore, with corresponding economic implications.[55] Rare earth innovation began to increase in the United States again around 2010; however, patent filings increased even more dramatically outside of the United States during this period, suggesting strong global competition in innovation of cutting-edge rare earth technologies and resulting economic implications.

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[i] Adapted from Clean Energy Manufacturing Analysis Center.

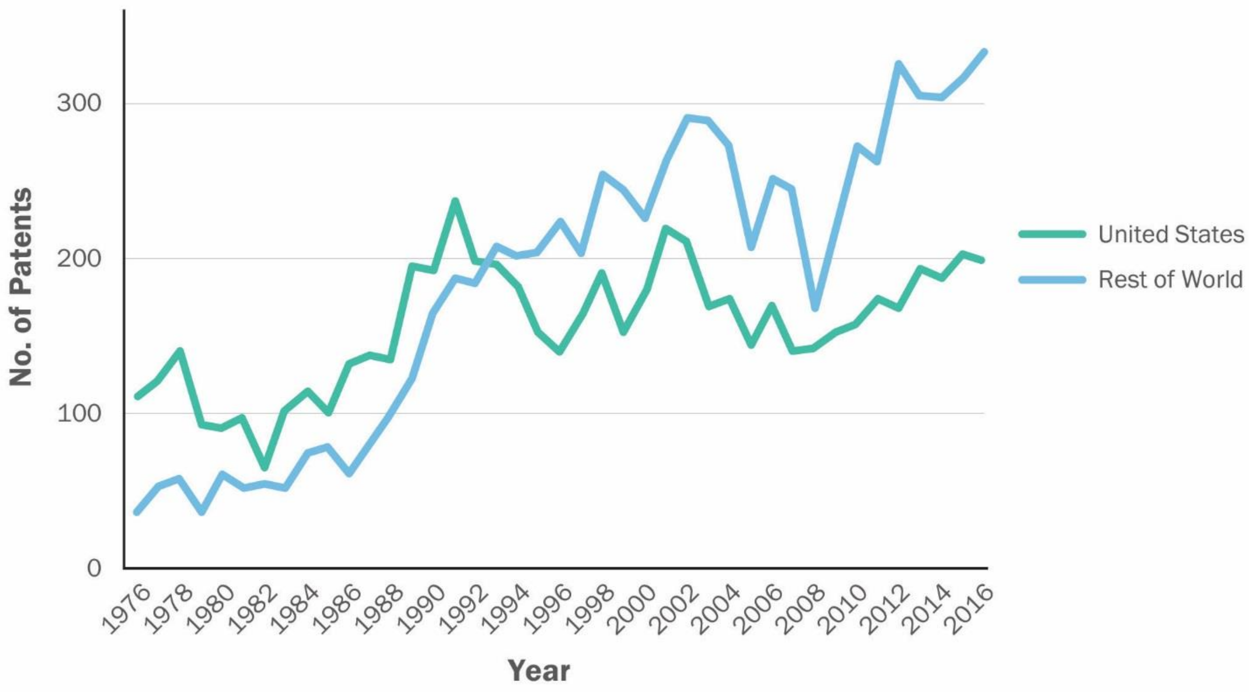

Figure 2-13. U.S. and rest of world rare earth patents (1976–2016)[56]

Innovation resulting from basic science and applied research not only spurs development of more efficient, better-performing technologies and processes, it can also catalyze the establishment of entire industries that shift global materials markets. For example, early in the 21st century, North American and European light bulb manufacturers were struggling to remain profitable given demand for cheap commodity lamps from China and other less-developed countries. Anticipating the opportunity for solid-state lighting and fueled by decades of sustained research and innovation, these firms pursued joint ventures with semiconductor firms that they would eventually acquire.[57] These research investments and scientific breakthroughs resulted in the relatively rapid emergence of LEDs; this has led to unexpected increases in gallium demand, which has inherent supply risks. This illustrates the need for the U.S. to support research across the full supply chain, helping developers of these emerging technologies navigate and address issues related to raw material supply. This can include demand-side innovations, such as manufacturing processes that use materials more efficiently, as well as component and material substitution. Supply-side innovations are also important, including advanced separation techniques and recovering critical materials from waste streams.

Fostering research along the entire supply chain can also accelerate innovation because it encourages beneficial information sharing between researchers with complementary knowledge and expertise. For example, during the development of blue LEDs, researchers were struggling to address common defects that were hindering brightness. The cause of the defects was eventually identified and addressed in the early 1990s, but it could have been addressed 10 years earlier if LED researchers had collaborated with semiconductor researchers who were well aware of the problem.[58]

2.4 Conclusion

The 2011 *Critical Materials Strategy* report stressed three pillars of response: 1) diversifying global supply chains to mitigate supply risk; 2) developing material and technology substitutes; and 3) promoting recycling, reuse, and more efficient use. This chapter has illustrated that the markets for key raw materials in energy technologies reside in a broader context of dynamic global supply chains, with implications for domestic materials production, manufacturing, and other downstream economic activity. Investing in R&D and sustaining policy engagement that addresses the three pillars in a balanced way can give the market more options for response and also help build the foundation for jobs and economic growth.

2.5 Endnotes

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3 Use of Key Materials in Energy Technologies

This chapter explores how deployment of select energy technologies could lead to imbalances of supply and demand for key materials. To assess these risks, four trajectories representing a range of potential future demand for each key material are compared with current levels of supply. The basic methodology used to estimate future demand is the same as was used in both the 2010 and 2011 *Critical Materials Strategy* reports except that the demand trajectories now use 2015 instead of 2010 as the base year. The available market and policy responses to supply and demand imbalances for key materials are different in the immediate and longer terms. For example, if faced with inadequate supply of a key material, technology manufacturers tend to adjust their demand relatively rapidly while new sources of supply can take several years to come online. Similarly, policies on upholding fair trade practices can be deployed faster than investing in research and development to provide technical solutions. Thus, a distinction is made between the supply and demand situations in the short term (2015–2020) and medium term (2020–2030).

Another important difference in the methodology for this 2019 *Critical Materials Strategy* report is the elimination of assessments of expected future supply of key materials. Analysis in the 2010 and 2011 *Critical Materials Strategy* reports showed estimated increases in supply of key materials in energy technologies; however, for many materials, little of this potential supply actually came online. Therefore, this 2019 *Critical Materials Strategy* report uses estimates of current production and capacity, with qualitative discussion of potential future supply.

As in the 2011 *Critical Materials Strategy* report, this report includes qualitative discussion of other energy technologies and materials to watch (Section 3.5).

3.1 Methodology for Estimating Future Demand for Key Materials

The central part of the analysis is bounding the possibilities for future annual demand for individual key materials for select energy technologies in the short term (2015–2020) and medium term (2020–2030). As described in Chapter 1, while a larger number of technologies were considered, the analysis focuses on components within five energy technologies:

- Wind Turbines
    - Magnets
- Solar Photovoltaics (PVs)
    - Coatings
- Grid Storage
    - Batteries (new)
- Vehicles
    - Batteries
    - Magnets
    - Lightweighting (new)
    - Catalytic converters (new)
- Lighting
    - LEDs (new).

The demand for key materials in these five energy technologies is referred to as 'energy demand' throughout this report. However, many of the key materials examined in this report have energy demand beyond these five technologies. Furthermore, their use in some non-energy applications (*e.g.*, in industrial catalysts) has implications for energy consumption.

Estimates of future demand for key materials in each energy technology are calculated as the product of three factors:

1. Deployment: Total new installations of the energy technology in a given year (*e.g.*, vehicle sales)
2. Market Share: The percentage of new energy technology installations that use a component that requires a key material examined in this report (*e.g.*, lithium-ion [Li-ion] batteries)
3. Material Intensity: Mass of key material in each unit of the energy technology (*e.g.*, cobalt per battery)

Looking out over the period 2015–2030, the rate of future technology deployment for wind turbines, solar PV, grid storage, vehicles, and high-efficiency lighting is uncertain. Also uncertain are the particular components that will succeed and support technology deployment. To bound the possibilities for future material demand, this report develops a high penetration scenario and a low penetration scenario. The high penetration scenario combines a high level of global deployment of the energy technology (*e.g.*, vehicles) with a high market share for the components that require the key materials examined in this report (*e.g.*, Li-ion batteries). The low penetration scenario combines a low level of global deployment of the energy technology with a low market share for the components that require the key materials examined in this report. Global deployment for vehicles, wind turbines, solar PVs, and grid storage is based on two estimates from the International Energy Agency's (IEA's) World Energy Outlook (WEO): The Current Policies Scenario and The 450 Scenario. This year's high-efficiency lighting demand is derived from U.S. Department of Energy (DOE) estimates of deployment of LEDs.

There is also significant uncertainty about the amount of material needed for each energy application—the material intensity—looking forward to 2030. To account for this uncertainty, a low material intensity scenario was constructed, reflecting a low but feasible estimate of material required per unit of technology deployed. Estimates are based on the literature, as well as input from technology experts and researchers in industry, academia, and government. Similarly, a high material intensity scenario was constructed, describing a high but feasible estimate of material required. Discussions of technologies and assumptions for each scenario are covered in Section 3.2, and the calculations underlying these assumptions are described in-depth in Appendix B (Material Intensity Calculations). In some cases, the range of material intensities reflect material requirements for components and technologies that are currently deployed commercially. In other cases, the range of material intensities reflect stated targets of ongoing research. Section 3.3 describes the supply of key materials and relevant assumptions. Section 3.4 discusses the implications of these contrasting types of assumptions to the outlook for raw material use in energy technologies.

Future demand for key materials will come from both energy and non-energy sources. For simplicity, this analysis assumes that demand for key materials in non-energy technologies increases at the rate of growth for the global economy projected in IEA's WEO 2016. Accordingly, non-energy demand is assumed to increase from its current levels at a compound annual growth rate of 3.4% from 2014 to 2030. To estimate non-energy demand in 2014, an estimate of 2014 energy demand is subtracted from total material demand in 2014. Data on total material demand are sourced from the most recent U.S.

Geological Survey (USGS) *Minerals Yearbook* for each material, where available.[1] USGS did not report estimated demand for manganese, nickel, and magnesium, so data from market sources were used.[2,3,4]

For each material, the high and low assumptions for rates of technology deployment, market share, and material intensity were combined and added to the non-energy demand to develop four future demand trajectories. Two trajectories—Trajectory A and Trajectory B—represent the low penetration scenario combined with the respective high and low assumptions for material intensity. Similarly, two trajectories—Trajectory C and Trajectory D—represent the high penetration scenario combined with the respective low and high assumptions for material intensity. Table 3-1 lists the characteristics describing Trajectories A, B, C, and D.

Table 3-1. Assumptions to Estimate Future Trajectories of Material Demand

Trajectory of Demand	**Market Penetration**		**Material Intensity of the Energy Component**
	Global Deployment Level of the Energy Technology	Market Share of Energy Technology Using Key Component	
Trajectory A	Low	Low	Low
Trajectory B	Low	Low	High
Trajectory C	High	High	Low
Trajectory D	High	High	High

None of the four trajectories is intended to imply a prediction of future demand for energy technologies or key materials used in making them. That demand will depend on a number of factors, including technological progress, policy consistency, and market conditions. Instead, the demand trajectories are intended to illustrate a range of future possibilities and explore the impact of different assumptions concerning technology deployment rates, market shares, and material intensity on future requirements for key materials. Trajectories A and D represent the lower and upper extremes, respectively, for potential material demand.

3.2 In-Depth Discussion of Technologies and Relevant Assumptions

The following sections cover relevant trends in the markets for wind turbines, solar PV, grid storage, vehicles, and lighting, including trends that underlie assumptions for technology market penetration and material intensity. For the technologies covered in the 2011 *Critical Materials Strategy* report, there is a discussion of what has changed in the past 6 years, including shifts to new materials, components, or technologies; differences in recent technology deployment from previous projections; and changes in material intensity.

3.2.1 Wind Turbines

As was true in the 2011 *Critical Materials Strategy* report, this analysis considers demand for key materials in wind turbines because they are expected to be deployed substantially over the next 15 years, and because they employ a large amount of some less-common materials, specifically neodymium and dysprosium.

Since 2011, global annual wind capacity additions have surpassed the high deployment scenario used in the 2011 *Critical Materials Strategy* report, driven largely by growth in demand in Asia (Figure 3-1). While the growth in demand for wind turbines in Europe has been relatively steady, demand in Asia and North America has been more variable. This can be linked to the intermittent nature of some government policies in these regions, such as lapses in the production tax credit in the United States and feed-in tariff reductions in China.[5,6] Spurred by growth in Brazil, Latin America has begun to ramp up annual capacity additions.[7]

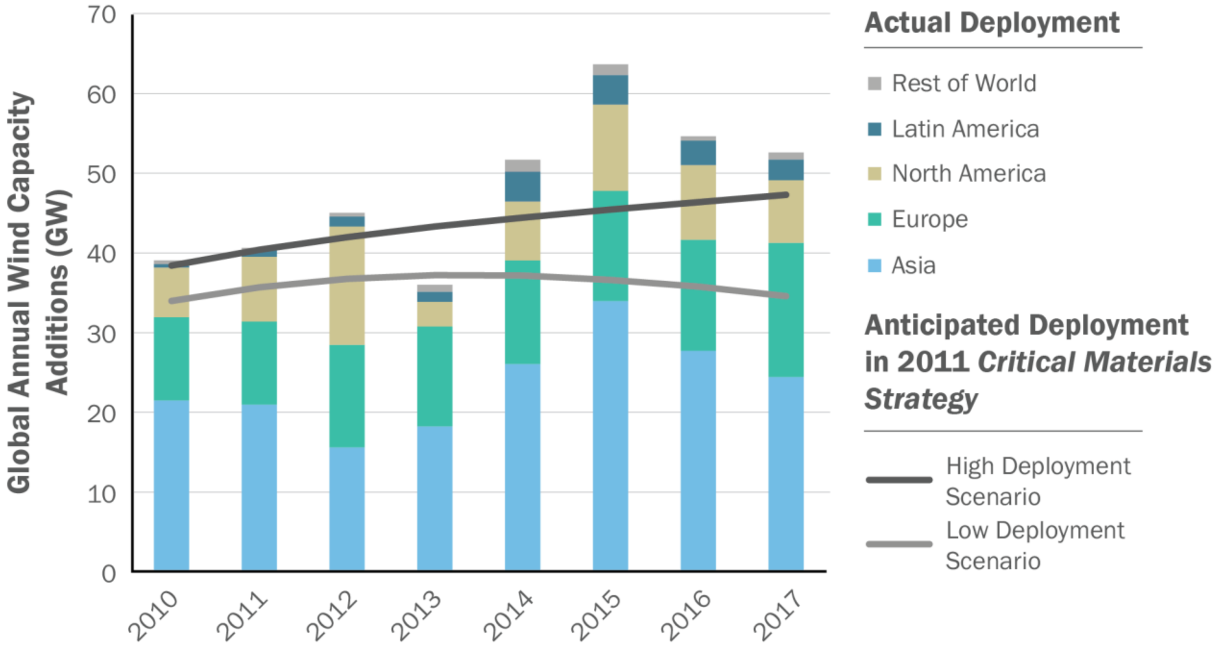

Figure 3-1. Global annual wind capacity additions by region and comparison to 2011 *Critical Materials Strategy* report deployment scenarios (2010–2017)[8,9]

Global Deployment Assumptions: The outlook for global annual wind capacity additions is stronger than it was in 2011 (Figure 3-2). The low deployment scenario shows a constant amount of wind turbine manufacturing, with about 40 gigawatts (GW) of added capacity every year. The high deployment scenario shows wind turbine manufacturing more than doubling, with more than 100 GW of new wind capacity in 2030. The high deployment scenario also shows an expansion in annual additions of offshore wind turbines from 3.3 GW per year in 2015 to 17.4 GW per year in 2030.

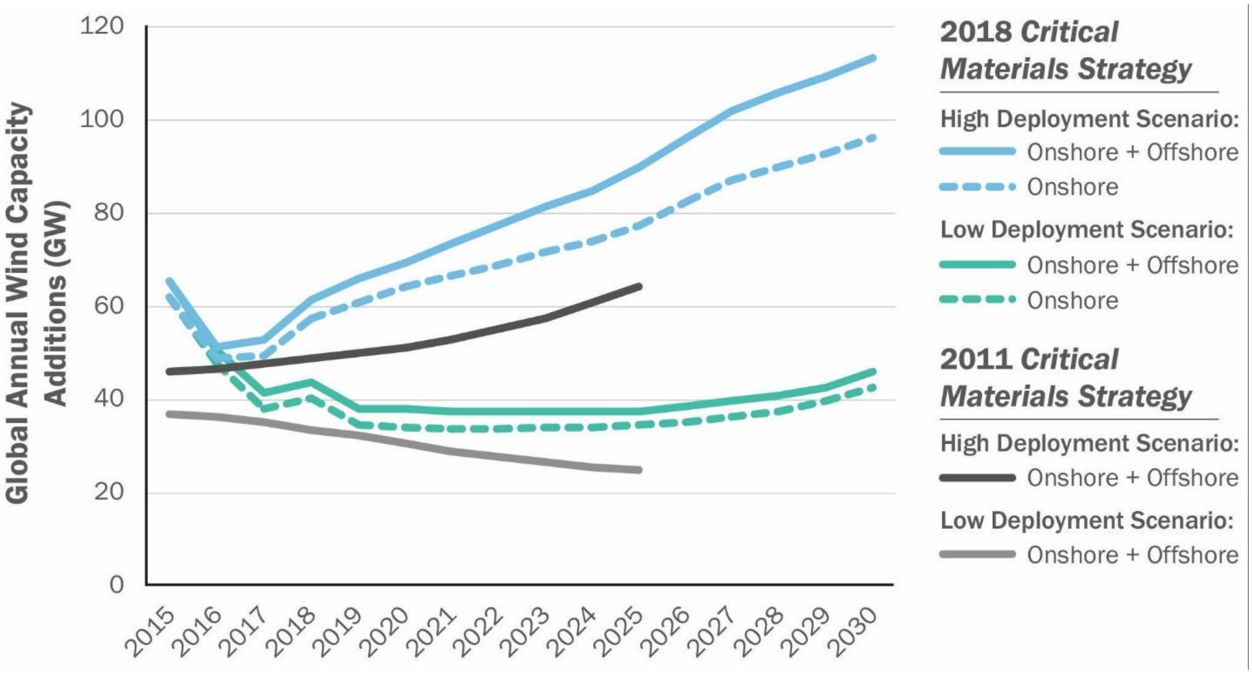

Figure 3-2. Future scenarios for global annual wind capacity additions and comparison to 2011 *Critical Materials Strategy* report deployment scenarios (2015–2030)[10,11]

Market Share Assumptions: The key materials for wind power (neodymium and dysprosium) appear in turbines that employ direct-drive or hybrid-drive permanent magnet generators, which are less common than traditional gearbox generators, but have the potential for increased market share. In the past, lower-cost gearbox generators had sufficient performance in the high wind speed areas being targeted for wind farm development. However, direct-drive permanent magnet generators have significant performance benefits in areas with low wind speeds, where demand for wind turbines is increasing as regions with smaller wind resources set high targets for renewable generation. Direct-drive permanent magnet generators are also less costly to maintain and are significantly smaller and lighter than gearbox generators, both of which are especially useful as turbines are getting larger. The average size of onshore wind turbine installations in the United States has increased from 1.6 MW in 2006 to 2.2 MW in 2016, an increase of about 40% (Figure 3-3).[12] In China, the average size of wind turbine installations more than doubled from 0.8 MW in 2003 to 1.7 MW in 2013.[13] The average size of wind turbine installations in Germany is already 2.8 MW.[14] Direct-drive permanent magnet generators are especially beneficial for offshore wind turbines, which can be costly to maintain and tend to be larger than onshore wind turbines. The worldwide average size of offshore wind turbines is 4.8 MW.[15] Hybrid-drive permanent magnet generators pair a smaller permanent magnet generator with a geared drive, which reduces neodymium and dysprosium content while still retaining some performance benefits over traditional gearbox generators.

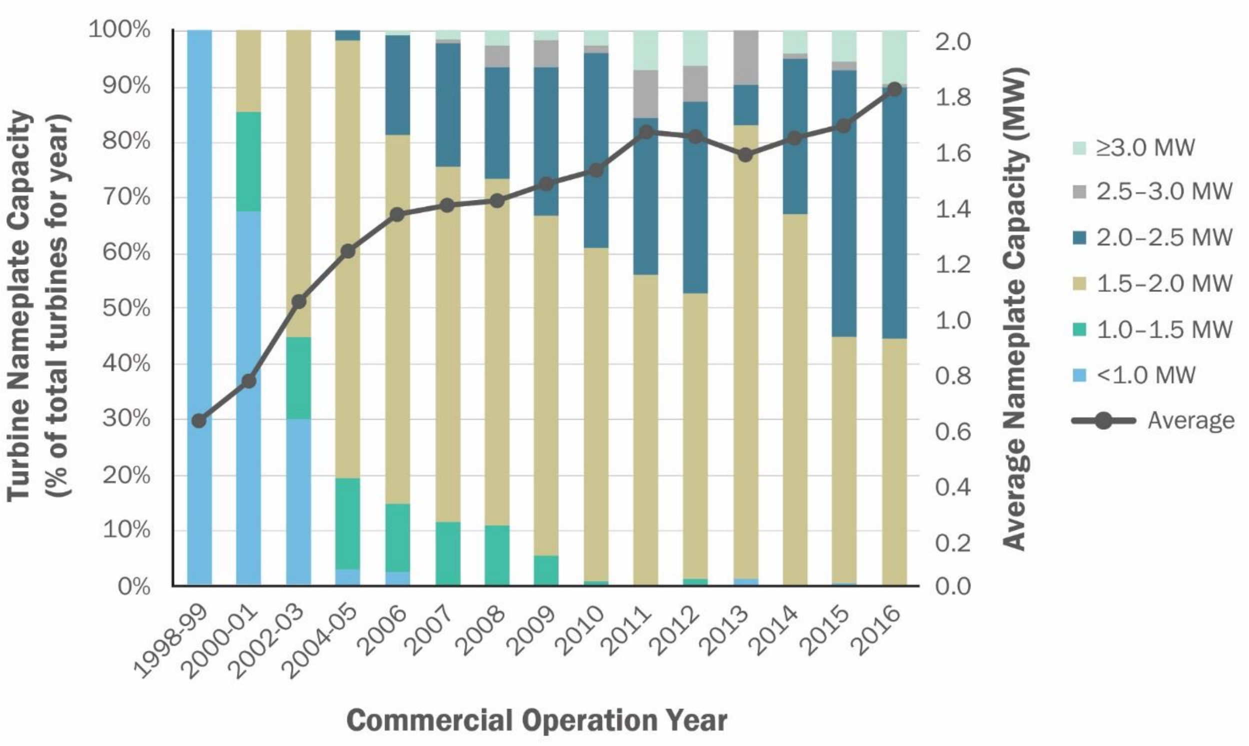

Figure 3-3. Trends in wind turbine nameplate capacity in the United States (1998–2016)[16]

The 2011 *Critical Materials Strategy* report assumed the market share for new onshore turbines using direct-drive or hybrid-drive permanent magnet generators to be 15% for the low penetration scenario and 75% for the high penetration scenario. This year's report lowers the assumed market share in the high penetration scenario to 50% in order to reflect the tempered expectations for widespread adoption of permanent magnet generators following the constraints on the supply of rare earths in 2009 and 2010. These assumed market shares take into account differences among countries in the likelihood of employing permanent magnet generators. For example, most wind turbines using permanent magnet generators are installed in China, whereas wind turbine installations in the United States tend to favor traditional gearbox generators. The assumed market shares for new offshore wind turbines using permanent magnet generators are the same as they were in the 2011 *Critical Materials Strategy* report despite the rare earth supply constraints because the reduced maintenance costs associated with direct-drive permanent magnet generators mean they still have the potential to become the preferred technology for offshore applications.

Material Intensity Assumptions: Concerns over rare earth supply drove reductions in the material intensity of permanent magnet generators in wind turbines. Hybrid designs, as described above, reduce the weight of the magnet from 600 kilograms (kg)/MW to 200 kg/MW.[17] In 2011, wind turbine models used magnets with 3%–6% dysprosium, but newer wind turbine models use magnets with as little as 1% dysprosium (by weight).[18] This was largely achieved by using strategies such as optimizing placement of dysprosium in the magnet's crystal structure, or by redesigning generators to reduce the operating temperatures and thus the need for dysprosium to maintain coercivity.[19] Some manufacturers have even begun developing turbine models with dysprosium-free magnets.[20] Although similar reductions in material intensity for neodymium have not been achieved, current research is targeting 20% neodymium content by 2030, which is significantly lower than the current state of the art (29%–32%).[21]

Table 3-2 summarizes assumptions made in this report about technology deployment, market share, and material intensity used to estimate future demand for key materials in wind turbine magnets.

Table 3-2. Assumptions Used to Estimate Future Demand for Key Materials in Wind Turbine Magnets

	Assumption	Low Penetration	High Penetration
Annual Deployment in 2030	Global capacity additions, onshore (GW)	42.0	96.1
	Global capacity additions, offshore (GW)	3.4	17.4
Market Share	Share of onshore capacity additions using permanent magnets	15%	50%
	Share of offshore capacity additions using permanent magnets	25%	75%
	Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Weight of magnet (kg/MW)	200	600
	Neodymium share of magnet weight	20%	32%
	Dysprosium share of magnet weight	0%	3%

3.2.2 Solar PVs

The 2011 *Critical Materials Strategy* report analyzed material demand for thin-film solar PVs to assess the potential material supply risks associated with rapid solar PV deployment and with a potential increase in market share for thin-film solar PVs, which utilize less-common materials, specifically indium, gallium, and tellurium. Although thin-film solar PVs have not gained as much market share as expected, global solar PV deployment has outpaced previous projections. Therefore, this analysis again considers demand for indium, gallium, and tellurium in thin-film solar PVs.

Global Deployment Assumptions: Since 2011, solar PV deployment has surpassed previous projections (Figure 3-4). Globally, installed capacity has more than quadrupled from 70 GW in 2011 to 291 GW in 2016.[22] China, India, and the United States have led much of this growth, primarily enabled by government policies, including the Investment Tax Credit extensions in the United States and feed-in tariffs in China. Additionally, more than 150 countries have adopted policies for renewables-based power. In the low deployment scenario, annual solar PV capacity additions plateau in the medium term at about 30 GW per year, while the high deployment scenario shows annual capacity additions steadily increasing from 55 GW per year in 2015 to 91 GW per year in 2030. By 2030, solar generating capacity could account for 8%–13% of global installed capacity compared to 3% today.[23]

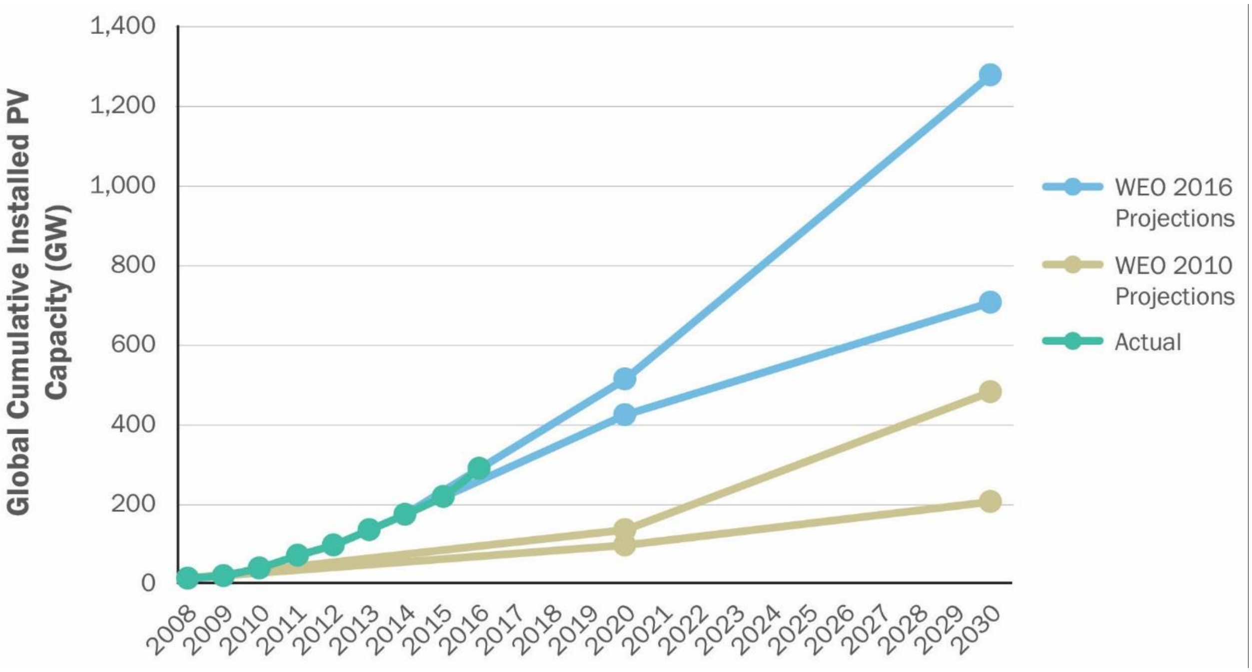

Figure 3-4. Comparison of projected global cumulative installed solar PV capacity (2008–2030)[24,25,26]

Market Share Assumptions: The 2011 *Critical Materials Strategy* report assumed that copper-indium-gallium-selenide (CIGS) thin-film solar PVs could constitute 5%–50% of global annual solar PV capacity additions, and that cadmium telluride (CdTe) thin-film solar PV could constitute 10%–50% of global annual solar PV capacity additions. Much of this optimism was because thin films were projected, at the time, to be less expensive to manufacture than crystalline silicon (c-Si) solar PVs and were gaining market share (Figure 3-5). In addition to performance benefits, c-Si module costs have since fallen significantly, which thin-film technologies have been challenged to match. In addition, the proprietary nature of thin-film technologies has played a role in limiting widespread deployment. Since 2011, the market share for c-Si solar PVs has increased from 86% to 94% of global solar PV module sales.[27] Despite growing market share for c-Si modules, thin-film solar PVs may maintain some market share due to sustained demand for defense and aerospace applications where weight is an important aspect of performance. Consequently, this 2019 *Critical Materials Strategy* report assumes a more modest market share for the two thin-film formulations—2%–5% for CIGS and 3%–10% for CdTe.

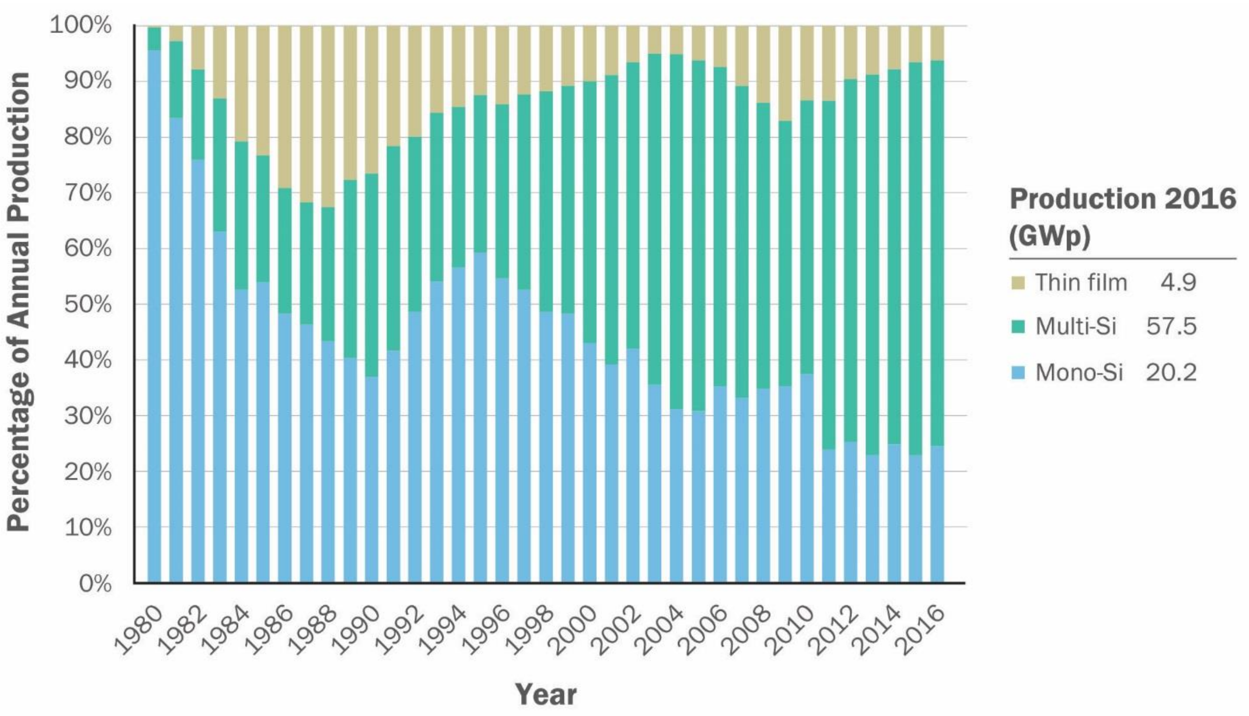

Figure 3-5. Market share of global annual solar PV capacity additions by technology (1980–2016)[28]

Material Intensity Assumptions: One of the distinct advantages of thin films is their flexibility, which allows them to be used in a variety of applications, including consumer products. Improving light absorption improves the overall performance of the cells, and it also allows for thinner cells, resulting in material savings and reduced module costs. For CIGS, reducing the film thickness from 2.0 micrometers (μm) to 1.0 μm, along with material recovery improvements during the manufacturing process, could theoretically reduce material content by 70%. Indium content would decrease from 23 tonnes/GW to 6.3 tonnes/GW and gallium content from 7.5 tonnes/GW to 2.1 tonnes/GW. This assumes a constant stoichiometric ratio of indium to gallium. Similar reductions in film thickness for CdTe (from 2.5 μm to 1.0 μm) and improvements in manufacturing efficiencies could result in a 75% reduction in material content, decreasing tellurium content from 69 tonnes/GW to 17 tonnes/GW.[29] For CdTe cells in particular, where material cost comprises nearly half of the module cost,[30] material savings could dramatically improve their competitiveness.

Table 3-3 summarizes assumptions made in this report about technology deployment, market share, and material intensity used to estimate future demand for key materials in solar PV technologies.

Table 3-3. Assumptions Used to Estimate Future Demand for Key Materials in Solar PV Technologies

	Assumption	Low Penetration	High Penetration
Annual Deployment in 2030	Global PV capacity additions (GW)	31.4	90.8
Market Share	CIGS share of added PV capacity	2%	5%
	CdTe share of added PV capacity	3%	10%
	Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Weight of indium in CIGS (tonnes/GW)	6.3	23
	Weight of gallium in CIGS (tonnes/GW)	2.1	7.5
	Weight of tellurium in CdTe (tonnes/GW)	17	69

3.2.3 Grid Storage

Previously noted as a technology to watch in the 2011 *Critical Materials Strategy* report, grid storage batteries have become increasingly popular for storing excess electricity and providing essential grid services to enable greater flexibility and reliability of the electricity system. Globally, cumulative grid storage battery installations have more than tripled from 265 MW in 2011 to 1 GW in 2015, three-quarters of which has been deployed in the United States, India, China, and Europe.[31,32] Given this rapid growth and the number of materials of interest used in these batteries—lithium, cobalt, nickel, manganese, and vanadium—an analysis of the material demand from this technology was performed.

Global Deployment Assumptions: The low deployment scenario shows a steadily decreasing level of annual grid storage capacity additions from 1.70 GW per year in 2015 to 0.32 GW per year in 2030. The high deployment scenario shows a steadily increasing amount of annual grid storage capacity additions, reaching 10 GW per year in 2030. These global deployment scenarios cover all storage technologies, including batteries, pumped-storage hydroelectricity, and thermal storage.

Market Share Assumptions: Batteries are one of several grid storage technologies available, but they offer particular advantages in terms of siting flexibility and size. Pumped-storage hydroelectricity is a mature technology that has historically provided the majority of total grid storage capacity (95% globally in 2015). However, pumped storage—like compressed air energy storage—often utilizes geological features, such as water reservoirs or depleted salt caverns, respectively. While these features provide significant storage capacity, they restrict where the storage can be deployed. These technologies also have lengthy permitting times. Other grid storage technologies—flywheels, hydrogen storage, and thermal energy storage—represent a smaller but growing fraction of grid storage, and their power output and duration make them more suited for particular grid applications. In contrast, batteries are suitable for a wide range of applications, from large utility-scale installations to transmission and distribution infrastructure. This flexibility, though advantageous, has created some unique challenges for wholesale electricity markets and led to uncertainty in the demand for batteries. Batteries represent only 1% of total installed grid storage capacity. However, the battery storage capacity added each year has steadily increased to 670 MW in 2016 (Figure 3-6), which is 17% of the total grid storage capacity added that year. This report assumes that battery storage could constitute anywhere from 12% to 50% of future global annual grid storage capacity additions.

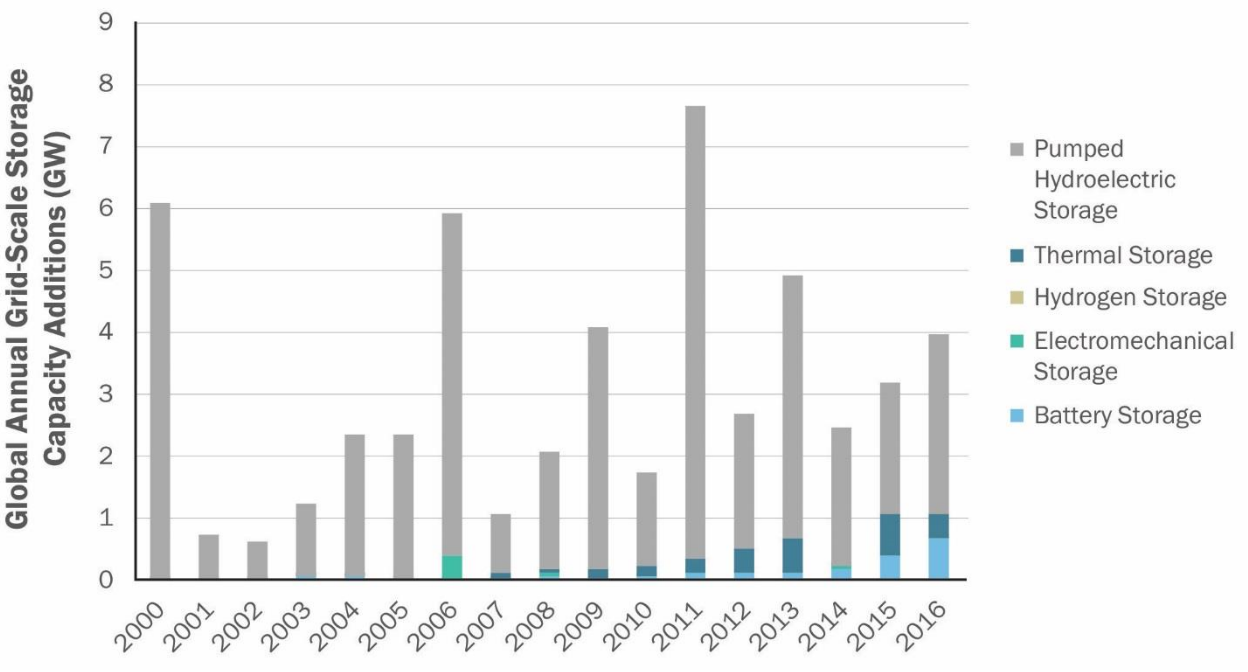

Figure 3-6. Market share of global annual grid storage capacity additions by technology (2000–2016)[33,a,b]

Among the various battery types for grid storage, Li-ion is currently leading, primarily due to its high energy density, technology advancements improving its safety, and falling costs. Between 2014 and 2016, global annual battery grid storage capacity additions tripled, driven largely by growth in Li-ion battery deployment (Figure 3-7). Other battery types—including lead-acid batteries, sodium-based batteries, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and vanadium redox flow batteries (VRBs)—are also being installed.[34] The main drawback of lead-acid, NiCd, and NiMH batteries is that they have lower energy densities than Li-ion batteries, though they have lower capital costs and fewer maintenance requirements. Redox flow batteries using vanadium, zinc/bromine, or iron/chromium also remain a promising technology, but they comprised a small share of battery grid storage capacity additions in 2016 (3%); their ability to easily be scaled up with minimal self-discharge by increasing the amount of active material in electrolyte storage reservoirs is a desirable feature as storage demand shifts toward increasingly larger individual battery systems. This report assumes that Li-ion batteries could constitute anywhere from 80% to 95% of future global annual battery grid storage capacity additions. It also assumes that VRBs could constitute anywhere from 1% to 9% of future global annual battery grid storage capacity additions.

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[a] Battery storage includes a small amount of storage using electrochemical capacitors.

[b] Electromechanical storage refers to flywheels and compressed air energy storage.

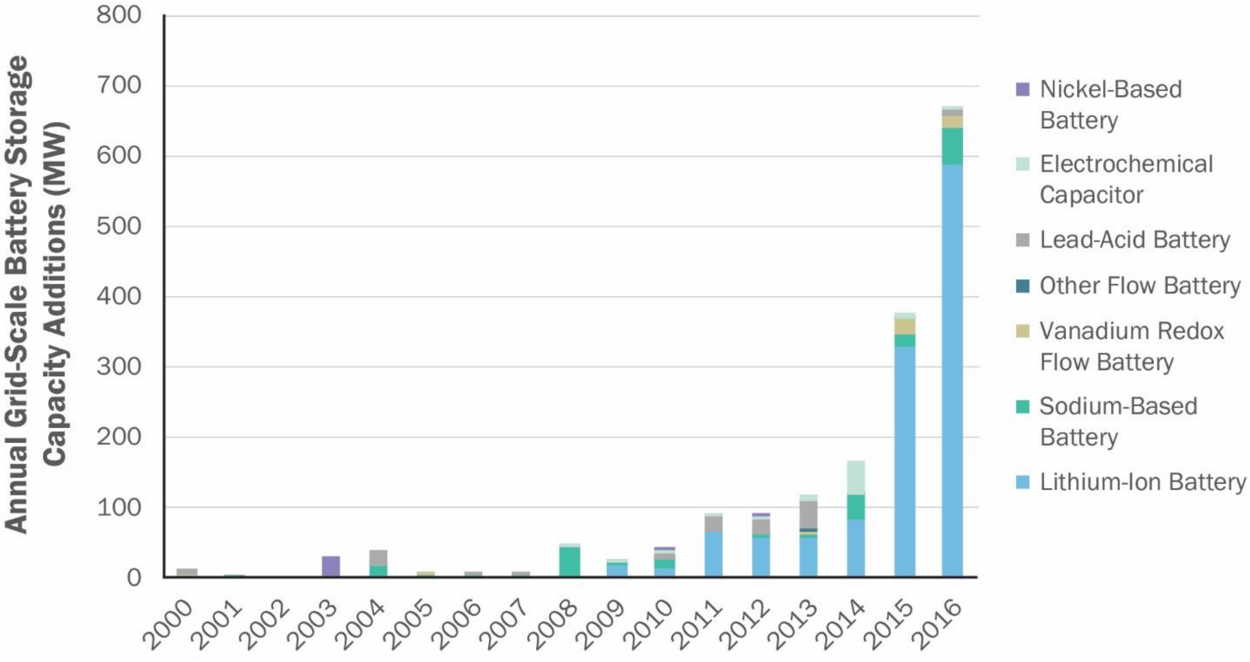

Figure 3-7. Market share of global annual battery grid storage capacity additions by battery (2000–2016)[35]

Material Intensity Assumptions: Key materials for battery grid storage include lithium, nickel, cobalt, and manganese for Li-ion batteries, as well as vanadium for VRBs. The range in material intensity for each of these batteries depends on the particular formulation of the battery chemistry. For Li-ion batteries, five cathode formulations were considered: two nickel manganese cobalt chemistries (NMC622/NMC333), one nickel cobalt aluminum chemistry (NCA-G), one lithium iron phosphate chemistry (LFP-G), and one lithium manganese oxide chemistry (LMO-G). For each material, the material requirements for the least material-intense chemistry was chosen for the low intensity assumption and the material requirements for the most material-intense chemistry were chosen for the high intensity assumption. Material requirements for each chemistry were calculated using output from Argonne National Laboratory's Battery Performance and Cost (BatPaC) model, assuming a pack energy of 200 kilowatt-hours.[36] The BatPaC model is designed for vehicle batteries, which have different system configurations and power requirements than grid storage batteries, but the impact on material intensity is assumed to be minimal. For VRBs, material intensity ranges were calculated based on several assumptions about electrolyte solution molarity and a typical VRB size.[37]

Table 3-4 summarizes assumptions made in this report about technology deployment, market share, and material intensity used to estimate future demand for key materials in grid storage batteries.

Table 3-4. Assumptions Used to Estimate Future Demand for Key Materials in Grid Storage Batteries

		Assumption	Low Penetration	High Penetration
Annual Deployment in 2030		Global grid storage capacity additions (GW)	0.32	9.91
Market Share		Battery share of added grid storage capacity	12%	50%
		Li-ion share of added battery storage capacity	80%	95%
		VRB share of added battery storage capacity	1%	9%
		Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Li-ion Battery	Weight of lithium (tonnes/GW)	506	641
		Weight of cobalt (tonnes/GW)	0	1,495
		Weight of nickel (tonnes/GW)	0	2,752
		Weight of manganese (tonnes/GW)	0	6,353
	VRB Battery	Weight of vanadium (tonnes/GW)	6,365	24,450

3.2.4 Vehicles

Given expected growth in electric vehicle (EV) sales, driven by strengthening fuel economy and other performance standards, the 2011 *Critical Materials Strategy* report examined materials in magnets and batteries for EVs. Understanding the portfolio of options vehicle manufacturers have to meet such standards, this report expands the analysis to include assessment of key materials in vehicle lightweighting and catalytic converters, both of which were noted as technologies with potential implications for material criticality in the *2011 Critical Materials Strategy* report.

Global Deployment Assumptions: According to IEA, 95 million vehicles were sold globally in 2015, and overall sales are expected to increase in the coming decades (Figure 3-8).[38] This means that demand for materials used in certain vehicle technologies—including batteries, magnets, lightweighting, or catalytic converters—is likely to increase as well. Figure 3-8 shows that sales outside of the United States are driving the growth. Total vehicle sales only differ by 1.1 million between the low and high deployment scenarios, but the types of vehicles deployed changes drastically. The low deployment scenario shows many more sales of internal combustion engine (ICE) vehicles in 2030, while the high deployment scenario shows many more sales of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (AEVs).

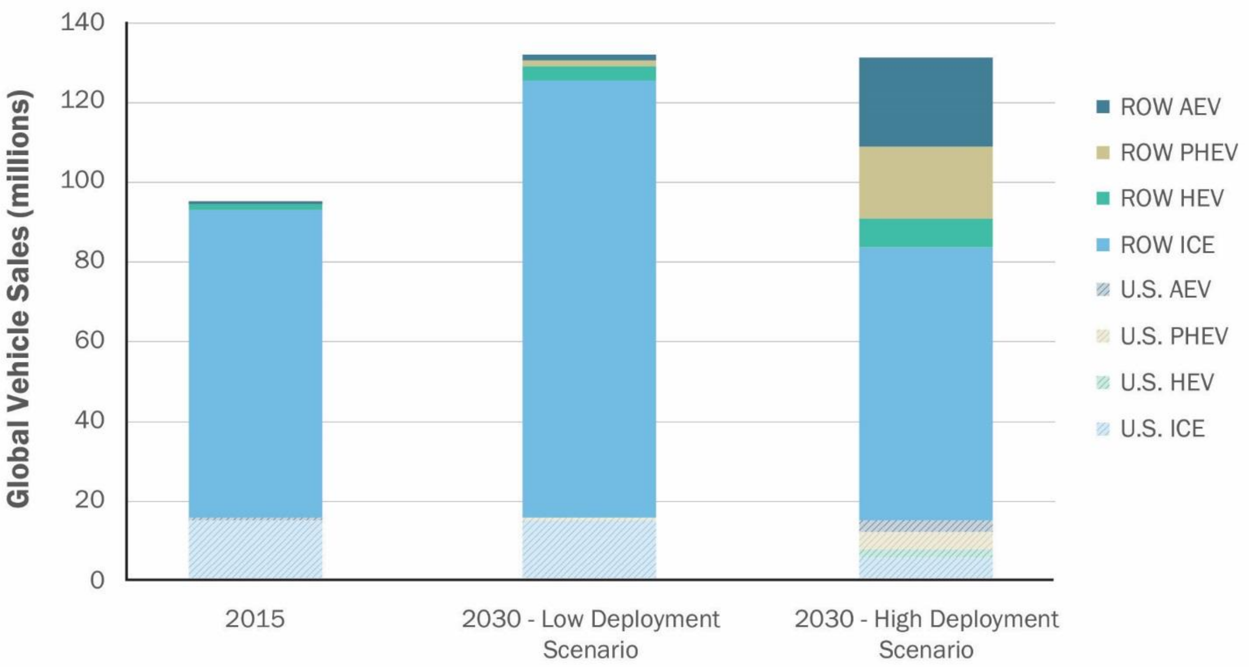

Figure 3-8. Current and projected future global vehicle sales in 2030 under different scenarios—United States versus rest of world (ROW)[39]

EV sales have increased over the last decade, and growth is expected to continue, or possibly accelerate, through 2030. Figure 3-9 shows historic and projected future vehicle sales under low and high deployment scenarios. Both scenarios show growth in EV sales, but the high deployment scenario anticipates 58 million EV sales in 2030 compared to only 7.7 million in the low deployment scenario. Since 2011, EV sales have been slightly higher than the low deployment scenario employed in the 2011 *Critical Materials Strategy* report, but not as robust as the high deployment scenario. The 2011 *Critical Materials Strategy* report expected EV sales to reach 37 million in 2025 in the high deployment scenario—a number that now is not expected to be reached until 2027 in the high deployment scenario. Key drivers for EV sales growth include improved vehicle performance, lower vehicle costs, a variety of policies incentivizing adoption, the build out of charging infrastructure, and regulations incentivizing higher-efficiency vehicles. Volvo recently announced that by 2019 it will only make fully electric or hybrid vehicles.[40]

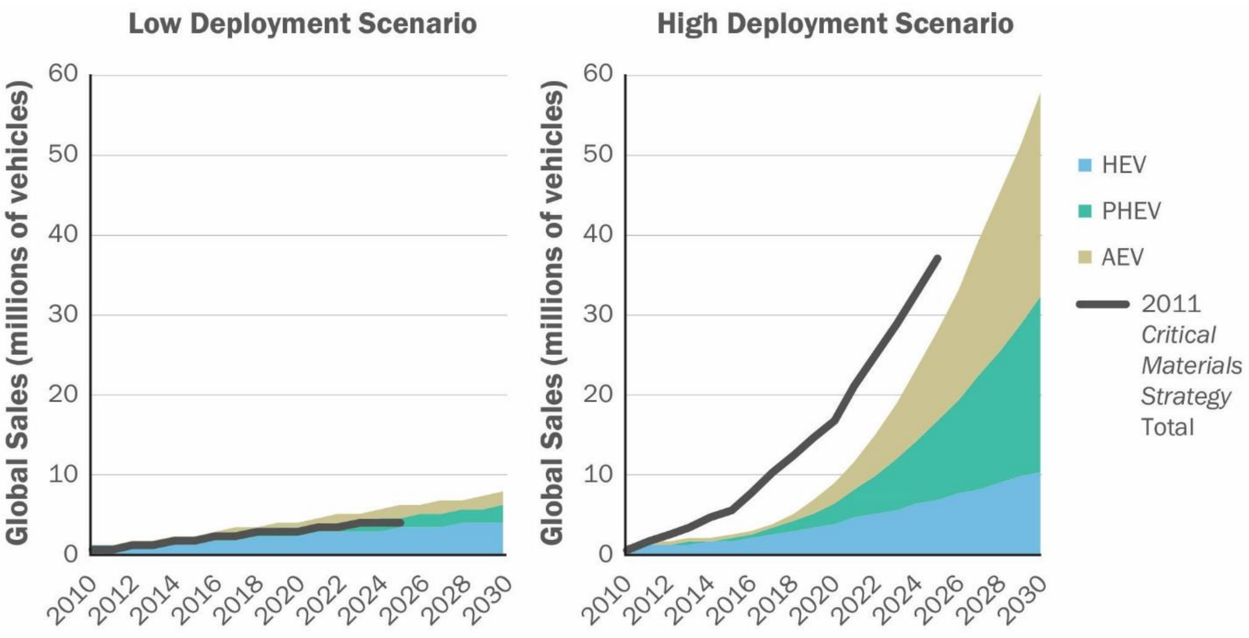

Figure 3-9. Historic and future scenarios for global EV sales by vehicle type and comparison to 2011 *Critical Materials Strategy* report deployment scenarios (2010–2030)[41,c]

Batteries in Vehicles

In EVs, batteries transfer energy to a vehicle's drivetrain for propulsion. They partially or fully replace power from gasoline and ICE vehicles. Batteries are deployed in three configurations: HEVs, which pair a small battery with an ICE; PHEVs, which pair a medium-size battery with an ICE; and AEVs, which utilize larger, stand-alone electric motors. Depending on battery type and chemistry, EV batteries can require various amounts of lithium, cobalt, nickel, manganese, lanthanum, cerium, and neodymium.

Market Share Assumptions: Two major battery types are currently deployed in vehicles: Li-ion and NiMH. Li-ion batteries are considered the most promising technology for the near future by a majority of literary sources, while NiMH is considered a more mature technology that has reached its best potential.[42] NiMH batteries are currently only used in HEVs, most prominently in the Toyota Prius. Thus, the assumed market share for NiMH batteries in HEVs ranges from 0% in the low penetration scenario to 50% in the high penetration scenario, with the remainder using Li-ion batteries. Li-ion batteries are assumed to hold 100% market share for PHEVs and AEVs in both scenarios.

Material Intensity Assumptions: A large part of improved EV performance can be attributed to improved battery performance—typically measured in energy and power densities. Over the past decade, battery energy densities (per unit mass) improved by 60%.[43] These improvements have led to large range increases and significantly faster acceleration options. The 2011 *Critical Materials Strategy* report examined batteries with ranges of 4, 40, and 100 miles. Today, some EVs have ranges over 350 miles, so this update examines larger battery sizes with extended ranges.

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[c] IEA reports actual vehicle sales in 2010 and 2015 and projects vehicle sales in 2020, 2030, and 2040. Sales in the interceding years were interpolated.

Depending on the chosen chemistry, Li-ion batteries can require various amounts of lithium, cobalt, nickel, and manganese. Five battery chemistries were examined: two nickel manganese cobalt chemistries (NMC622/NMC333), one nickel cobalt aluminum chemistry (NCA-G), one lithium iron phosphate chemistry (LFP-G), and one lithium manganese oxide chemistry (LMO-G). The nickel manganese cobalt chemistries are new additions to this year's analysis because they have become increasingly popular. The 2011 *Critical Materials Strategy* report analyzed the lithium manganese oxide-titanium oxide (LMO-TiO) chemistry; however, it is not included in this year's analysis because it has fallen out of favor. For each material, the material requirements for the least material-intense chemistry was chosen for the low intensity assumption and the material requirements for the most material-intense chemistry was chosen for the high intensity assumption. Argonne National Laboratory's BatPaC model provides material requirements for each chemistry by battery size and vehicle type.[44]

NiMH batteries use lanthanum, cerium, neodymium, cobalt, nickel, and manganese. This report employed the same methodology as the 2011 *Critical Materials Strategy* report for calculating material intensity ranges for NiMH batteries. The calculation is based on several assumptions about capacity and chemistry (*i.e.*, anode and cathode composition) for a battery with a power rating and cell voltage equivalent to the battery used in a third-generation Toyota Prius.

Table 3-5 summarizes assumptions made in this report about technology deployment, market share, and material intensity used to estimate future demand for key materials in vehicle batteries.

Table 3-5. Assumptions Used to Estimate Future Demand for Key Materials in Vehicle Batteries

		Assumption	Low Penetration	High Penetration
Annual Deployment in 2030		Global sales (HEVs), millions	4.0	10.3
		Global sales (PHEVs), millions	2.1	22.0
		Global sales (AEVs), millions	1.5	25.5
Market Share		Share of HEV sales using NiMH batteries	0%	50%
		Share of HEV sales using Li-ion batteries	50%	100%
		Share of PHEV sales using Li-ion batteries	100%	100%
		Share of AEV sales using Li-ion batteries	100%	100%
		Assumption	**Low Intensity**	**High Intensity**
Material Intensity	HEV 4 NiMH Battery	Weight of lanthanum (kg/battery)	0.5	0.7
		Weight of cerium (kg/battery)	0.7	1.0
		Weight of neodymium (kg/battery)	0.2	0.3
		Weight of cobalt (kg/battery)	0.4	0.7
		Weight of nickel (kg/battery)	2.1	3.2
		Weight of manganese (kg/battery)	0.2	0.3
	HEV 4 Li-ion Battery	Weight of lithium (kg/battery)	0.4	0.5
		Weight of cobalt (kg/battery)	0.0	1.4
		Weight of nickel (kg/battery)	0.0	2.7
		Weight of manganese (kg/battery)	0.0	6.2
	PHEV 28/56 Li-ion Battery	Weight of lithium (kg/battery)	1.0	2.7
		Weight of cobalt (kg/battery)	0.0	7.3
		Weight of nickel (kg/battery)	0.0	13.5
		Weight of manganese (kg/battery)	0.0	31.0
	AEV 102/340 Li-ion Battery	Weight of lithium (kg/battery)	3.0	13.5
		Weight of cobalt (kg/battery)	0.0	36.9
		Weight of nickel (kg/battery)	0.0	68.3
		Weight of manganese (kg/battery)	0.0	156.1

Magnets in Vehicles

Market Share Assumptions: Due to their superior power-to-weight ratio, motors with rare earth permanent magnets are used in almost all electric drive vehicles. Permanent magnet motors are expected to dominate the market well into the medium term. Induction motors that do not use permanent magnets account for a notable market share—especially for AEVs in the United States—due to their use in Tesla's Model X and Model S. These models accounted for 60% of total U.S. AEV sales in 2016.[45] Worldwide, Tesla sold more than 75,000 vehicles in 2016,[46] which accounted for 16% of the nearly 500,000 AEVs sold that year.[47] Tesla has also made its patents for induction motors available to be licensed at no cost.[48] However, Tesla's lower cost model (Model 3), which began production in 2017, uses rare earth permanent magnets. There are other non-rare earth motors that have the potential for commercial use in HEVs and PHEVs.[49] This analysis assumes that rare earth permanent magnets would be deployed in 90%–100% of HEVs and PHEVs and 80%–90% of AEVs sold globally.

Material Intensity Assumptions: For vehicle types that have an electric motor as the primary source of propulsion (*i.e.*, PHEVs and AEVs), the average weight of a magnet used in the electric motor is 1–2 kg. HEVs use electric motors as a secondary propulsion source and thus require as much as 58% less magnetic material (by weight).[50] Concerns over stable supply of rare earths have driven manufacturers to produce EVs with permanent magnets that include less rare earth content. For example, efforts are underway to optimize motor designs in pursuit of high torque densities with less magnetic material. One approach has been to embed magnets in advanced rotor structures, which can reduce the average weight of a vehicle magnet and its constituent materials by 50%. This approach has already been deployed in the BMW i3 (AEV) and BMW 7 (PHEV).[51,52] Other approaches include using more efficient production processes, such as grain boundary diffusion to optimize placement of dysprosium in the magnet's crystal structure, which can reduce dysprosium content from 7.5% to 2.5% of a magnet's weight. [53] Unlike manufacturers of wind turbine magnets, manufacturers of EV magnets have found it difficult to completely eliminate dysprosium because of the temperature requirements for electric propulsion in EVs. However, temperature requirements are not as high for hybrid motors because the electric motor works in tandem with the engine, and Honda has successfully eliminated dysprosium from magnets used in some of its hybrid models.[54] Although similar reductions in material intensity for neodymium have not been achieved, current research is targeting 20% neodymium content by 2030, which is significantly lower than the current state of the art (30%).[55]

Table 3-6 summarizes assumptions made in this report about technology deployment, market share, and material intensity used to estimate future demand for key materials in vehicle magnets.

Table 3-6. Assumptions Used to Estimate Future Demand for Key Materials in Vehicle Magnets

	Assumption	Low Penetration	High Penetration
Annual Deployment in 2030	Global sales, HEV (millions)	4.0	10.3
	Global sales, PHEV (millions)	2.1	22.0
	Global sales, AEV (millions)	1.5	25.5
Market Share	Share of HEV sales using permanent magnets	90%	100%
	Share of PHEV sales using permanent magnets	90%	100%
	Share of AEV sales using permanent magnets	80%	90%
	Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Weight of magnet per HEV (kg)	0.42	0.84
	Weight of magnet per PHEV/AEV (kg)	0.5	2
	Neodymium share of magnet weight	20%	30%
	Dysprosium share of magnet weight in HEV	0%	7.5%
	Dysprosium share of magnet weight in PHEV/AEV	2.5%	7.5%

Vehicle Lightweighting

Vehicle weight plays an important role in determining fuel efficiency; all else being equal, heavier vehicles require more fuel to move them forward. This has led manufacturers to continually look for ways to reduce vehicle weights to improve fuel economy, which has led to greater focus on lightweighting materials. Material substitution is the standard method for weight reduction. Most opportunities for substitution occur in the body, structure, and chassis systems, which together account for 68% of a vehicle's total weight, on average.[56] The total amount of lightweighting materials in vehicles—including high/medium strength steel, aluminum, magnesium, and plastics/composites—has been steadily increasing since 1996 (Figure 3-10).[57] Manufacturers are continuing to look for additional opportunities to reduce vehicle weights, which will in turn impact future lightweighting material demand.

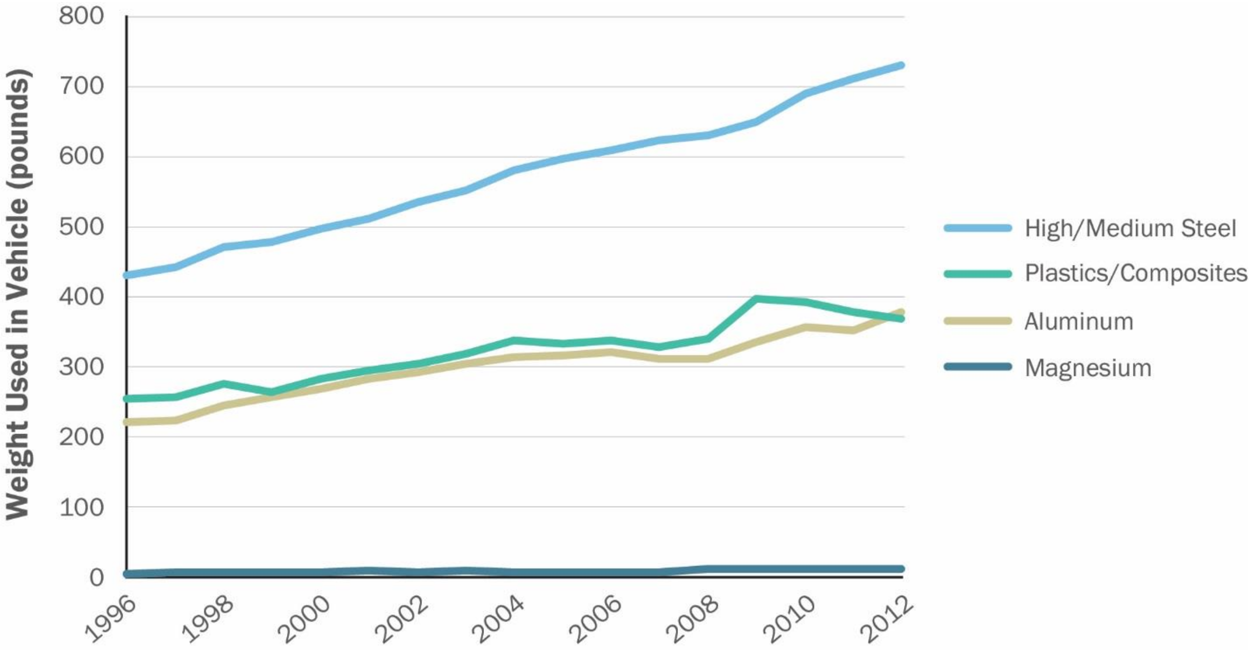


Figure 3-10. Trends in use of lightweight materials in vehicles (1996–2012)[58]

High/medium strength steel is the most common lightweighting material and can include as much as 24% manganese to increase strength and stretchability.[59] Aluminum alloys are also a prevalent lightweighting material. In the United States, aluminum alloys now make up roughly 10% of the weight of light-duty vehicles, although this number may vary globally. In 2014, the first mass-market vehicle with an all-aluminum body was released—the Ford-150 truck.[60] Common lightweighting aluminum alloys include materials such as magnesium and manganese to add strength, corrosion resistance, and other such desirable characteristics.

Magnesium alloys are also attractive lightweighting options because of their high strength-to-weight ratio; however, there are currently technical difficulties associated with incorporating high amounts of magnesium into vehicles. Magnesium alloys are currently being used in the gearbox, steering column, driver's airbag housing, steering wheels, seat frames, and fuel tank covers in high-end vehicles, but their use is not uniform across the industry. Active research is ongoing to expand magnesium use in vehicle systems.

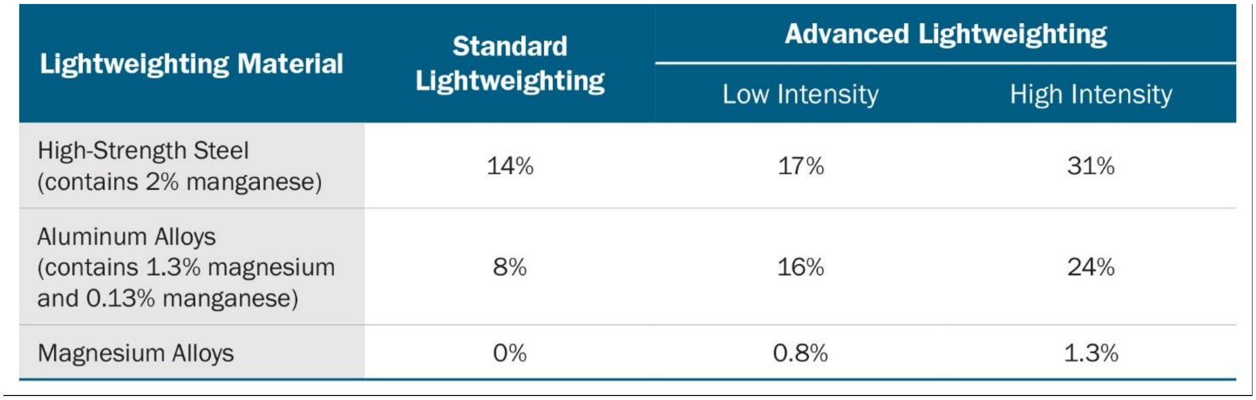
Carbon fiber is also a very promising lightweighting option because it offers high stiffness and high tensile strength with low weight. However, it's currently cost-prohibitive to include carbon fiber in significant quantities in mass-market vehicles. Section 3.5 includes further discussion of the potential for using carbon fiber in energy technologies.

This analysis examines the range of possible future demand for manganese in high-strength steel and aluminum alloys and for magnesium in aluminum alloys and magnesium alloys.

Market Share Assumptions: As discussed above, most vehicle manufactures today employ some amount of lightweighting materials. This analysis assumes that a large share of vehicles sold globally will use a 'standard lightweighting' package that includes a small amount of high-strength steel and aluminum alloys, among other lightweighting materials. In the future, new vehicles may move toward higher-intensity lightweighting strategies that include materials such as magnesium alloys, and they may also increase the amount of aluminum alloys and high-strength steel. The low market share scenario assumes that 5% of vehicles sold globally each year will employ this ‘advanced lightweighting’ package, with the remaining 95% receiving ‘standard lightweighting.’ The high market share scenario assumes that 40% of vehicles sold globally each year will employ ‘advanced lightweighting’ while the remaining 60% receive ‘standard lightweighting.’

Material Intensity Assumptions: The ‘standard lightweighting’ package is assumed to result in a vehicle that weighs 2,144 kg in the United States and 2,083 kg in the rest of the world. Fourteen percent of the vehicle weight is assumed to be high-strength steel and 8% is assumed to be aluminum alloys. The low intensity scenario assumes an ‘advanced lightweighting’ package that results in a 10% reduction in vehicle weight. This lower vehicle weight is comprised of 17% high-strength steel, 16% aluminum alloys, and 0.8% magnesium alloys. The high intensity scenario assumes an ‘advanced lightweighting’ package that results in a 22% reduction in vehicle weight. This lower vehicle weight is comprised of 31% high-strength steel, 24% aluminum alloys, and 1.3% magnesium alloys. This analysis also assumes that manganese constitutes 2% of the weight of high-strength steel and 0.13% of the weight of aluminum alloys. Magnesium is assumed to constitute 1.3% of the weight of aluminum alloys (Table 3-7).

Table 3-7. Assumed Vehicle Lightweighting Packages (share of final vehicle weight)



Lightweighting Material	Standard Lightweighting	Advanced Lightweighting	
		Low Intensity	High Intensity
High-Strength Steel (contains 2% manganese)	14%	17%	31%
Aluminum Alloys (contains 1.3% magnesium and 0.13% manganese)	8%	16%	24%
Magnesium Alloys	0%	0.8%	1.3%

This analysis is focused on the manganese and magnesium content of materials used in vehicle lightweighting, but these lightweighting packages and resulting reductions in vehicle weight include materials beyond those mentioned in this report.[61] In addition, these represent general vehicle lightweighting packages; however, manufacturers will develop part-specific material strategies because each part has different formability, strength, temperature, and resistance requirements. This will translate into unique material requirements for each vehicle.

It is important to note that lightweighting is different than the other technologies examined in this report; as lightweighting improves, a single vehicle is likely to incorporate more lightweighting materials. For other technologies discussed in this report, the material intensities tend to decrease as the technologies improve.

Table 3-8 summarizes assumptions made in this report about technology deployment, market share, and material intensity for key materials in vehicle lightweighting based on magnesium and manganese content in aluminum alloys and magnesium content in magnesium alloys.

Table 3-8. Assumptions Used to Estimate Future Demand for Key Materials in Vehicle Lightweighting

		Assumption	Low Penetration	High Penetration
Annual Deployment in 2030		Global sales, total vehicles (millions)	131	132
Market Share		Share of vehicles sold with standard lightweighting	95%	60%
		Share of vehicles sold with advanced lightweighting	5%	40%
		Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Standard Lightweighting (United States)	Weight of magnesium (kg/vehicle)	2.3	
		Weight of manganese (kg/vehicle)	6.2	
	Standard Lightweighting (rest of world)	Weight of magnesium (kg/vehicle)	2.2	
		Weight of manganese (kg/vehicle)	6.0	
	Advanced Lightweighting (United States)	Weight of magnesium (kg/vehicle)	19.6	27.1
		Weight of manganese (kg/vehicle)	7.0	10.9
	Advanced Lightweighting (rest of world)	Weight of magnesium (kg/vehicle)	19.0	26.3
		Weight of manganese (kg/vehicle)	6.8	10.6

Catalytic Converters

Catalytic converters are utilized in nearly all new ICE vehicles (including HEVs and PHEVs) to control hydrocarbon, carbon monoxide, and nitrogen oxides emissions.[62] To remove these pollutants, converters typically use cerium and a mix of platinum group metals (PGMs—*i.e.*, platinum, palladium, and/or rhodium). Specific types of catalytic converter technology and material usage is typically a function of vehicle engine size, fuel type, regulatory standards, and manufacturer preference (*i.e.*, proprietary formulations).[63] Since 2011, a number of studies have suggested that further analysis is warranted as 1) there is an inseparable link between material use and vehicles, 2) there are a number of complicated factors driving material intensity, and 3) PGMs may face supply risks.

Essentially mandated by standards enacted under the Clean Air Act, catalytic converters have been used in U.S. vehicles since the 1970s. Today, most national governments throughout the world have followed suit, adopting European or U.S. regulations.[64] As a result, catalytic converter deployment mirrors worldwide ICE vehicle deployment—expected to increase anywhere from 33% to 77% by 2030.[65] In concert, governments across the globe are increasingly enacting more stringent vehicle emission standards. For example, in Europe, the most recently implemented standards required a 56% reduction in nitrogen oxides emissions from light-duty vehicles. Similarly, more stringent legislation in North America and China will be phased in during the next several years, and average catalyst loadings in catalytic converters are expected to rise by approximately 2%.[66]

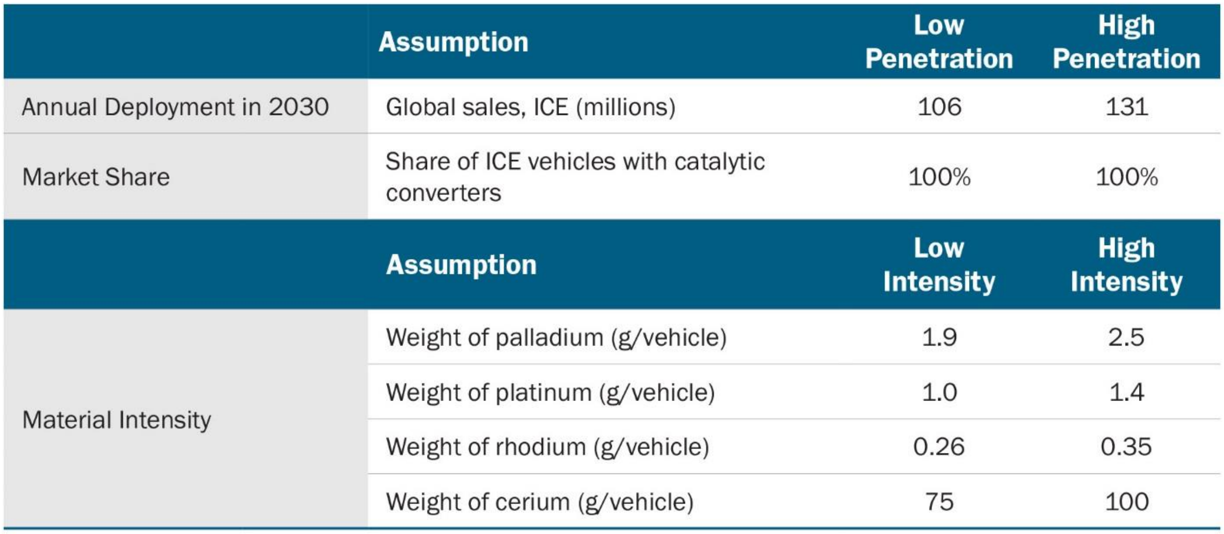
Meanwhile, technological advances have continued to improve engine performance. Overall horsepower has gone up, while vehicle engine size has generally decreased, reaching an all-time low in the United States in 2016.[67] Likewise, over the past 20 years, driven by material costs, automotive catalysis research has optimized material formulations and efficiencies, making converters less material intense per quantity of pollutant removed. As part of this, the average concentration and proportion of catalyst materials in catalytic converters has become more variable.[68] Palladium and platinum are somewhat substitutable, and manufacturers have oscillated between the two depending on prices. Platinum has historically been more expensive than palladium, so manufacturers have increasingly favored palladium.[69]

Market Share Assumptions: The low and high penetration scenarios both assume all ICE vehicles employ catalytic converters.

Material Intensity Assumptions: The low material intensity scenario uses estimates of current global average PGM and cerium requirements per vehicle.[70,71] The high intensity scenario takes into account two potential opposing trends: reductions in engine size (decreasing material intensity) and additional global regulatory stringency (increasing material intensity), which is estimated to result in a 36% net increase in material intensity.

Table 3-9 summarizes assumptions made in this report about technology deployment, market share, and material intensity for key materials in catalytic converters.

Table 3-9. Assumptions Used to Estimate Future Demand for Key Materials in Catalytic Converters



	Assumption	Low Penetration	High Penetration
Annual Deployment in 2030	Global sales, ICE (millions)	106	131
Market Share	Share of ICE vehicles with catalytic converters	100%	100%
	Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Weight of palladium (g/vehicle)	1.9	2.5
	Weight of platinum (g/vehicle)	1.0	1.4
	Weight of rhodium (g/vehicle)	0.26	0.35
	Weight of cerium (g/vehicle)	75	100

3.2.5 Lighting

In the 2011 *Critical Materials Strategy* report, DOE assessed material requirements for efficient lighting, specifically the five rare earths used in phosphor coatings in fluorescent lighting. The strong outlook for fluorescent lighting—driven by efficiency standards in many countries—combined with supply risks for yttrium, europium, and terbium led DOE to categorize these materials as critical. Since 2011, the shift from fluorescents to LEDs as the preferred technology in general lighting applications has been faster than expected. In 2010, LED sales were negligible, and DOE estimated that U.S. market share would reach 21% of lighting service sales (in lumen-hours) by 2020. When DOE repeated the analysis in 2012[72] and 2014,[73] that estimate increased to 36% and 48%, respectively. Furthermore, the 2014 analysis anticipated U.S. LED sales to reach 84% of total lighting sales by 2030.[74] Global estimates vary depending on the metric by which deployment is measured, but most sources agree that LEDs will constitute a significant market share in general lighting applications in the near term.[75] This shift in technology has mitigated some of the concerns over rare earths in lighting applications because LEDs use one to two orders of magnitude less rare earths per lumen of light output.[76] Increased attention is being paid to the materials employed as semiconductor materials in LEDs for general lighting applications, most commonly gallium and indium.

The increase in anticipated future demand for LEDs can be attributed to improved performance, including increased efficiency and color uniformity, as well as decreases in costs. For example, prices for A-type lamps, which are considered the classic type of light bulb for general purpose lighting, are down to $8 per bulb before any rebates or incentives. This represents a more than 80% price reduction from when they were first available to customers between 2007 and 2009.[77] While LEDs are expected to remain more expensive than conventional lighting for some time on a first-cost basis, higher operating efficiency and longer operating lifetime (Table 3-10) make LEDs competitive in terms of total cost of ownership, especially in high-usage commercial and industrial applications. Furthermore, the additional value-added functionality of LEDs makes price parity less important for consumer adoption.[78]

Table 3-10. Price and Performance Characteristics for A19 and A19 Replacement Lamps[79]

Product	Efficacy (lm/W)	Correlated Color Temperature (K)	Usable Life (hours)	Price ($/klm)
LED A19 Lamp (dimmable, warm white)	78	2,700	25,000	$10
Compact Fluorescent Lamp A19 Replacement (dimmable)	70	2,700	12,000	$10
Compact Fluorescent Lamp A19 Replacement	70	2,700	12,000	$2
Halogen A19	20	2,750	8,400	$2.50
Incandescent A19	15	2,760	1,000	$0.63

Global Deployment and Market Share Assumptions: This report uses output from a lighting market model developed by the Solid-State Lighting Program within DOE's Office of Energy Efficiency and Renewable Energy. This model incorporates anticipated improvements in product efficacy, lifetime, and price, as well as established technology diffusion rates, to estimate the expected future adoption of all lighting types in the United States, including LEDs. Prior to the most recent report in 2016, model results were reported in terms of lighting service (lumen-hours). However, in 2016, the model was adjusted to report results in terms of discrete lighting units (*e.g.*, lamps and luminaires). This update to the model was done to make results more intuitive and align with the units used in DOE's biennial adoption report. For the purposes of estimating material requirements, results on a unit basis are problematic because material use can vary widely between lighting products, whereas material requirements per lumen of light output is relatively consistent for broad classes of products. Therefore, this analysis uses the results from the 2014 report that show LEDs accounting for 84% of sales in general lighting applications in the

United States by 2030 (Figure 3-11). Total light sales decrease through 2030 because of increased average product lifetimes.

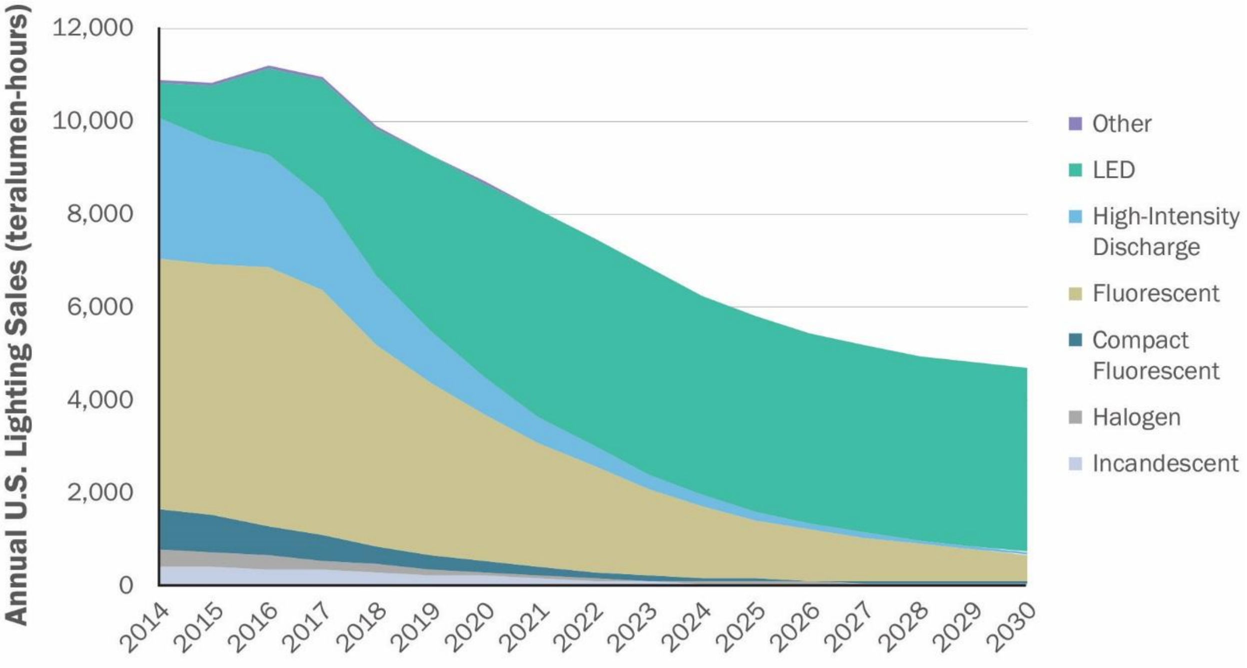


Figure 3-11. Lighting sales by lighting type in the United States (2015–2030)[80]

The DOE lighting market model estimates all types of lighting sales (incandescent, fluorescent, LEDs, etc.) by sector (residential, commercial, industrial, and outdoor) in the United States through 2030. For the low deployment scenario, this analysis takes the total lighting sales in the United States in 2014 and assumes that it represents 20% of the global market, which is an industry rule of thumb. It then applies a constant annual growth rate equivalent to IEA's assumed growth in global gross domestic product (3.4%).[81] The LED share of total global lighting sales by sector remains fixed at U.S. levels in 2014 (Table 3-11). For the high deployment scenario, this analysis assumes that U.S. LED sales by sector will follow the DOE lighting market model, and that this represents 20% of the global market (Figure 3-12).

Table 3-11. LED Share of Total Lighting Sales in the United States by Sector in 2014[82]

Sector	LED Share of Total Lighting Sales (% teralumen-hour)
Residential	1%
Commercial	4%
Industrial	3%
Outdoor	14%

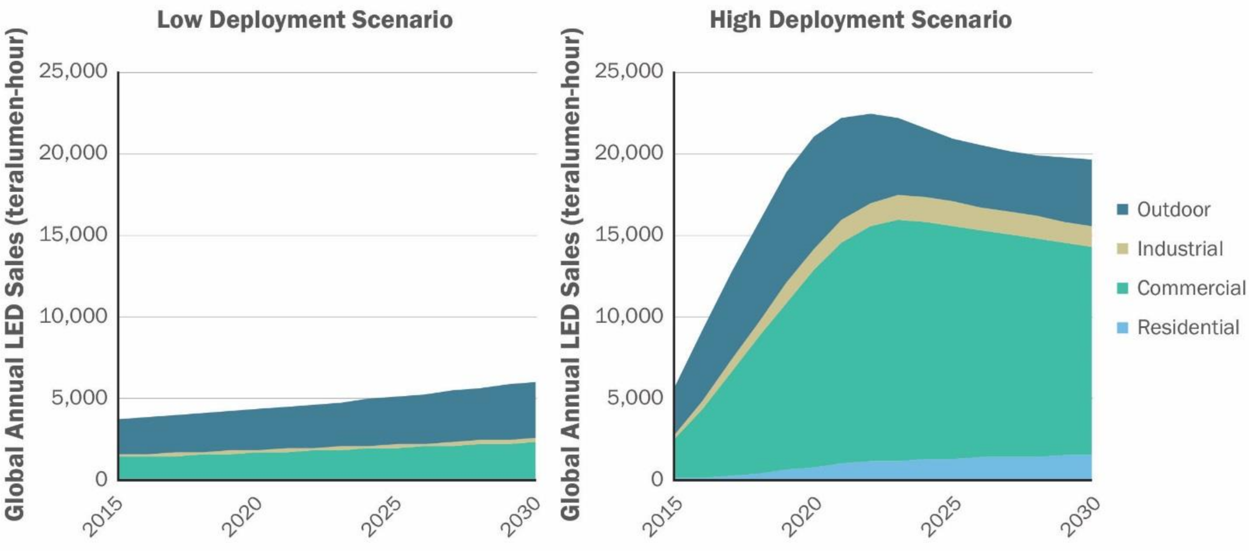


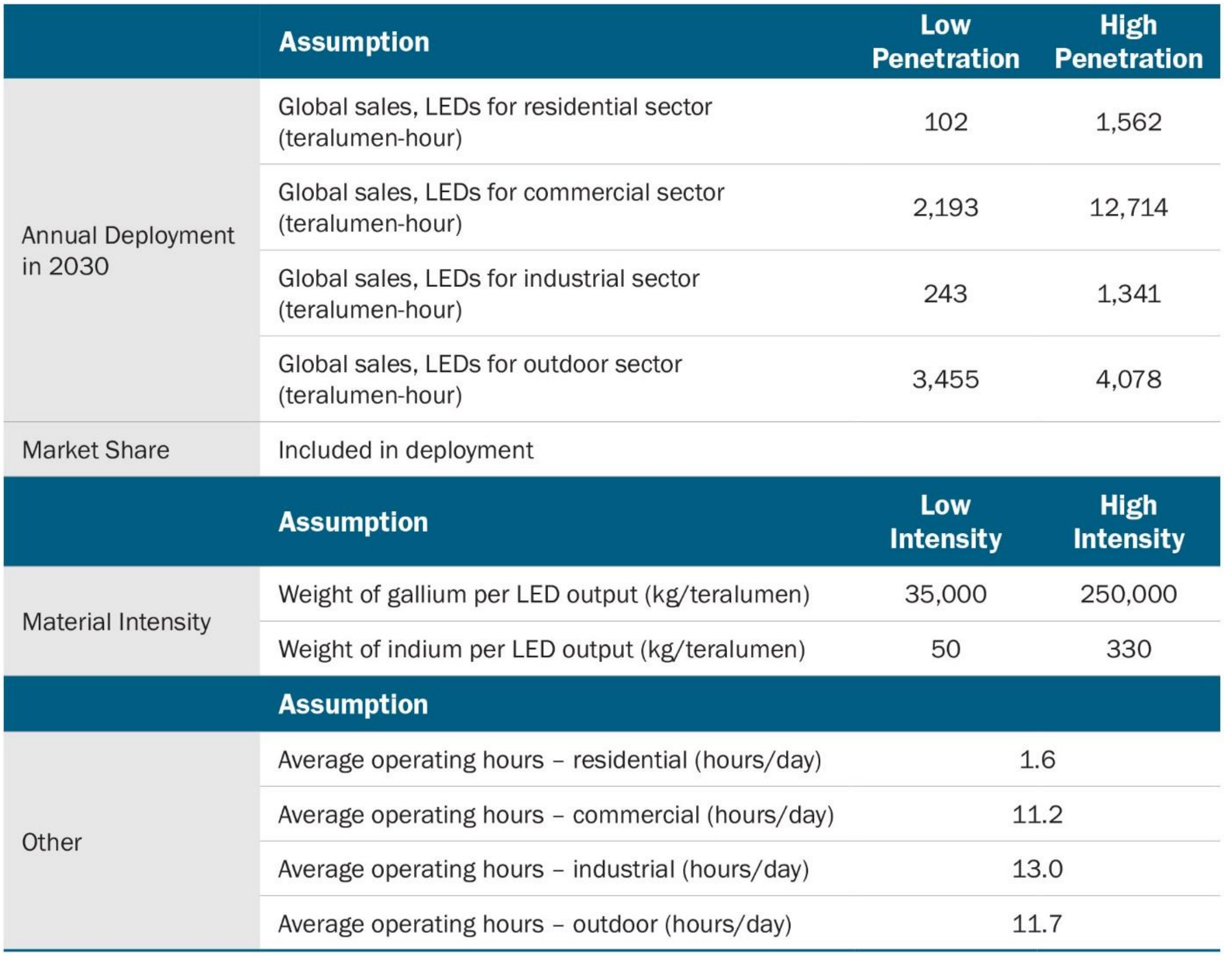
Figure 3-12. Assumed global LED sales by sector for low and high deployment scenarios (2015–2030)

In order to convert the deployment scenarios for global LED sales from units of lighting service (lumen-hours) into units of light output (lumens), this analysis assumes a constant average daily operating schedule for each sector (Table 3-12). These data are sourced from recent DOE publications and are the same data used as inputs into the lighting market model mentioned above.[83,84]

Material Intensity Assumptions: The high material intensity scenario uses unofficial estimates provided by DOE's Solid-State Lighting Program for gallium and indium weight per unit of light output (kg/teralumen). These estimates are for mid-power LEDs, which have been common in non-directional general lighting applications and are expected to continue being the favored package type in the medium term. It is also important to note that these estimates are for the elemental form of the material and do not include any yield losses that may occur during the manufacturing process. Because material intensity is directly linked to efficacy (lumen per watt [lm/W]), the low material intensity scenario assumes that material intensity could potentially improve in concert with the DOE Solid-State Lighting Program's efficacy targets (255 lm/W), which are an 86% improvement over the current state of the art (137 lm/W).[85]

Table 3-12 summarizes assumptions made in this report about technology deployment, market share, and material intensity used to estimate future demand for key materials in LEDs.

Table 3-12. Assumptions Used to Estimate Future Demand for Key Materials in LEDs



	Assumption	**Low Penetration**	**High Penetration**
Annual Deployment in 2030	Global sales, LEDs for residential sector (teralumen-hour)	102	1,562
	Global sales, LEDs for commercial sector (teralumen-hour)	2,193	12,714
	Global sales, LEDs for industrial sector (teralumen-hour)	243	1,341
	Global sales, LEDs for outdoor sector (teralumen-hour)	3,455	4,078
Market Share	Included in deployment		
	Assumption	**Low Intensity**	**High Intensity**
Material Intensity	Weight of gallium per LED output (kg/teralumen)	35,000	250,000
	Weight of indium per LED output (kg/teralumen)	50	330
	Assumption		
Other	Average operating hours – residential (hours/day)	1.6	
	Average operating hours – commercial (hours/day)	11.2	
	Average operating hours – industrial (hours/day)	13.0	
	Average operating hours – outdoor (hours/day)	11.7	

3.3 Supply of Key Materials and Relevant Assumptions

To explore the potential for future supply constraints, the future demand trajectories described in Sections 2 and 3.2 must be compared to estimates for material supply. The focus here is on possible constraints for raw materials and not on existing or potential constraints for the intermediate processing steps in the supply chain. These concerns are discussed in Chapter 2 (Criticality in the Context of Global Dynamic Supply Chains and Implications for the U.S. Economy) and taken into account in Chapter 4 (Criticality Assessment).

In the 2011 *Critical Materials Strategy* report, estimates for future supply of key materials were developed in consultation with USGS, typically by including the production capacity of mines that were under development and expected to come online by 2015. However, production for many materials did not reach these estimated levels. For example, only about half of the 80,000 tonnes of expected rare earth oxide (REO) production capacity came online. Furthermore, the major facilities that opened in Australia and India have yet to reach full capacity, and the Mountain Pass mine that opened in the United States began producing again in 2018 after its previous owner filed for bankruptcy and halted production. This is indicative of the degree to which future supply of materials is uncertain, which is especially true for specialty materials, such as those examined in this report.

Key materials for energy technologies, such as the rare earths, are often subject to market volatility that can make it difficult for projects to secure financing. This is in part because of the relatively small overall amounts of material in the market compared to other materials like iron or aluminum, and also in part because these materials are often by-products of other mining or enrichment processes. Production of these materials also often require technologically complex processes that can lead to underestimation of operating costs and slow ramp up. Due to the slow rate of change of production, demand is forced to respond by adjusting material needs, sometimes at a cost to efficiency or other metrics of performance. By the time producers secure financing or resolve technological complexities, prices may have changed, compounding difficulties for prospective sources of supply.

To address the market volatility for the materials in this study, this year's update compares the future demand trajectories described in Sections 2 and 3.2 to current levels of global production and production capacity. This is different from both the 2010 and 2011 *Critical Materials Strategy* reports, which assessed potential future supply. Deposits under development are still important to consider when assessing potential supply risk and are thus discussed in the text surrounding the demand and supply figures in Section 3.4.

Global Production: In the figures included in Section 3.4, a solid red horizontal line represents global production in 2014. This information is almost exclusively sourced from the latest iteration of the early warning screening tool developed by the National Science and Technology Council's Subcommittee on Critical and Strategic Mineral Supply Chains, which uses the most recent data collected by USGS.[86] The only exception is tellurium, where a lack of adequate data prevents USGS from reporting global production. Therefore, this analysis uses an estimated range of global tellurium production in 2015 as reported by a market source and cited by USGS in its *Minerals Yearbook*.[87] There are two cases where the USGS production data is augmented: 1) to estimate production of individual rare earths, and 2) to account for significant post-consumer recycling of PGMs. These calculations are discussed later in this section.

Global Production Capacity: To understand the opportunity for increasing production in the short term, the figures in Section 3.4 also include a dashed horizontal red line that represents a measure of global production capacity for each material. Actual production capacity is used when it is explicitly reported by USGS in its most recent *Minerals Yearbook*[88] or *Mineral Commodity Summaries*.[89] For PGMs, reported primary production capacity is adjusted to account for post-consumer recycling, the details of which are discussed later in this section. For rare earths, manganese, nickel, vanadium, and tellurium, USGS does not report production capacity, so other measures are used. Estimating production capacity for rare earths is discussed later in this section. The production capacity for manganese is calculated by applying a 70% estimated capacity utilization rate[90] to the USGS-reported 2014 production. For nickel and vanadium, maximum production over the last 5 years of available data is used to represent production capacity. This is an imperfect measure, but it helps to give a sense of how much headroom there may be to increase production (*i.e.*, if recent history saw more production of a key material, that capacity may still be available if demand increases). Lack of adequate data for tellurium prevented the development of a measure for production capacity.

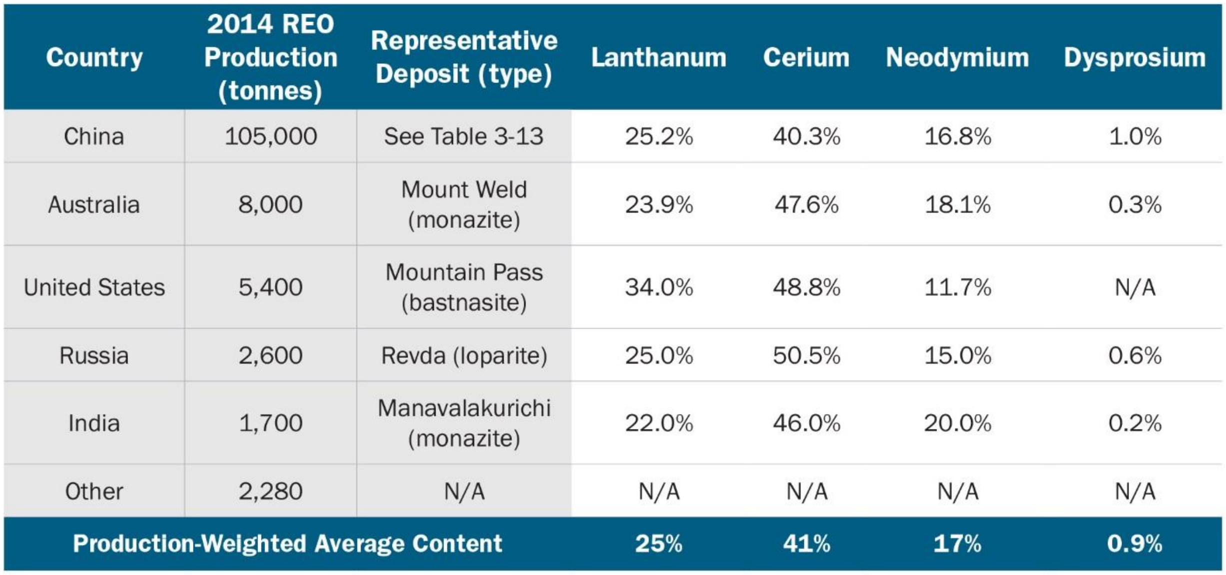
Global Rare Earth Production: Due to data limitations, USGS reports global production of REOs in aggregate. To estimate production of individual REOs, this analysis assumes an average share of total REO production for key materials. This is calculated by choosing a representative deposit from each producing country and taking the country-by-country production-weighted average of the REO content of each deposit. Choosing a representative deposit for Chinese production is problematic because there is a wide variety of sources with vastly different compositions. Therefore, this analysis uses a collection of select Chinese REO deposits and averages their REO content by provincial capacity (Table 3-13) to apply to total Chinese REO production. Table 3-14 reports the resulting average content that is applied to total REO production.

Table 3-13. Key Material Content for Select Chinese REO Deposits by Province[91]

Province	Production Capacity (tonnes)[1]	Select Deposits (type)	Lanthanum	Cerium	Neodymium	Dysprosium
Inner Mongolia	100,000	Bayan Obo (bastnasite)	23.0%	50.0%	18.5%	0.1%
Sichuan	47,800	Dechang (bastnasite)	35.6%	43.8%	13.1%	0.1%
		Maoniuping (bastnasite)	29.5%	47.6%	15.2%	0.2%
Jiangxi	30,000	Xunwu (rare earth laterite)	38.0%	3.5%	30.2%	1.8%
		Xinfeng (rare earth laterite)	27.3%	3.2%	17.6%	3.7%
		Longnan (rare earth laterite)	2.2%	1.1%	3.5%	7.5%
Guandong	6,000	Nangang (monazite)	23.0%	42.7%	17.0%	0.8%
		Southeast Guangdong (xenotime)	1.2%	3.0%	3.5%	9.1%
Shandong	2,000	Weishan (bastnastite)	35.5%	47.8%	10.9%	N/A
Capacity-Weighted Average Content for Chinese Deposits			**25.2%**	**40.3%**	**16.8%**	**1.0%**

[1] Source for production capacity: Matthew Riddle, Charles M. Macal, Guenter Conzelmann, Todd E. Combs, Diana Bauer, and Fletcher Fields, "Global critical materials markets: An agent-based modeling approach," *Resources Policy* 45 (2015): 307–321, doi:10.1016/j.resourpol.2015.01.002.

Table 3-14. Production-Weighted Average Content for Key REO Materials[92]



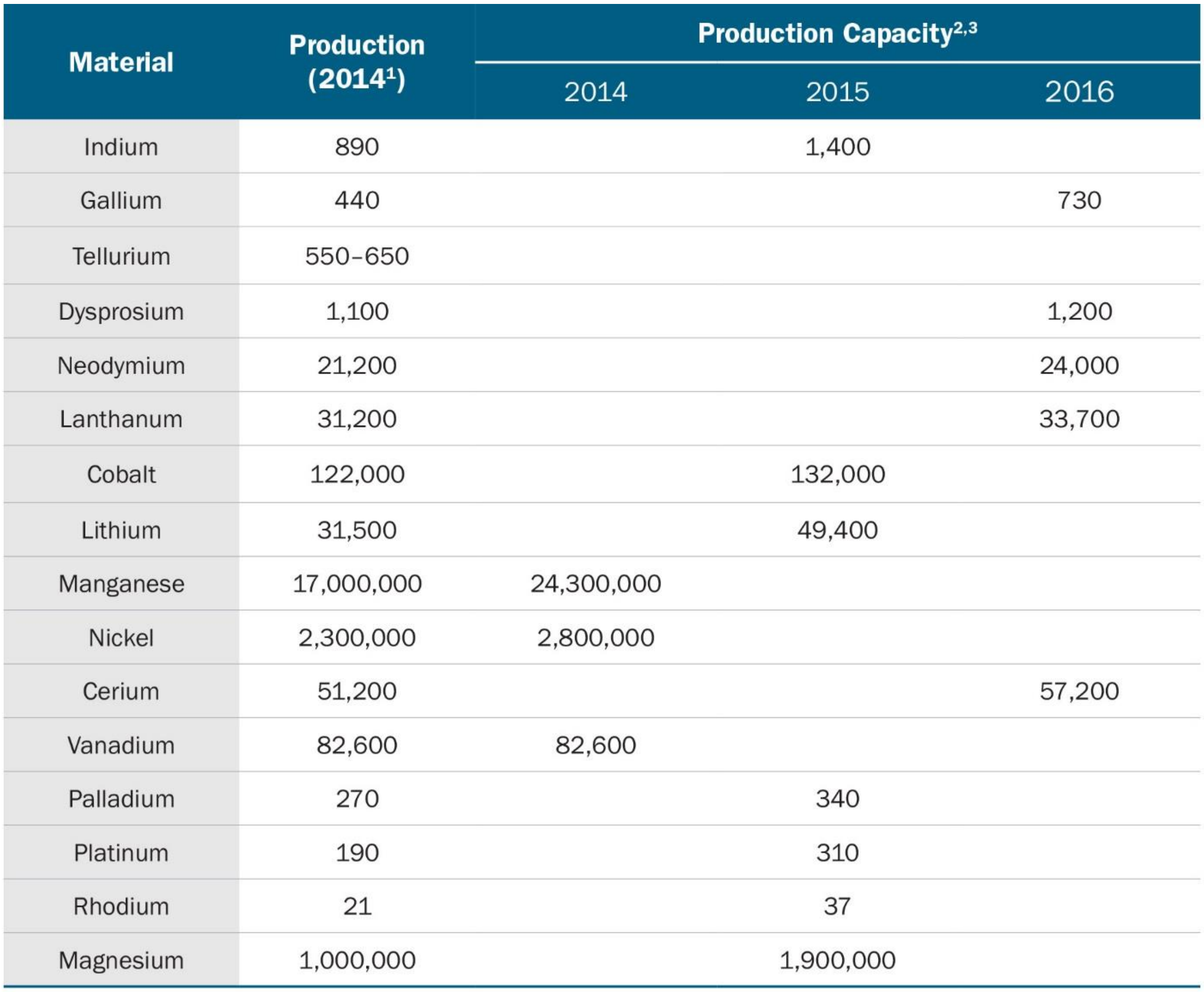
Country	2014 REO Production (tonnes)	Representative Deposit (type)	Lanthanum	Cerium	Neodymium	Dysprosium
China	105,000	See Table 3-13	25.2%	40.3%	16.8%	1.0%
Australia	8,000	Mount Weld (monazite)	23.9%	47.6%	18.1%	0.3%
United States	5,400	Mountain Pass (bastnasite)	34.0%	48.8%	11.7%	N/A
Russia	2,600	Revda (loparite)	25.0%	50.5%	15.0%	0.6%
India	1,700	Manavalakurichi (monazite)	22.0%	46.0%	20.0%	0.2%
Other	2,280	N/A	N/A	N/A	N/A	N/A
Production-Weighted Average Content			**25%**	**41%**	**17%**	**0.9%**

Global Rare Earth Production Capacity: To estimate 2016 REO production capacity, this analysis adds unused capacity in Australia (14,000 tonnes) and India (4,300 tonnes) to 2014 production and subtracts production from the United States (5,400 tonnes) to reflect the production hiatus of the Mountain Pass mine. The content reported in Table 3-14 for each country is then applied to these total volumes to estimate net additional capacity for the individual REOs. Although some market reports indicate a significant amount of unused capacity in China, it is unclear whether any additional production in China will enter the global marketplace.

Global PGM Production and Production Capacity: PGMs are another case in which USGS global production and capacity data was augmented. A significant share of global supply of PGMs is sourced from recycled catalytic converters. This secondary supply constitutes 28% of the total supply of palladium, 21% of the total supply of platinum, and 34% of the total supply of rhodium.[93] The 2014 primary production data reported by USGS was adjusted to incorporate this secondary supply, and the same volume of recycled PGMs was added to the reported 2015 production capacity.[94]

Table 3-15 summarizes assumed global production and production capacity for key materials analyzed in this report. It is important to note that estimates of material production for a given year may differ significantly from estimates of material demand in that same year as a result of supply chain dynamics such as inventory behavior. Thus, some of the figures in Section 3.4 show an existing mismatch in supply and demand, such as the figures for gallium and rhodium. Section 3.4 discusses the causes and implications of these existing mismatches in the text surrounding each figure.

Table 3-15. Assumed Global Production Statistics for Key Materials (tonnes)



Material	Production (2014[1])	Production Capacity[2,3]		
		2014	2015	2016
Indium	890		1,400	
Gallium	440			730
Tellurium	550–650			
Dysprosium	1,100			1,200
Neodymium	21,200			24,000
Lanthanum	31,200			33,700
Cobalt	122,000		132,000	
Lithium	31,500		49,400	
Manganese	17,000,000	24,300,000		
Nickel	2,300,000	2,800,000		
Cerium	51,200			57,200
Vanadium	82,600	82,600		
Palladium	270		340	
Platinum	190		310	
Rhodium	21		37	
Magnesium	1,000,000		1,900,000	

[1] Except for tellurium, where the reported global production is for 2015.

[2] Production capacity for indium, gallium, cobalt, lithium, and magnesium are reported by USGS in its most recent *Minerals Yearbook* or *Mineral Commodity Summaries*.

[3] See Section 3.3 for details on how production capacity was calculated for rare earths, PGMs, manganese, nickel, and vanadium.

3.4 Trajectories of Future Demand for Key Materials

In this section, the assumptions for technology market penetration, material intensity, and non-energy demand are combined to derive four future demand trajectories for key materials in energy technologies.[d] The resulting demand trajectories for each material, as well as estimates of material supply,[e] are summarized in a figure. Using these figures, this section describes the potential for supply and demand imbalances in the markets for these materials and the implications for possible market responses. For key materials that are used in more than one energy technology, the trajectories of

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[d] The methodologies for these calculations are described in Sections 2 and 3.2.

[e] The data sources and/or methodologies for calculating material supply are described in Section 3.3.

future demand are presented as an aggregate for all relevant technologies. The contribution of each application is noted in the discussion of the figure.

3.4.1 Trajectories of Future Demand for Materials in LEDs

Material use in LEDs drives energy demand for gallium. LEDs also use indium, but energy demand for indium is dominated by solar PV technologies. Section 3.4.6 discusses future demand trajectories for indium.

Demand for LEDs is expected to rise dramatically in the short term, driving energy demand for gallium from 18% of total gallium demand in 2015 to anywhere from 36% to 80% in 2030, depending on material intensity. Although solar PV technologies also use gallium, more than 96% of energy demand for gallium comes from LEDs in all trajectories. Figure 3-13 illustrates that current production capacity of gallium does not appear adequate to meet the additional demand given current material intensities (Trajectory D). Current gallium production capacity could be sufficient if significant reductions in gallium content, in accordance with efficiency targets set by DOE’s Solid-State Lighting Program, are achieved (Trajectory C). Even under a less optimistic LED deployment scenario, production capacity utilization would need to increase in the medium term if material intensity reductions are not realized (Trajectory B). In addition, there is potential for significant increased demand for gallium in non-energy applications, which would put additional strain on gallium supply. For example, global sales of 3G and 4G smartphones, which use ten times more gallium than 2G cellular telephones, are expected to grow. Gallium demand in the defense sector is also likely to surge due to increasing use of gallium arsenide devices in radar, electronic warfare, communications, and other defense applications.

Production of gallium increased from 280 tonnes in 2010 to 440 tonnes in 2014 in anticipation of increased demand. Much of the new capacity has been developed in China, driven by government incentives to increase LED lighting demand and production.[95] In the meantime, excess supply of gallium has driven down prices, prompting producers to reduce output and forcing some to shut down completely, including one plant in Germany. Kazakhstan was a leading producer in 2012 but has not reported any production since. In 2013, 67% of gallium production was concentrated in China, and preliminary reports indicate Chinese share of production has increased to 93%.[96]

Supply of gallium is heavily dependent on aluminum demand because most gallium is produced as a by-product of aluminum production when processing bauxite into alumina. Adding gallium production capacity to major existing bauxite refining operations in Canada, India, Australia, Brazil, Norway, and the United States could help diversify supply. Currently, only 2% of the gallium contained in bauxite is recovered[97] because it does not appear in sufficient concentrations to overcome cost of recovery at current prices. With very few gallium production facilities under development, one way for the supply of gallium to meet increased demand from LEDs and non-energy technologies could be by improving recovery rates in existing operations.

On the demand side, if faced with gallium supply constraints, LED manufacturers could use alternative package types, such as high-brightness LEDs, which are more expensive but use significantly less gallium. There is also opportunity to use alternative down converters, such as quantum dots. The lighting industry could also revert back to favoring fluorescent lights, but these technologies are faced with similar supply constraints on rare earths.

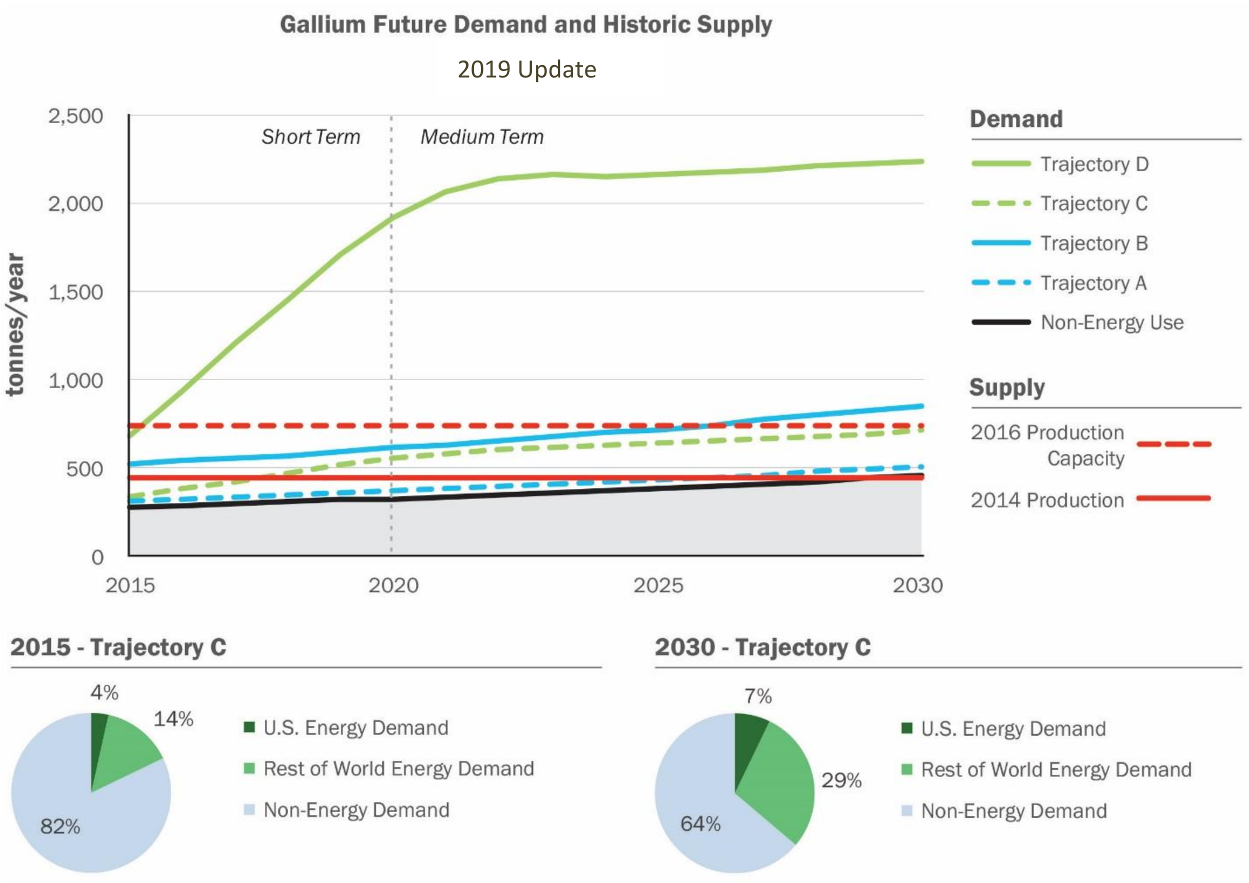

Figure 3-13. Future demand and historic supply for gallium

3.4.2 Trajectories of Future Demand for Materials in Battery Technologies

Material use in vehicle batteries drives energy demand for lithium, cobalt, nickel, and lanthanum, while material use in grid storage batteries drives energy demand for vanadium. Vehicle battery technologies also use neodymium, manganese, and cerium, but energy demand for neodymium is dominated by magnet technologies; energy demand for manganese is dominated by vehicle lightweighting; and energy demand for cerium is dominated by catalytic converters. Sections 3.4.3, 3.4.4, and 3.4.5 discuss future demand trajectories for neodymium, manganese, and cerium, respectively.

Figure 3-14 illustrates that current production capacity of lithium appears adequate to meet demand in the short term but potentially inadequate in the medium term, especially under a high penetration scenario for EVs (Trajectories C and D). Several lithium production facilities are under development,[98] but it is unclear which ones, if any, are likely to begin operations in the medium term.

Global energy demand for lithium as a percentage of total demand increases dramatically from about 22% in 2015 to 71%–91% in 2030 under the high penetration scenario (Trajectories C and D). This increase is driven by deployment of EVs and high market share for Li-ion batteries, with currently available battery chemistries offering little opportunity to reduce material intensity and balance lithium supply with potential future demand. Even under a low penetration scenario (Trajectories A and B), energy demand could constitute as much as 40% of total lithium demand in 2030. These lithium demand trajectories are higher than they were in the 2011 *Critical Materials Strategy* report due to more rapid deployment of EVs in the high deployment scenario coupled with larger batteries that extend vehicle ranges. Lithium production has been relatively constant since 2011, with less production capacity coming online than expected in the 2011 *Critical Materials Strategy* report.

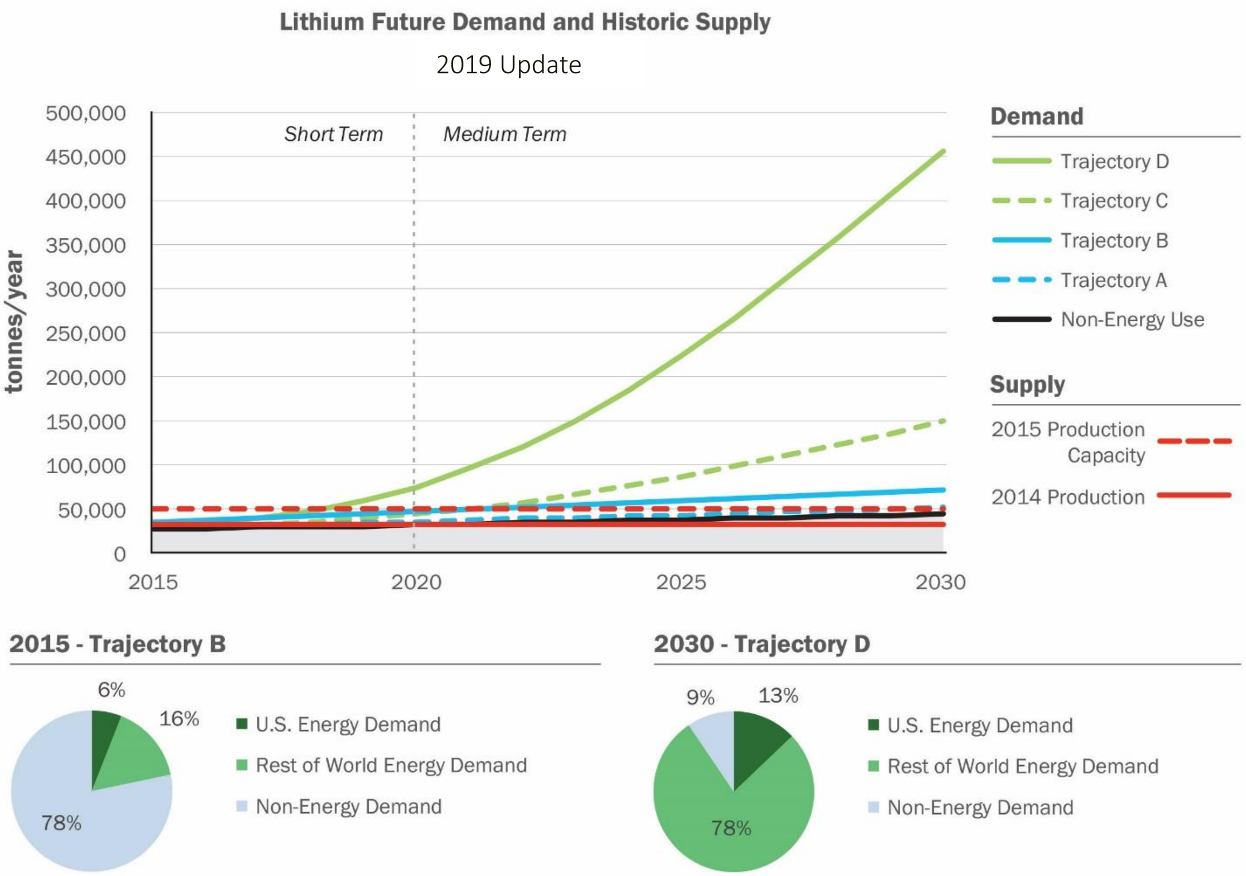

Figure 3-14. Future demand and historic supply for lithium

EV batteries are the key driver for energy demand for cobalt, which could constitute a large share of total cobalt demand in 2030 under the high material intensity scenarios—40% in Trajectory B and 91% in Trajectory D. Figure 3-15 illustrates that current cobalt production appears sufficient to meet demand in the short term under all but the highest demand trajectory (Trajectory D), but additional production capacity would be required in the medium term under the high material intensity scenario (Trajectories B and D). Although 30,000 tonnes of additional cobalt production capacity is expected to come online by 2020,[99] the likelihood of these facilities reaching full production in the short term is unknown. Regardless, even with this additional capacity, cobalt supply would still be insufficient to meet demand under Trajectory D. If faced with cobalt supply constraints, EV manufacturers could opt for cobalt-free Li-ion battery chemistries or less cobalt-intense NiMH batteries (Trajectories A and C), but both may result in diminished performance.

Cobalt demand trajectories have increased significantly since the 2011 *Critical Materials Strategy* report due to more rapid deployment of EVs in the high deployment scenario coupled with larger batteries that extend vehicle ranges. Cobalt production has increased by about 36% since 2011, and increases in production capacity failed to meet expectations laid out in the 2011 *Critical Materials Strategy* report.

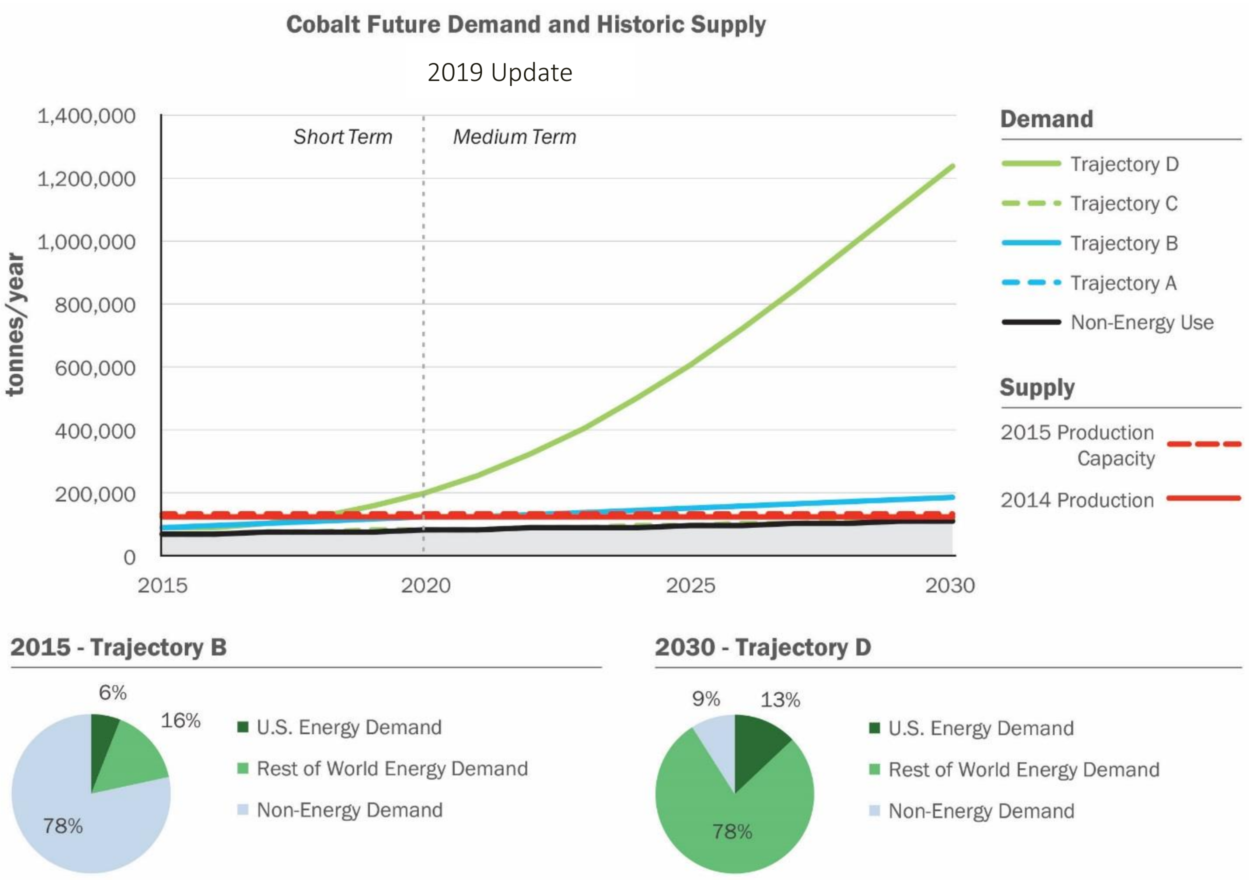

Figure 3-15. Future demand and historic supply for cobalt

EV batteries are the key driver for energy demand for nickel. However, non-energy demand currently represents the vast majority of nickel demand and continues to do so until 2030 in all trajectories except Trajectory D, where it could constitute as much as 40% of total nickel demand. Current nickel production capacity appears sufficient to meet demand in the short term, but additional production capacity would be required in the medium term under the highest demand trajectory (Trajectory D) (Figure 3-16). An additional 770,000 tonnes of nickel production capacity is under development,[100] but how much of this actually comes online is highly uncertain, and nickel supply would still be insufficient to meet demand under Trajectory D. If faced with a nickel supply constraint, vehicle manufacturers could opt for nickel-free Li-ion battery chemistries or less nickel-intense NiMH batteries, but both may result in diminished performance.

Nickel demand trajectories have increased significantly since the 2011 *Critical Materials Strategy* report due to more rapid deployment of EVs in the high deployment scenario coupled with larger batteries that extend vehicle ranges. Nickel production has increased about 44% since 2011, with less production capacity coming online than expected in the 2011 *Critical Materials Strategy* report.

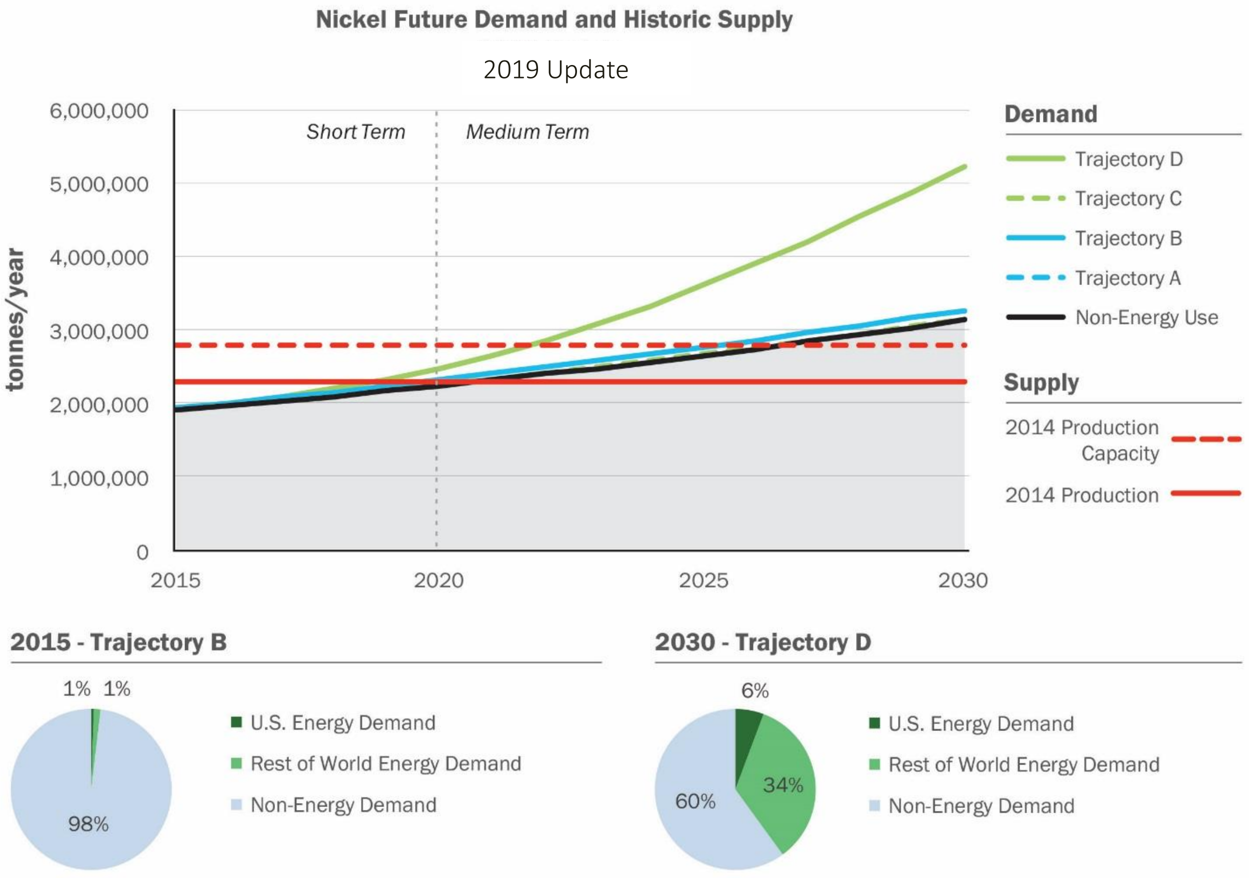

Figure 3-16. Future demand and historic supply for nickel

Energy demand for lanthanum is driven by deployment of HEVs, which are the only EVs that employ the lanthanum-consuming NiMH batteries. PHEVs and AEVs are not expected to use NiMH batteries. Although Figure 3-17 shows lanthanum demand trajectories outstripping production capacity in the short and medium terms, a majority of the anticipated demand growth will come from non-energy end uses. Even under high penetration rates for NiMH batteries in HEVs (Trajectories C and D), energy demand for lanthanum only reaches 5%–8% of total demand in 2030, depending on material intensity. Trajectories employing the low penetration scenario (Trajectories A and B) show zero energy demand for lanthanum, which reflects the potential for HEV manufacturers to switch from NiMH batteries to the now favored Li-ion batteries.

It is important to note that the demand for lanthanum is most likely overstated. Lanthanum's share of total REO consumption is assumed to be equal to the average lanthanum content of rare earth deposits at operational production facilities. In reality, lanthanum's share of a rare earths deposit is much greater than its share of consumption. Production for REOs is largely driven by demand for neodymium; however, because lanthanum is one of the most abundant materials in most rare earth deposits, it tends to be oversupplied.

This year's lanthanum demand trajectories are lower than those in the 2011 *Critical Materials Strategy* report because fewer HEVs are expected to be deployed. Current IEA deployment scenarios show PHEVs and AEVs supplanting some of the market share that had previously been expected for HEVs. Since

2011, lanthanum production has remained relatively flat, with much less additional capacity coming online than expected in the 2011 *Critical Materials Strategy* report.

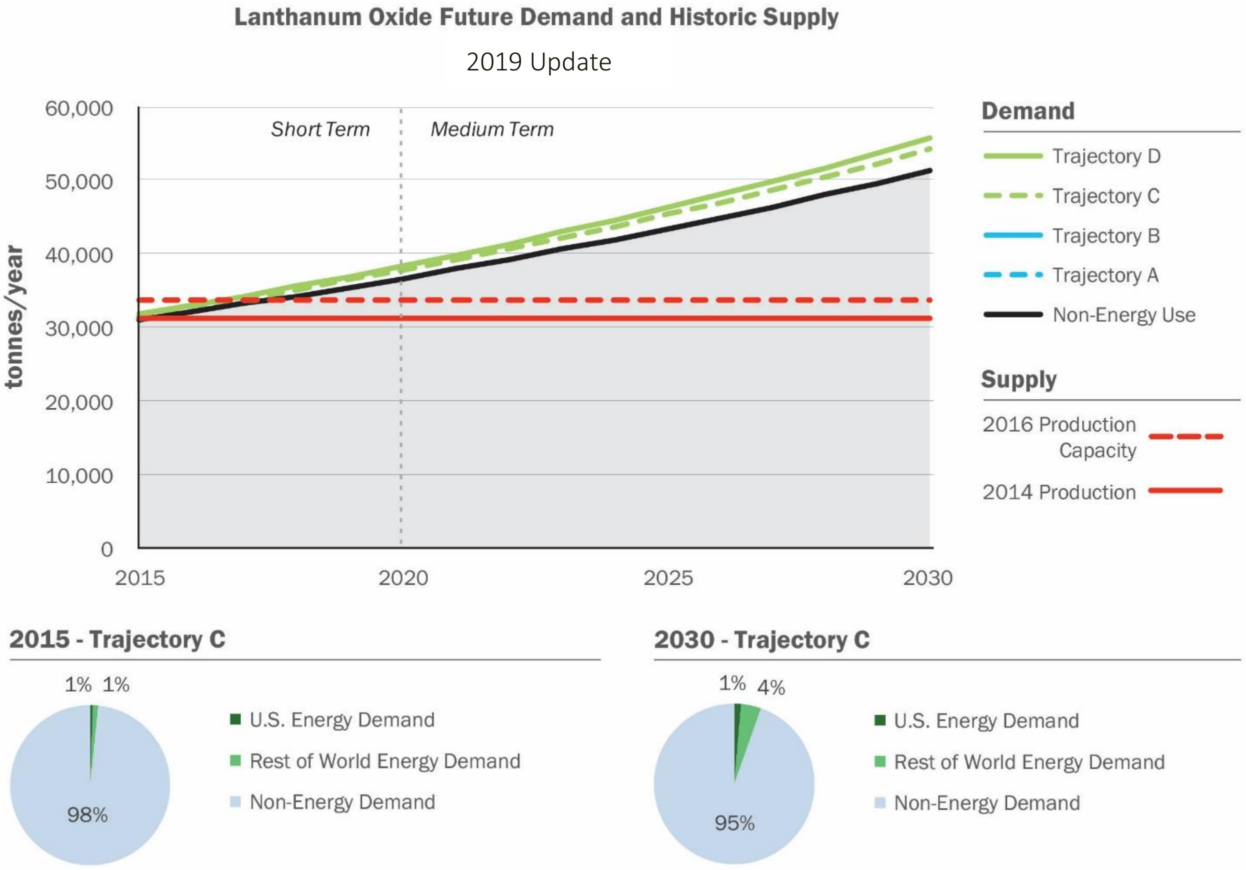

Figure 3-17. Future demand and historic supply for lanthanum oxide

Energy demand for vanadium is driven by demand in grid storage batteries. Although Figure 3-18 shows vanadium demand trajectories outstripping production capacity in the short and medium terms, most of the anticipated demand growth will come from non-energy end uses. Even under high penetration rates for VRBs (Trajectories C and D), energy demand for vanadium only reaches 2%–8% of total demand in 2030, depending on material intensity. However, redox flow batteries provide unique grid services that may be difficult to deliver using other types of batteries (*i.e.*, Li-ion batteries). With very little production capacity under development, a vanadium supply constraint driven by growth in non-energy demand would require switching to zinc/bromine or iron/chromium redox flow batteries.

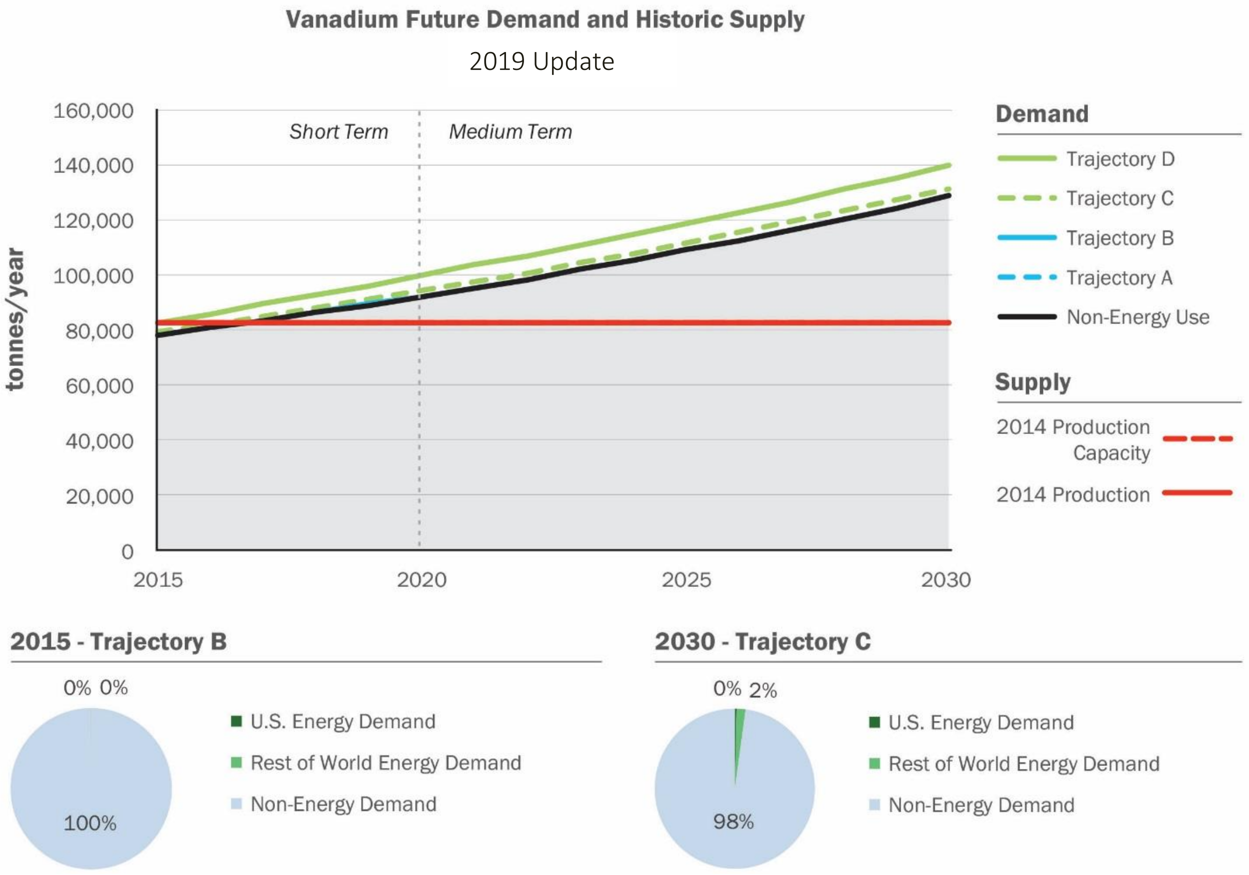

Figure 3-18. Future demand and historic supply for vanadium

3.4.3 Trajectories of Future Demand for Materials in Magnet Technologies

Material use in magnets for EVs and wind turbines drives energy demand for neodymium and dysprosium. Neodymium is also used in battery technologies, but even under a high penetration scenario (Trajectories C and D), batteries only constitute 4%–12% of energy demand for neodymium in 2030, depending on material intensity.

In the short term, before expected deployment for EVs ramps up, energy demand for neodymium is dominated by its use in wind turbine magnets. In the medium term, increased EV sales drive neodymium use in vehicle magnets above that of wind turbine magnets. This trend is especially pronounced in the high penetration scenario (Trajectories C and D), where more wind turbines using rare earth permanent magnets are deployed in the short term and the increase in EV sales in the medium term is more dramatic.

Figure 3-19 illustrates that neodymium production capacity could cover demand in the short term under the low penetration scenario (Trajectories A and B) but not in the high penetration scenario (Trajectories C and D) unless significant reductions in material intensity are achieved. Additional capacity will be needed to cover demand in the medium term, especially under Trajectories C and D, where energy demand increases to 25% and 61% of total neodymium demand, respectively. In the low penetration scenario, energy demand grows at the same rate as non-energy demand, maintaining a 3%–15% share of total annual neodymium demand through 2030, depending on material intensity. Recent market reports forecast a 38% increase in overall supply of rare earths between 2014 and 2020,[101] which would cover any potential supply deficits in the short term under all but the highest demand trajectory (Trajectory D) but be inadequate to cover medium-term demand in the high penetration scenario (Trajectories C and D).

Although the expected deployment of wind turbines and EVs has risen since 2011, this year's demand trajectories for neodymium are lower than those in the 2011 *Critical Materials Strategy* report. This is due to a less favorable outlook for market share of rare earth magnets in wind turbines and AEVs combined with recent (and anticipated) advances in reducing neodymium intensity. On the supply side, neodymium production has remained relatively flat, with much less additional capacity coming online than expected in the 2011 *Critical Materials Strategy* report.

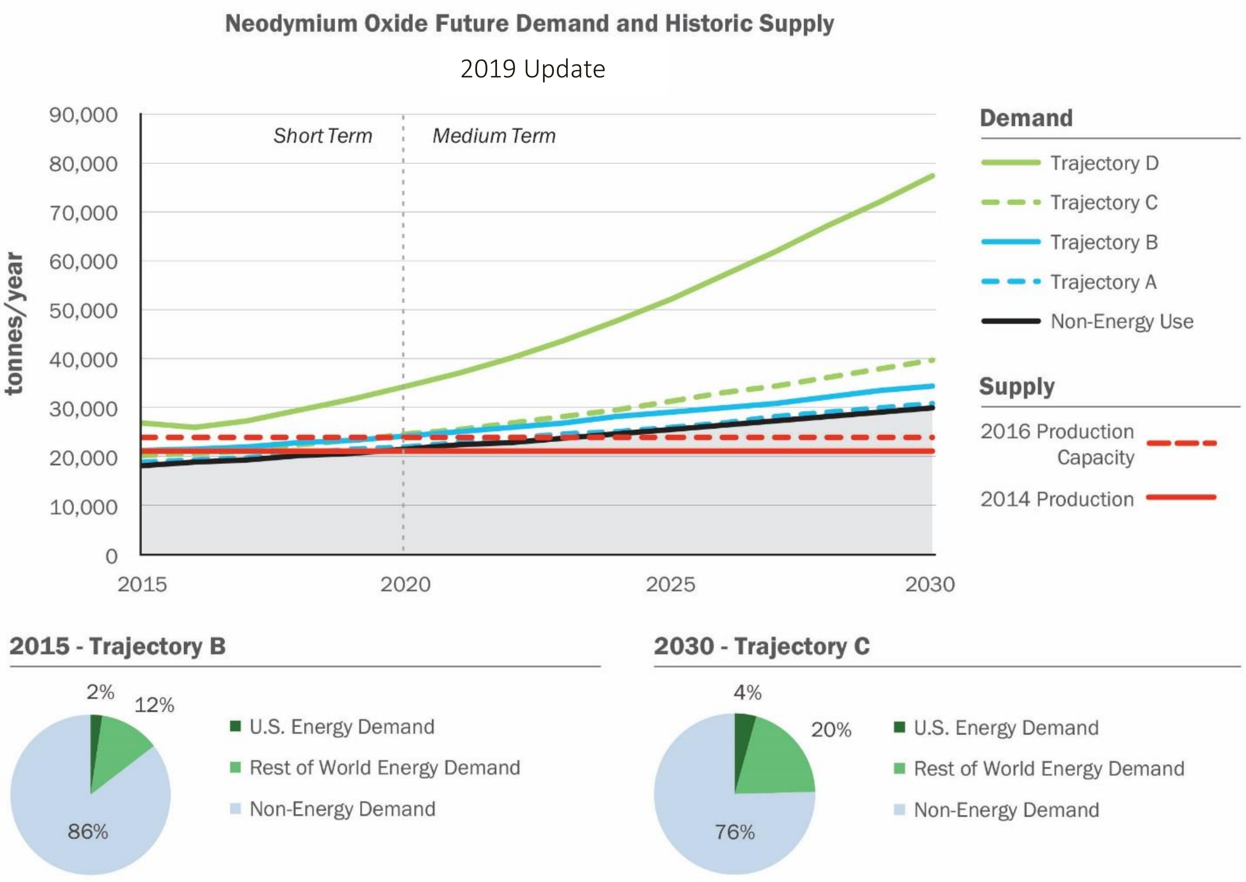

Figure 3-19. Future demand and historic supply for neodymium oxide

Like neodymium, energy demand for dysprosium in the high material intensity scenario (Trajectories B and D) is dominated by wind turbines in the short term, before deployment for EVs ramps up and drives energy demand for dysprosium in vehicle magnets above that of wind turbine magnets. However, in the low intensity scenario (Trajectories A and C), wind turbine magnets are assumed to have no dysprosium, so energy demand for dysprosium in these scenarios is driven exclusively by its use in vehicle magnets.

Figure 3-20 illustrates that dysprosium production capacity will be insufficient to cover demand in the short term under both high and low penetration scenarios given current material intensity (Trajectories B and D). This is exacerbated in the medium term when EV sales increase dramatically under Trajectory D. Although employing existing pathways to reducing dysprosium intensity in magnets would help (Trajectory C), it would not bring supply and demand into alignment. Additional production capacity will be needed to cover dysprosium demand in the medium term, especially under Trajectories B, C, and D, where energy demand increases anywhere from 33% to 88% by 2030. Recent market reports forecast a 38% increase in overall supply of rare earths between 2014 and 2020,[102] which would cover any potential dysprosium supply deficits in the short term under all but the highest demand trajectory (Trajectory D). However, it would be inadequate to cover medium-term dysprosium demand under Trajectories B, C, and D.

Although the expected deployment of EVs has risen since 2011, this year's dysprosium demand trajectories are lower than those in the 2011 *Critical Materials Strategy* report. This is due to a less favorable outlook for market share of rare earth magnets in AEVs, which have supplanted some of the market share that had previously been expected for HEVs. There have also been advances in reducing dysprosium intensities in EVs. On the supply side, dysprosium production has remained relatively flat, with much less additional capacity coming online than expected in the 2011 *Critical Materials Strategy* report.

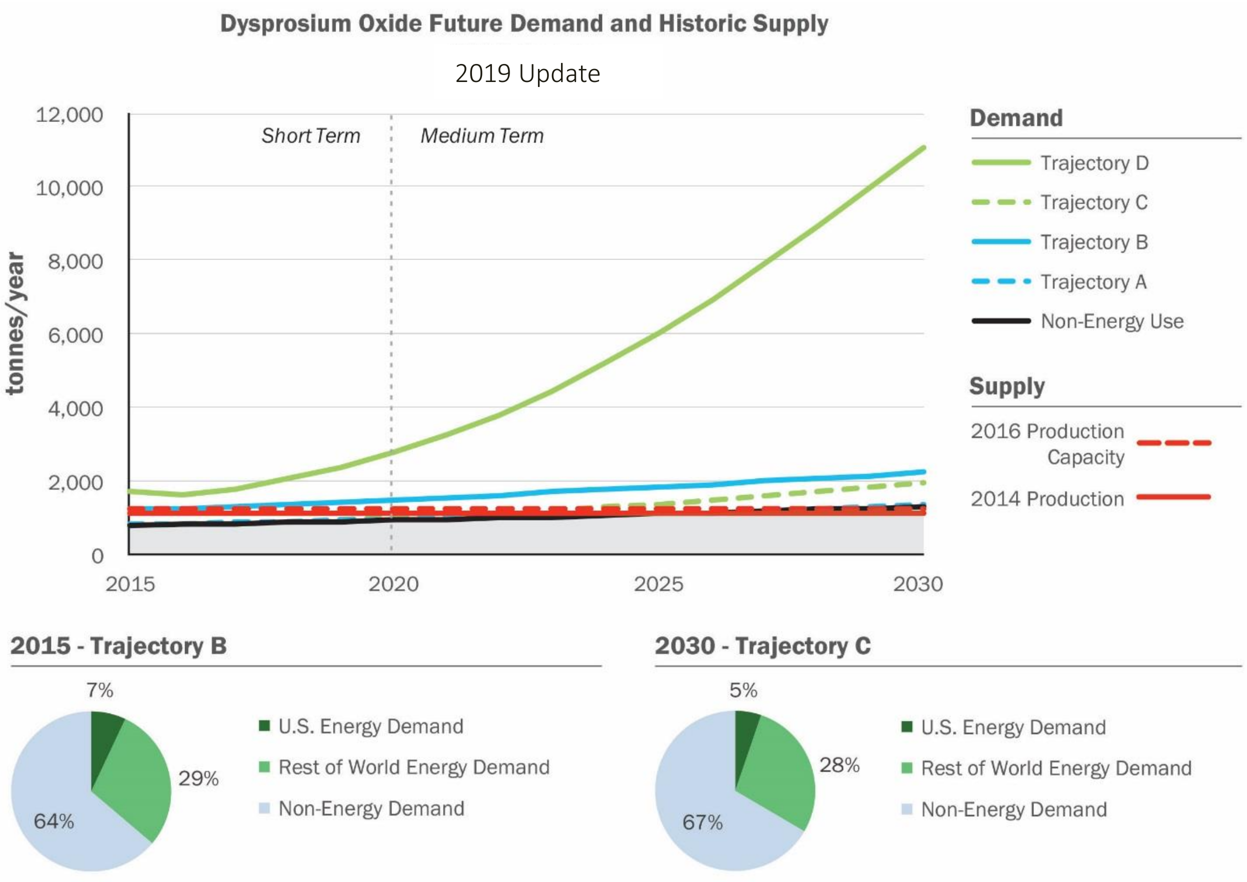

Figure 3-20. Future demand and historic supply for dysprosium oxide

3.4.4 Trajectories of Future Demand for Materials in Vehicle Lightweighting

Material use for vehicle lightweighting drives energy demand for magnesium and manganese via their use in high-strength steel, aluminum alloys, and magnesium alloys.

Currently, about 28% of annual magnesium demand is attributable to vehicle lightweighting. This share may increase to as much as 56% by 2030, depending on market penetration and material intensity. Current production capacity is able to meet demand in the short term in all trajectories except Trajectory D (Figure 3-21). This indicates that short-term increases in magnesium demand will only outstrip supply if a high penetration of additional lightweighting at a high material intensity occurs. Both demand trajectories under the high penetration scenario (Trajectories C and D) surpass current production capacity in the medium term. A handful of planned magnesium production facilities in the United States, China, Canada, and Australia are under development, which could increase production capacity by about 170,000–200,000 tonnes.[103] Recent market reports predict 255,000 tonnes of additional magnesium production capacity to come online by 2020.[104] However, this additional capacity would still be insufficient to meet increased magnesium demand under the highest demand trajectory (Trajectory D).

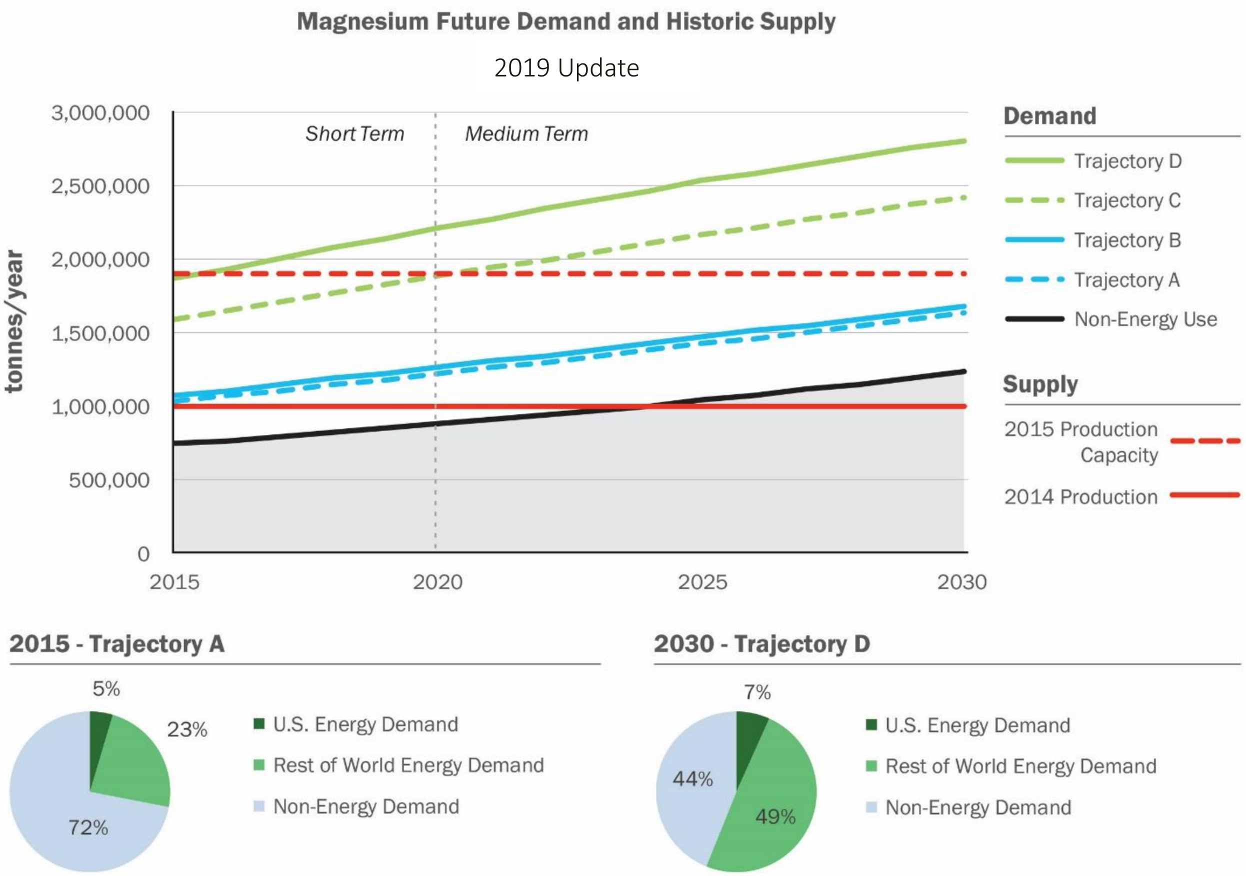

Figure 3-21. Future demand and historic supply for magnesium

Energy demand for manganese is driven by demand for vehicle lightweighting except in the highest demand trajectory (Trajectory D) where a combination of high EV penetration and high material intensity results in demand for manganese in EV batteries, constituting 80% of energy demand for manganese by 2030. Nonetheless, energy demand for manganese represents a modest share of total manganese demand, ranging from 3%–4% of total manganese demand through 2030 except in Trajectory D where demand for material-intense Li-ion batteries drives energy demand for manganese to 17% of total manganese demand in 2030. If faced with a manganese supply constraint, EV manufacturers could opt for manganese-free chemistries with little impact on performance. With significant unutilized manganese production capacity, current manganese supply can handle increased demand in the short term. However, additional manganese production capacity is needed by the middle of the medium term to cover growth in both energy and non-energy demand for manganese in all demand trajectories (Figure 3-22). Since 2011, manganese production has increased, and several facilities are under development[105] even though high stock levels and low ore prices have driven 11.7 million tonnes of capacity cuts in recent years.[106] This year's manganese demand trajectories are higher than those in the 2011 *Critical Materials Strategy* report because the previous report's analysis did not consider demand for manganese in vehicle lightweighting in its estimates for energy demand for manganese.

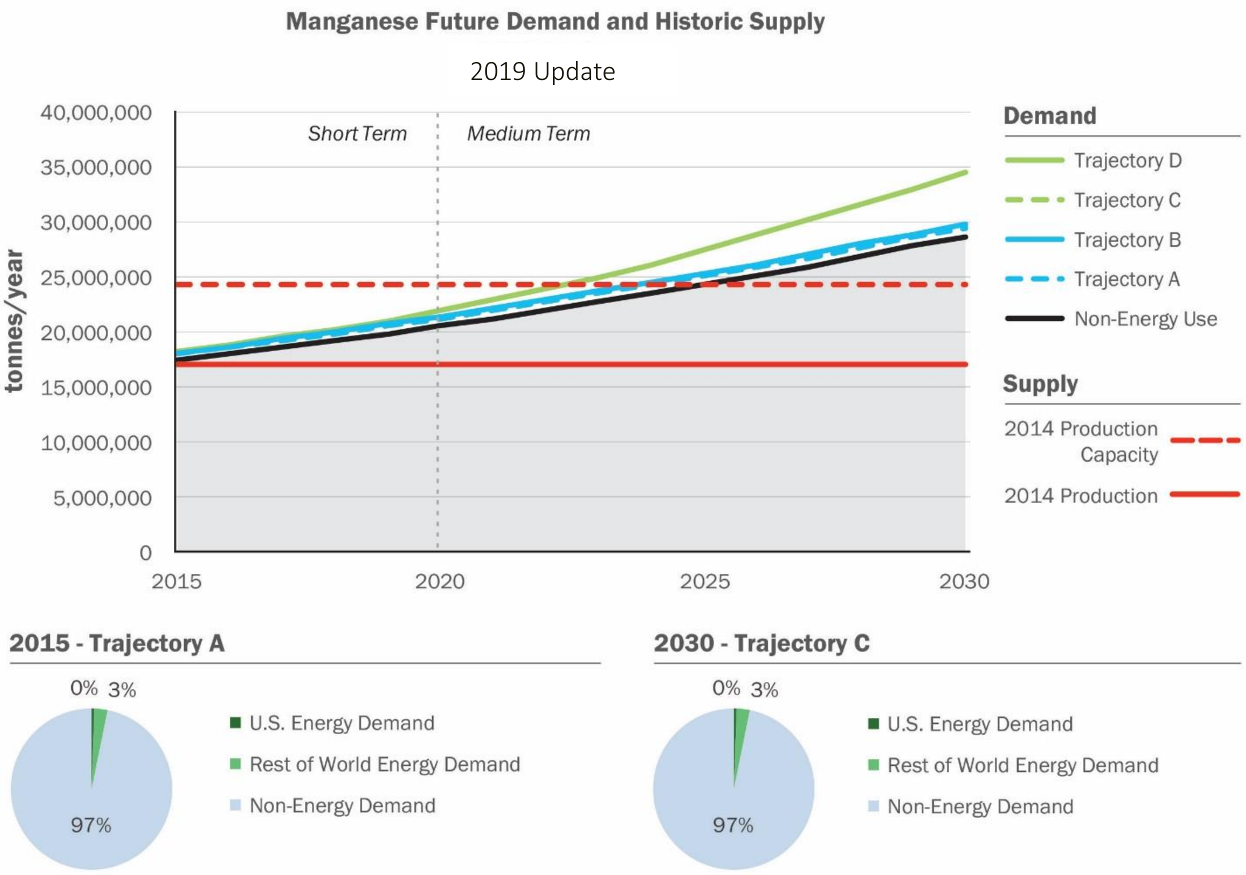

Figure 3-22. Future demand and historic supply for manganese

3.4.5 Trajectories of Future Demand for Materials in Catalytic Converters

Material use in catalytic converters drives energy demand for palladium, platinum, rhodium, and cerium.

Energy demand for palladium currently constitutes 61%–68% of total annual palladium demand, a share that could potentially decrease to 52%–65% by 2030, depending on market penetration and material intensity. Existing palladium production capacity could cover demand in the short term given current material intensities (Trajectories A and C), but any increases in material requirements for catalytic converters would require additional production capacity. All four trajectories show demand surpassing current palladium production capacity in the medium term (Figure 3-23).

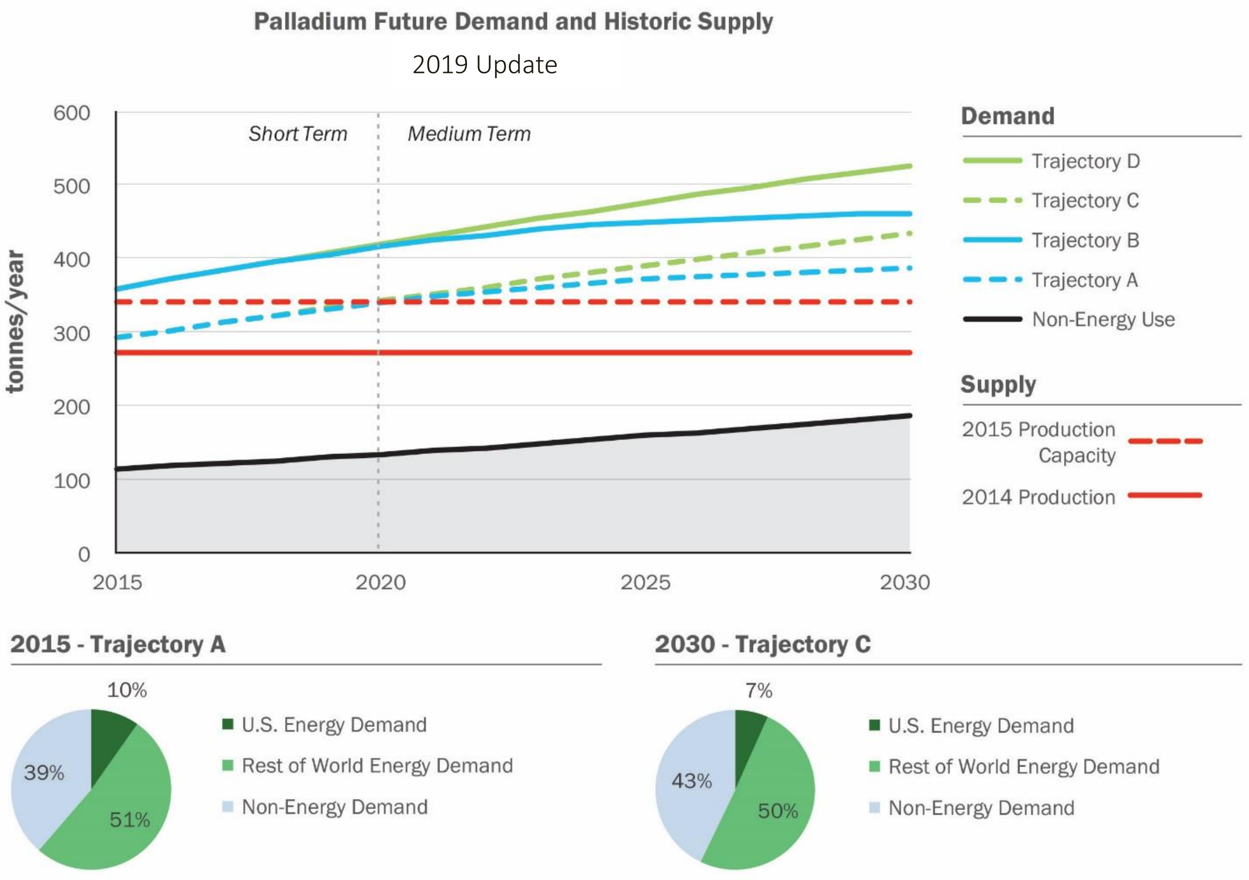

Figure 3-23. Future demand and historic supply for palladium

Energy demand for platinum currently constitutes 42%–50% of total annual platinum demand, a share that could potentially decrease to 33%–46% by 2030, depending on market penetration and material intensity. Existing platinum production capacity could cover demand in the short term under all four demand trajectories (Figure 3-24). In the medium term, any increases in material intensity (Trajectories B and D) would require additional platinum production capacity. Even with current material intensities (Trajectories A and C), additional platinum production capacity would be required by 2026–2028.

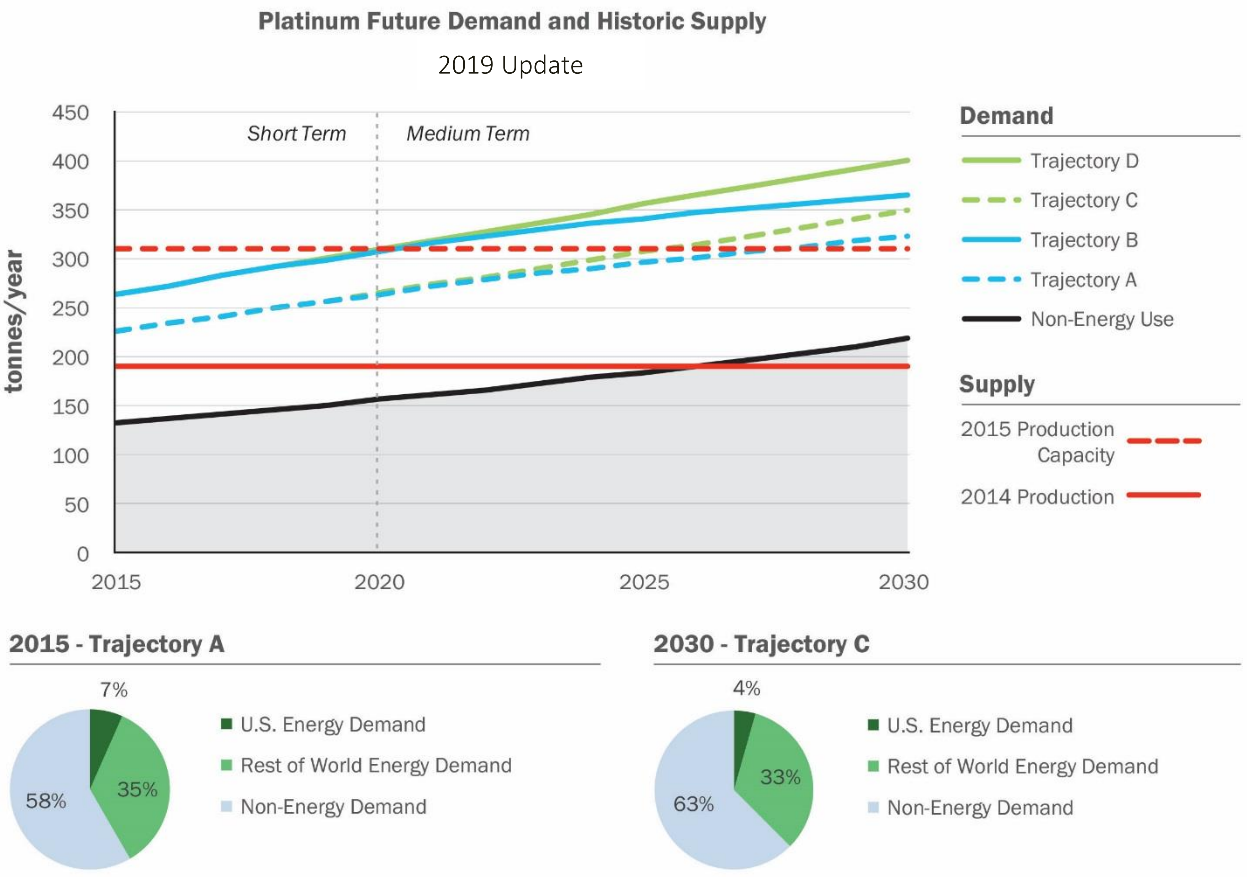

Figure 3-24. Future demand and historic supply for platinum

Energy demand for rhodium currently constitutes 76%–81% of total annual rhodium demand, a share that could potentially decrease to 68%–78% by 2030, depending on market penetration and material intensity. In recent years, total annual rhodium demand has outstripped total production as inventory holders have built up their positions in an effort to increase prices.[107] Moving forward, existing rhodium production capacity could cover demand in the short term given current material intensities (Trajectories A and C), but any increases in material requirements for catalytic converters would require additional production capacity. All four trajectories show demand surpassing current rhodium production capacity in the medium term (Figure 3-25).

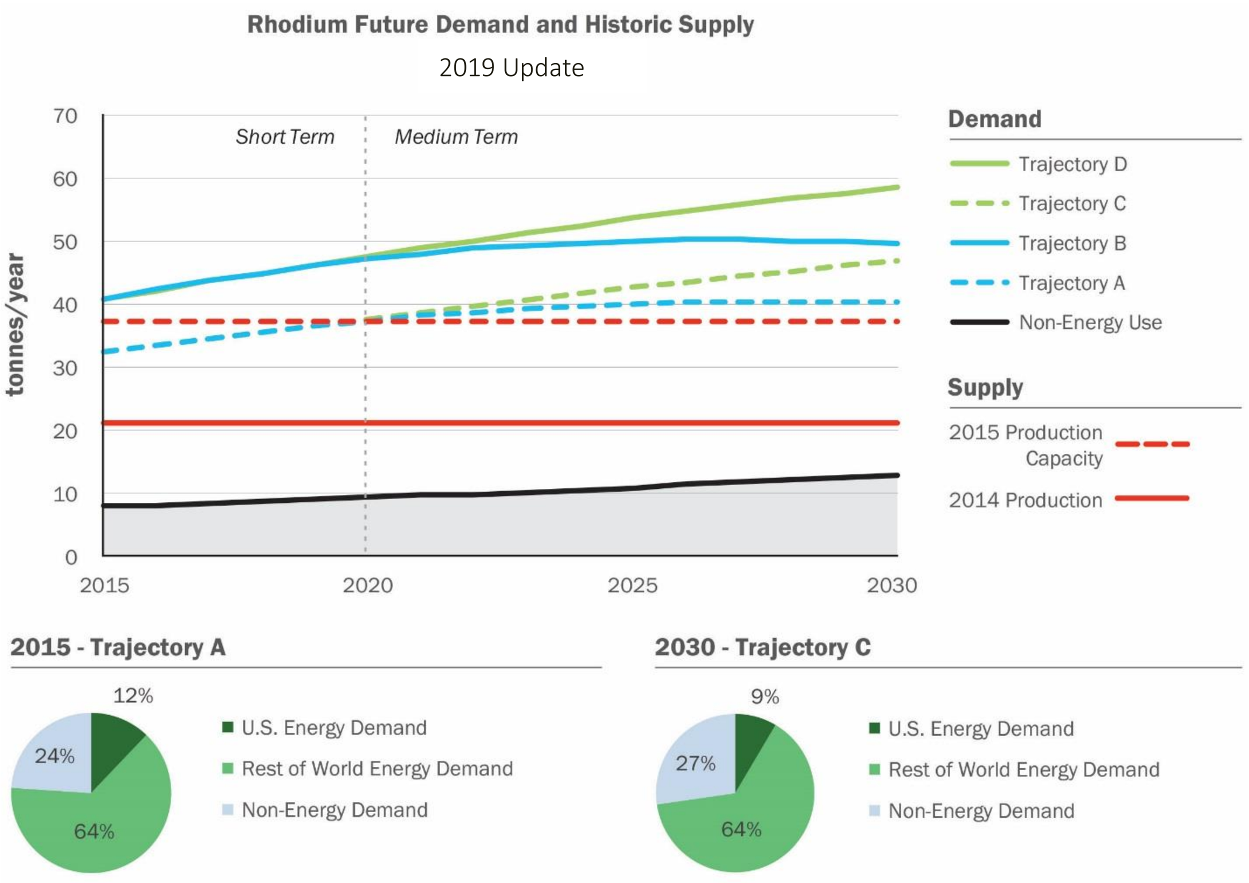

Figure 3-25. Future demand and historic supply for rhodium

Energy demand for cerium is expected to increase at the same rate as non-energy demand, maintaining a 12%–21% share of total cerium demand through 2030, depending on market penetration and material intensity of energy technologies. The nearly parallel trajectories in Figure 3-26 reveal an interesting tradeoff in cerium demand among energy technologies. In the low penetration scenario (Trajectories A and B), all of the energy demand for cerium is for catalytic converters because cerium-consuming NiMH batteries in vehicles have an assumed market share of zero. Growth in demand for catalytic converters under that scenario requires an additional 3,000–4,000 tonnes of cerium between 2015 and 2030. In the high penetration scenario (Trajectories C and D), only 1,100–1,500 tonnes of additional cerium is required by 2030 for catalytic converters because 19% fewer ICE vehicles are deployed. However, the reduction in demand growth for cerium in catalytic converters under the high penetration scenario is replaced by demand for NiMH batteries in HEVs.

Current cerium production capacity is nearly adequate to cover demand in the short term, but additional capacity may be needed to cover demand in the medium term if non-energy demand continues to increase. Recent market reports forecast a 38% increase in overall supply of rare earths between 2014 and 2020.[108] Even with this additional capacity, additional supply of cerium may be needed by 2027–2029, depending on market penetration and material intensity.

It is important to note that the demand for cerium is most likely overstated. Cerium's share of total REO consumption is assumed to be equal to the average cerium content of rare earth deposits at operational production facilities. In reality, cerium's share of a rare earths deposit is much greater than its share of consumption. Production for REOs is largely driven by demand for neodymium; however, because cerium is one of the most abundant materials in most rare earth deposits, it tends to be oversupplied.

This year's cerium demand trajectories are lower than those in the 2011 *Critical Materials Strategy* report because fewer HEVs are expected to be deployed. Current IEA deployment scenarios show PHEVs and AEVs supplanting some of the market share that had previously been expected for HEVs. Since 2011, cerium production has risen by about 22%, but much less additional capacity has come online than expected in the 2011 *Critical Materials Strategy* report.

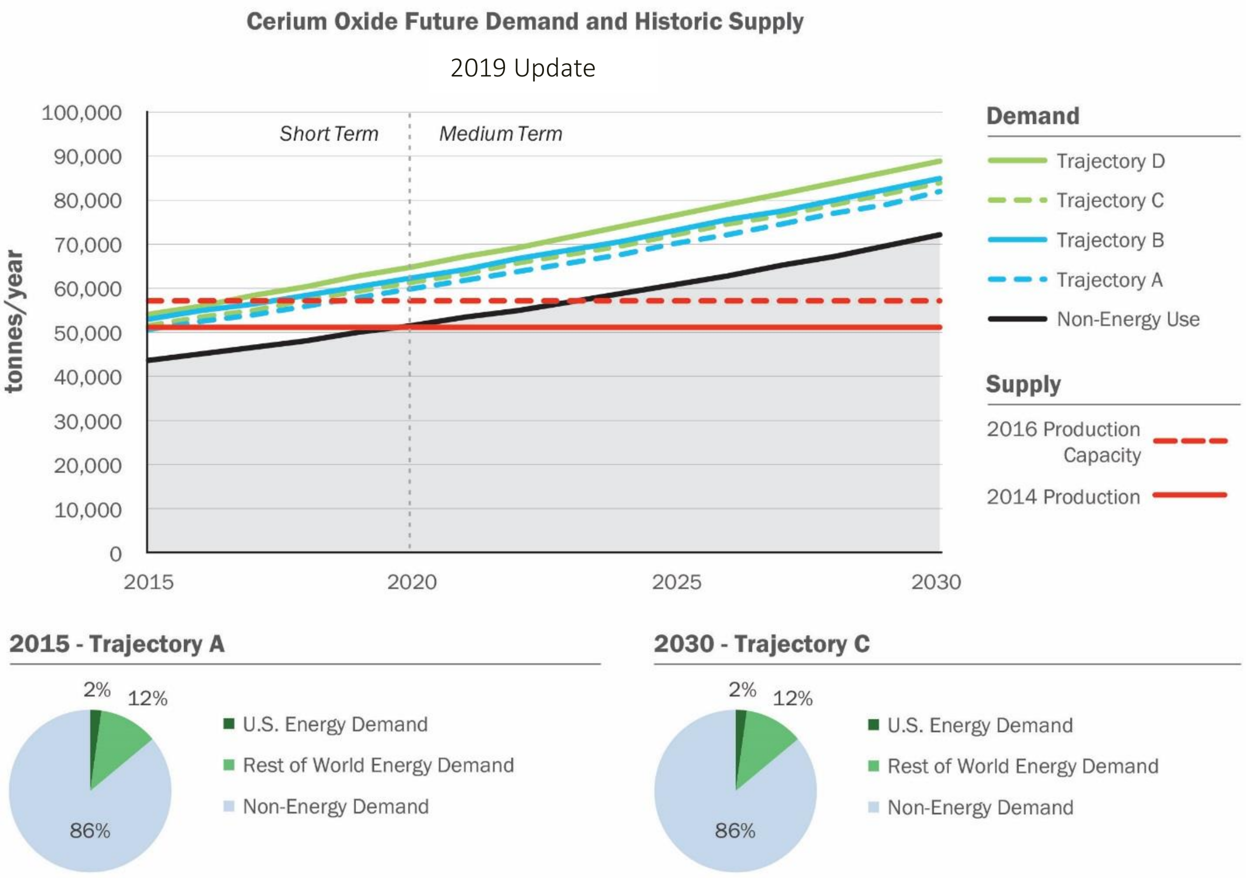

Figure 3-26. Future demand and historic supply for cerium

3.4.6 Trajectories of Future Demand for Materials in Solar PV Technologies

Material use in solar PV technologies drives energy demand for tellurium and indium. Solar PV technologies also use gallium, but energy demand for gallium is dominated by LEDs. Section 3.4.1 discusses future demand trajectories for gallium.

Figure 3-27 shows that much of the expected increase in demand for tellurium will come from non-energy applications. In the low penetration scenario (Trajectories A and B), the share of tellurium demand for solar PV technologies decreases. Even in the high penetration scenario (Trajectories C and D), the share of tellurium demand for solar PV technologies only increases slightly by 4%–7%. In the short term, current supply of tellurium seems adequate to meet demand in all cases except when high penetration rates are combined with high material intensity rates (Trajectory D). If additional supply does not come online, cadmium telluride (CdTe) solar PV manufacturers would need to significantly reduce film thickness or lose additional market share to copper-indium-gallium-selenide (CIGS) or crystalline silicon solar PVs. Additional production capacity will be needed in the medium term under all four demand trajectories if non-energy demand for tellurium continues to rise.

Although the outlook for deployment of solar PV technologies has increased since 2011, the demand trajectories for tellurium are lower than those in the 2011 *Critical Materials Strategy* report because the expected market share for CdTe has decreased. Tellurium production has stayed roughly constant since 2011, with less production capacity coming online than expected in the 2011 *Critical Materials Strategy* report.

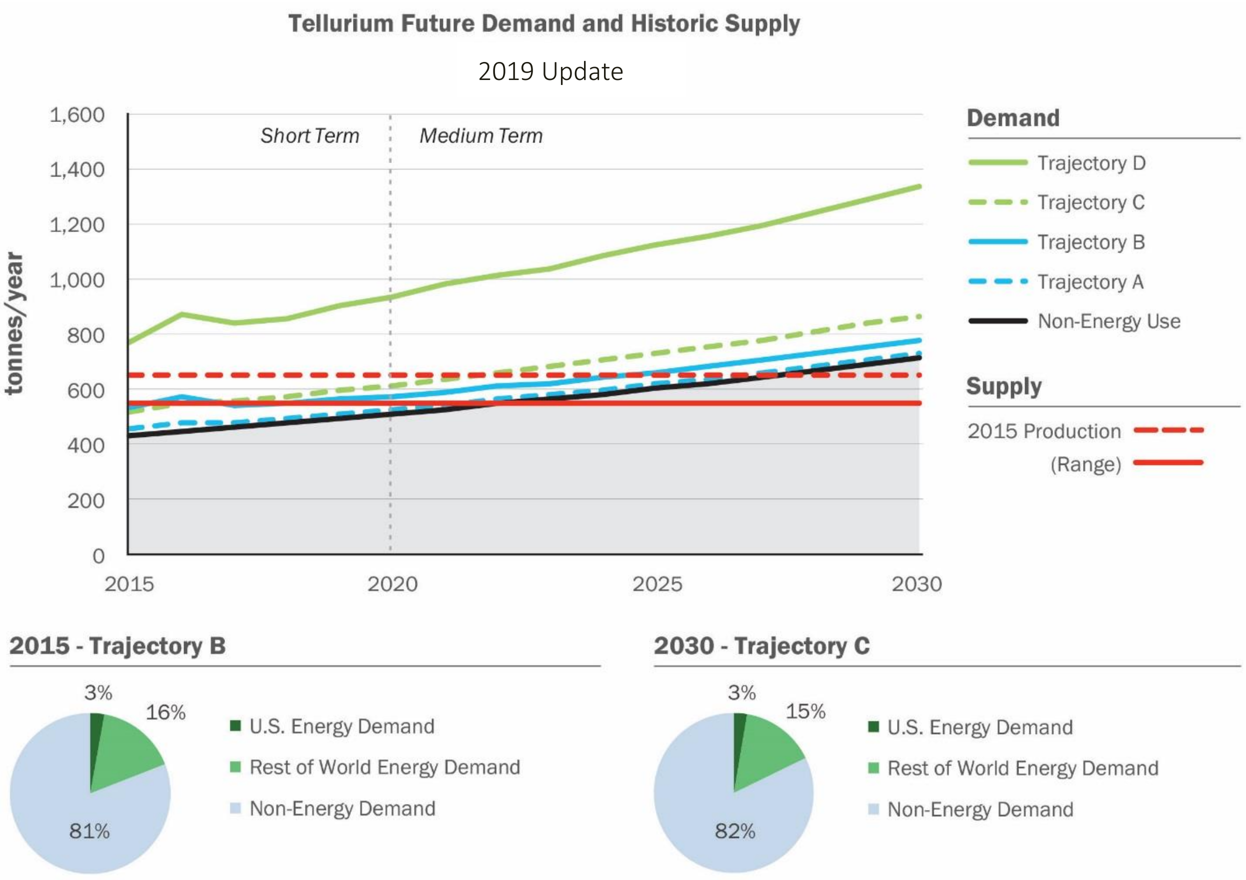

Figure 3-27. Future demand and historic supply for tellurium

Material use in solar PV technologies drives energy demand for indium, with very little required for LED technologies. However, much of the expected increase in demand for indium will come from non-energy applications (Figure 3-28). Indium production capacity is more than adequate through 2030. There is significant excess indium production capacity because recent increases in the efficiency of indium utilization in the manufacturing of flat-panel displays—the largest consumer of indium—has displaced some of the demand for primary indium.[109]

Although the outlook for deployment of solar PV technologies has increased since 2011, the demand trajectories for indium are lower than those in the 2011 *Critical Materials Strategy* report because the expected market share for CIGS has decreased. Indium production has decreased since 2011, and less production capacity has come online than expected in the 2011 *Critical Materials Strategy* report.

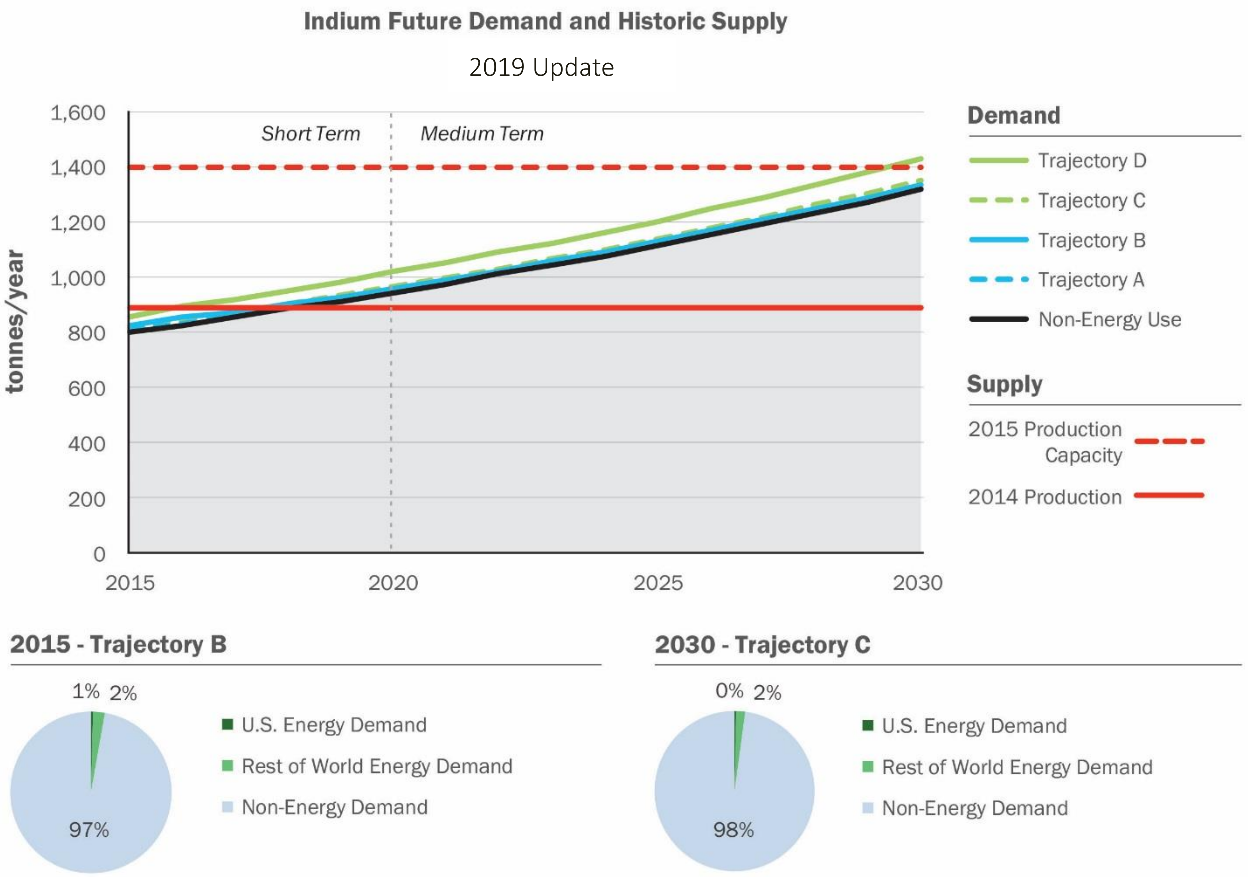

Figure 3-28. Future demand and historic supply for indium

3.5 Other Technologies and Materials to Watch

This section describes the use of key materials in energy technologies not included in the analysis because they are currently not responsible for a significant share of global material demand and their deployment is not expected to increase significantly in the short to medium term. These technologies do, however, have high growth potential in the longer term. This section also describes materials that were not examined but merit continued observation based on their supply characteristics and their potential for more widespread future use in energy technologies and other manufactured products.

3.5.1 Emerging and Notable Energy Technologies

Several energy technologies not examined in this report may contribute to key material demand in the longer term. These technologies are described below and may be considered for further analysis in future revisions to this report.

Oil and Gas Production

Innovations in hydraulic fracturing and horizontal drilling have opened up vast reservoirs of oil and gas resources, especially in the United States. According to IEA, this type of unconventional oil and gas production could increase, on average, 2.2%–3.9% annually between 2014 and 2040.[110] Hydraulic fracturing fluids contain a wide assortment of materials, including magnesium, manganese, lithium, and strontium.[111] These materials are generally found in small concentrations in hydraulic fracturing fluids; however, this may constitute a larger share of demand for these materials in the future if oil and gas production using hydraulic fracturing increases significantly.

Gas Turbines

Spurred by advances in oil and gas production technologies, low natural gas prices have driven a rapid increase in demand for natural gas-fired electricity. Natural gas turbines require a host of specialized materials and alloys to provide temperature resistance, corrosion protection, high efficiency, and long product lifetimes to components such as compressor blades, casings, exhaust systems, compressor wheels, and coatings. Examples include nickel, cobalt, molybdenum, vanadium, tantalum, and yttrium.[112] IEA expects global electrical capacity powered by natural gas to increase 1.4%–2.6% annually between 2014 and 2040, mostly due to growth in the Middle East, the European Union, and China.[113] With a relatively constant amount of expected annual capacity additions, the demand for key materials in gas turbines is unlikely to place additional strain on supply unless a more rapid expansion of natural gas-fired electricity capacity occurs.

Nuclear Power

Nuclear reactor control rods incorporate cobalt, indium, and several heavy rare earths. However, the nuclear industry's share of total annual demand for these materials is currently small, and it is not projected to grow significantly in the short to medium term. Current IEA projections show global nuclear generating capacity increasing, on average, 1.1%–2.8% annually between 2014 and 2040, led predominantly by China and India.[114]

Fuel Cells

Fuel cells are a promising energy technology for vehicle propulsion, auxiliary power, and distributed power generation. Common fuel cell chemistries for stationary applications rely on yttrium, but they may also contain lanthanum, cerium, nickel, and cobalt. Fuel cell vehicles contain PGMs. Although widespread deployment is not anticipated in the short to medium term, fuel cells are a proven technology and costs are expected to decrease, which warrants continued monitoring of developments in the fuel cells market and their material demand implications.

Advanced Electrical Components

Electrical components such as transformers, transistors, and inverters are ubiquitous in the power system. Silicon is the primary material in many electrical components; however, widespread electrification could necessitate a paradigm shift in the electrical components necessary to operate the next-generation power system. Researchers are examining germanium, gallium arsenide, and indium arsenide as possible substitutes for silicon in electrical components; however, there is a significant amount of uncertainty in the components that will be used to transform the power system, as well as the pace at which this transformation will occur. Nonetheless, the material requirements for such a radical change to the power system call for continued tracking of the trends in advanced electrical components.

3.5.2 Materials to Watch

Supply risks for several materials not covered in this report have the potential to impact the energy sector if demand for certain energy technologies and other manufactured products increases. These materials are described below and may be considered for further analysis in future revisions to this report.

Graphite

Graphite is a key material for the anodes within Li-ion batteries. Although non-energy uses such as brake linings, lubricants, and steelmaking constitute most of the demand for graphite, the expected growth in EVs could place stress on the supply of graphite. Vehicle battery manufacturers currently use a blend of natural graphite and synthetic graphite in battery anodes, but they tend to use less synthetic graphite due to the higher production costs and environmental impacts of its manufacturing process.[115] However, synthetic graphite may become increasingly desirable if expected growth in EVs places stress on natural graphite production. In 2014, China constituted 66% of the supply of graphite, followed by India (14%) and Brazil (7%) (Figure 3-29).[116] In recent years, China has closed or consolidated several graphite mines in an effort to reduce environmental and human health impacts and instituted export restrictions to support its domestic industries. [117] Natural graphite mines are under development outside of China, primarily in African countries,[118] but processing capacity resides almost exclusively in China. Producing graphite from other sources, such as carbon dioxide, is being explored.[119]

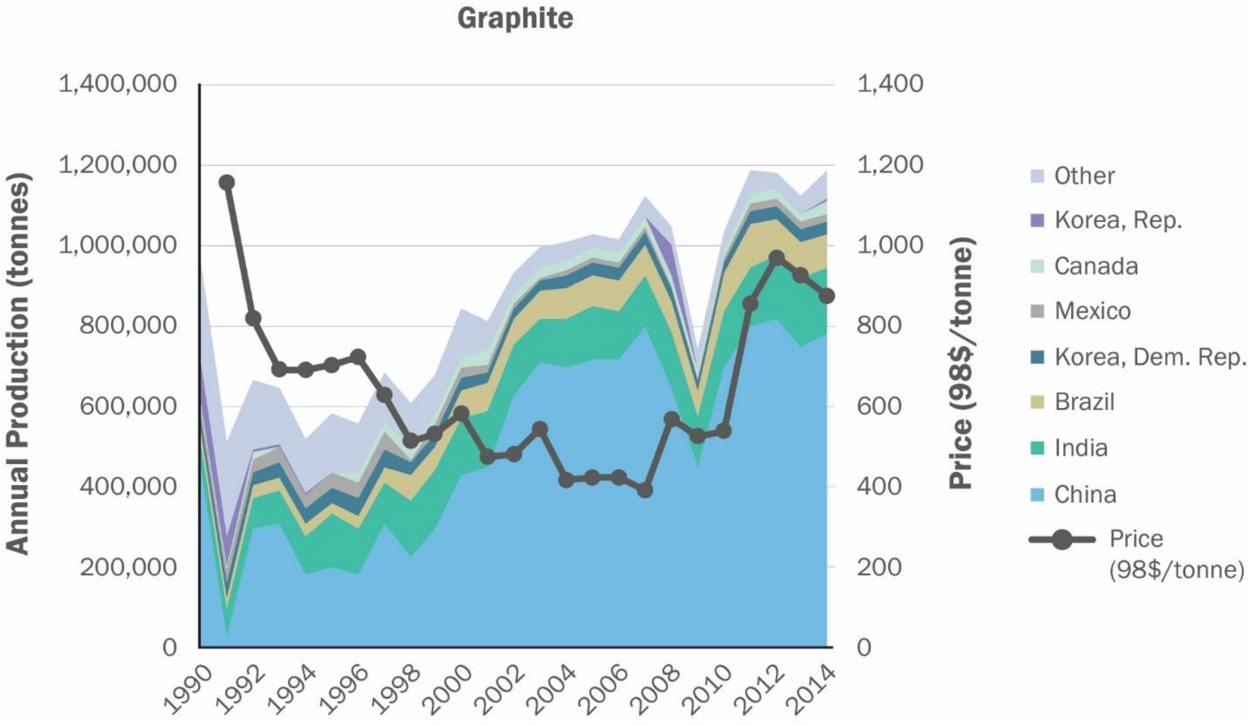

Figure 3-29. Annual global production of graphite by country and price (1990–2014)[120]

Carbon Fiber

Carbon fiber and carbon fiber reinforced polymers (CFRP) are useful in wind power, aerospace, automotive, and pressure vessel applications because of their high strength-to-weight ratio. Currently, these materials are relatively costly and only used in niche applications. However, their utilization could increase given significant research that is underway to decrease costs,[121] including a new manufacturing technology developed by Oak Ridge National Laboratory that is expected to decrease carbon fiber prices by 50%.[122] Carbon fiber and CFRP are produced by refining petroleum into precursor materials, including rayon, pitch, and polyacrylonitrile. The precursor materials are then transformed into carbon fibers or, after additional processing with special resins, into CFRP. The Institute for Advanced Composites

Manufacturing Innovation (ICAMI), an R&D consortium funded by DOE's Advanced Manufacturing Office, aims to reduce the embodied energy of CRFP manufacturing by 50%.

Antimony

The primary uses for antimony are in flame retardants and lead-acid batteries, accounting for 50% and 35% of global consumption, respectively.[123] Other smaller sources of demand include use in ceramics and glass; as chemical additive for heat stabilization and catalysis; and use in ammunition, fireworks, pigments, and electronics. Antimony is used in minute amounts across a number of energy applications, including lighting, transportation, electricity generation and storage, and power electronics. China constituted 77% of global antimony production in 2014[124] (Figure 3-30) and has a history of placing export restrictions on antimony.[125] Some secondary production of antimony occurs, primarily from recycled lead-acid batteries. While current supply is sufficient, some estimates expect demand in 2020 to be 13% higher than 2014 demand, with only a handful of other mining projects under development.[126] A recent price spike following supply disruptions in China drove manufacturers to reduce their use of antimony in flame retardants, but prices have since declined and manufacturers will likely reverse this substitution.[127]

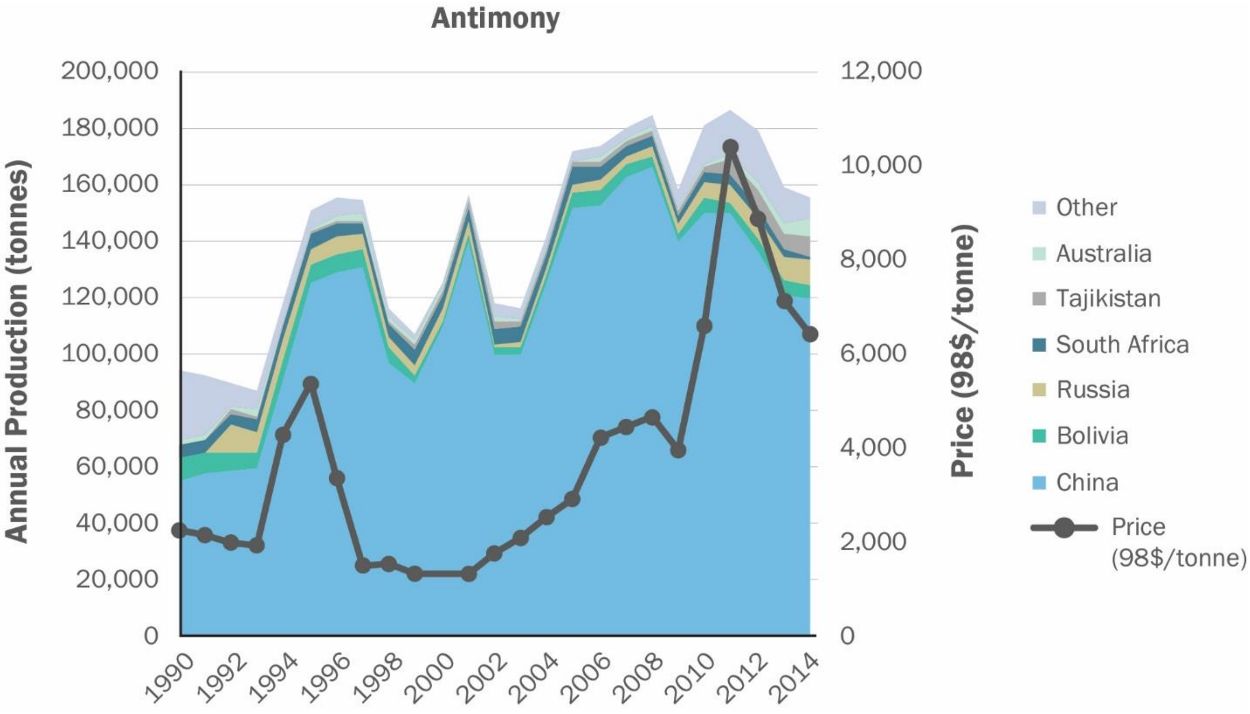

Figure 3-30. Annual global production of antimony by country and price (1990–2014)[128]

Tungsten

Tungsten is principally used as a component in cemented carbides—wear-resistant materials that are highly valued in heavy-duty industries such as oil and gas drilling and extraction, mining, construction, and manufacturing. To a lesser degree, tungsten is also used to make alloys and in components for electronic applications. China has and continues to dominate production and exports of tungsten concentrates (accounting for 82% of total world production as of 2014) (Figure 3-31), but this dominance is expected to shrink somewhat as international production improves or comes online. Demand is expected to be commensurate with growth in heavy-duty industries;[129] energy uses are not the primary driver, but higher global drilling activity over the last 10 years has generally increased consumption.

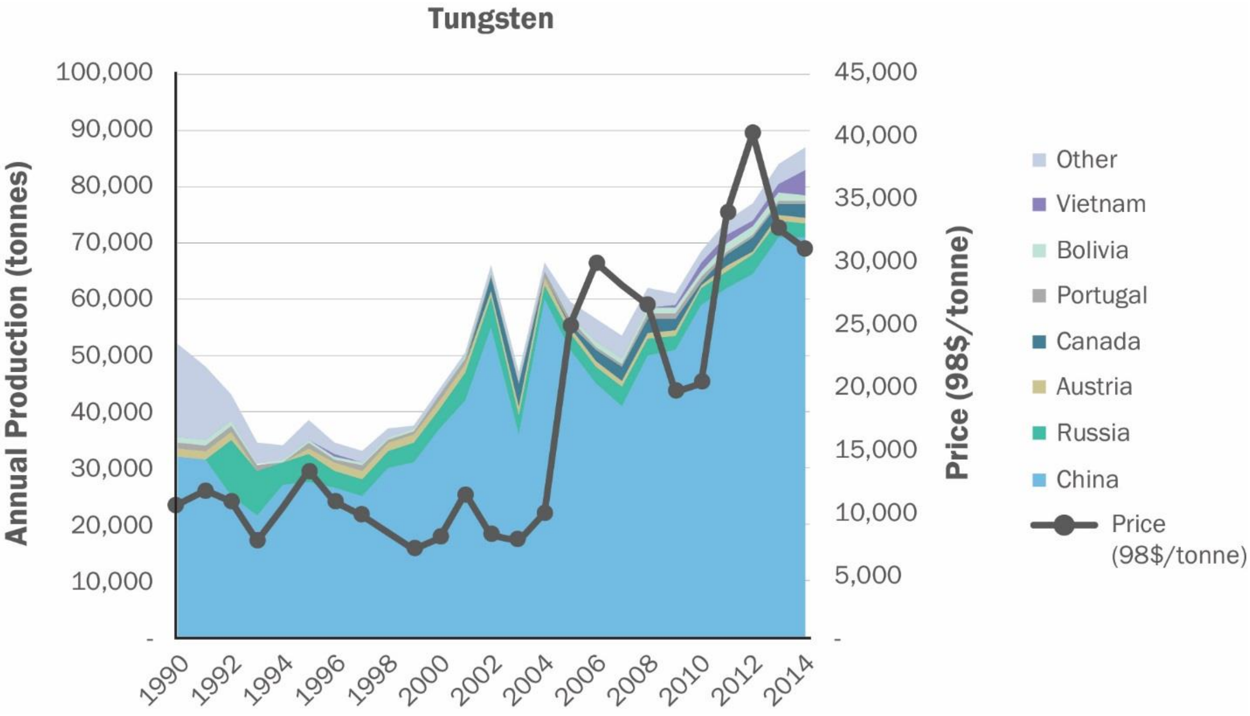

Figure 3-31. Annual global production of tungsten by country and price (1990–2014)[130]

Molybdenum

Molybdenum is a versatile and durable metal that has become increasingly important in the energy industry for lightweighting vehicles, hydrodesulfurizing fossil fuels, and manufacturing solar panels and wind turbines. Mostly used as an alloying agent in steel and cast iron, it is also employed as a catalyst. While China produces a large portion of total production, the United States is not far behind. With 10 operations producing as of 2014, [131] the United States share comprised 20% of the total (Figure 3-32). Molybdenum is also obtained from secondary production via the recycling of catalysts and steel scrap, which may provide up to 30% of supply.[132] Global demand is expected to continue to rise in coming years as the energy sectors expand and molybdenum is incorporated into other applications.[133] Molybdenum's availability and flexibility in use has made it attractive; however, it is not easily substituted in alloying applications.[134]

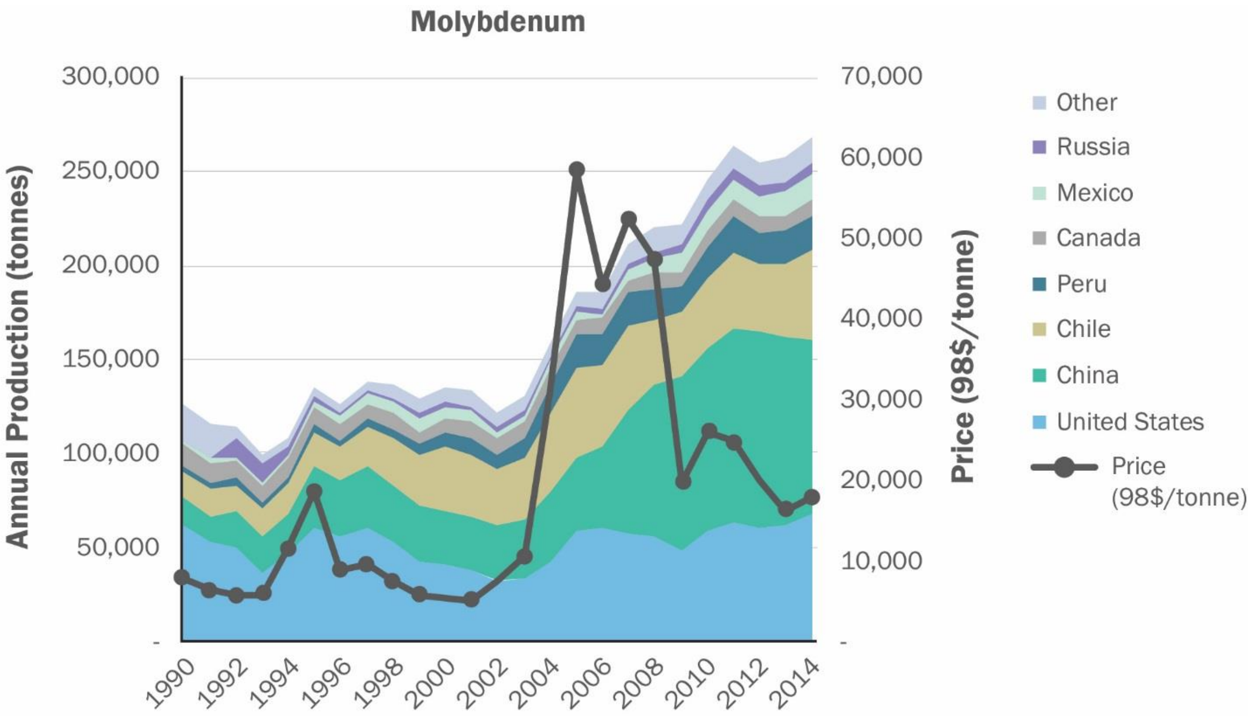

Figure 3-32. Annual global production of molybdenum by country and price (1990–2014)[135]

Germanium

Principally used in high technology applications, germanium is utilized in fiber optics, infrared optics, electronics, and solar applications. With properties similar to those of gallium, germanium is employed in energy applications as a substrate for wafers used in solar PVs and in LEDs. Similar to gallium, germanium is a by-product metal; however, it is largely recovered from zinc concentrates instead of aluminum. Germanium production is relatively concentrated.[136] China produces the vast majority of germanium and is increasingly consuming more of its domestic production as firms vertically integrate to produce germanium-containing products (an activity encouraged by the Chinese government via different policy levers). However, germanium is recyclable, and approximately 30% of germanium consumption is from secondary production.[137]

Strontium

Much of the strontium consumed in the United States is used as additive in drilling fluids for oil and natural gas wells.[138] High prices in other drilling fluid additives—such as barite—have increased the use of strontium in drilling fluids; however, in 2016, strontium imports dropped dramatically due to lower oil and gas drilling activity. Strontium is also used in ceramic ferrite magnets, pyrotechnics, master alloys, and pigment fillers.[139] The permanent ceramic ferrite magnets are used extensively in small direct current motors for automobile windshield wipers, loud speakers, and toys. Domestic production of strontium ceased in 2006. China currently accounts for the largest share of strontium production (Figure 3-33), but most domestic imports of strontium come from Mexico.

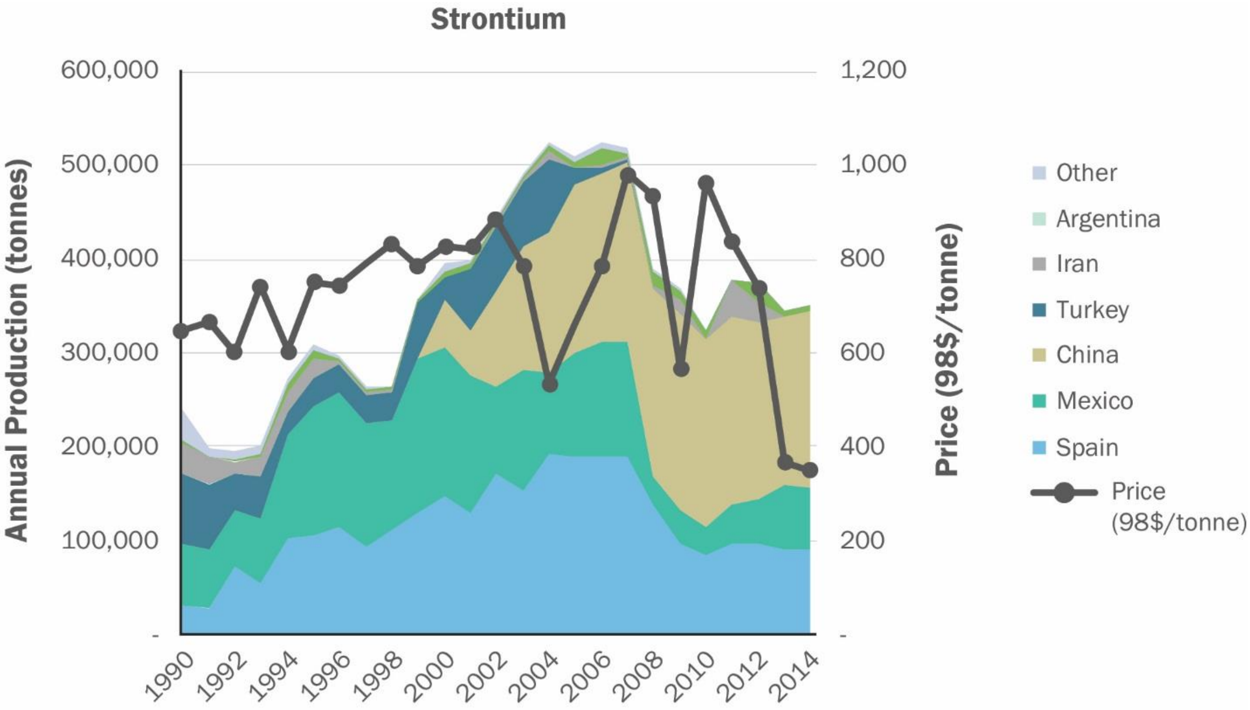

Figure 3-33. Annual global production of strontium by country and price (1990–2014)[140]

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4 Criticality Assessment

Previous chapters discuss key materials, sources of supply, and the materials' importance to energy technologies relative to other demands. This chapter summarizes short- and medium-term criticality assessments of the various key materials identified in Chapter 3 (Use of Key Materials in Energy Technologies). The assessments address two dimensions—importance to energy and supply risk. The basic premise is that rapidly increasing demand for key materials could hamper energy technology manufacturing by outpacing new production and causing supply-demand mismatches. Appendix A (Criticality Assessments by Material) presents detailed material-by-material assessments.

4.1 Assessment Methodology

The basic methodology used to assess the criticality of materials in this report is the same as was used in both the 2010 and 2011 *Critical Materials Strategy* reports, which adapted a methodology developed by the National Academy of Sciences (NAS).[1] The NAS methodology assesses the criticality of individual minerals along two dimensions: impact of supply disruption and supply risk. These two dimensions are rated on a scale from one to four and presented on a matrix to illustrate the relative criticality of individual minerals. According to this scheme, the upper right-hand corner of the matrix represents the highest criticality.

The NAS methodology has been adapted to address particular concerns for energy technologies. First, "impact of supply disruption" was reoriented to become "importance to energy." Second, factors used to characterize "supply risk" were adjusted. Third, assessments were completed for both short- and medium-term criticality, as these two time horizons have different supply and demand profiles and different policy response options. Here, short term is 2015–2020 and medium term is 2020–2030. Analogous to the NAS methodology, the two-dimensional criticality ratings are plotted on a matrix to enable comparison across materials for both the short and medium terms. The matrices inform a comparison among materials that can feed into prioritized research and development investment and policy attention. Each matrix has three regions: critical (red), near critical (yellow), and not critical (green).

It is important to keep in mind that these are qualitative assessments informed by quantitative analyses. While there is uncertainty in many of the factors examined, particularly in the medium term, the collection of assessments is valuable to inform policy priorities and research and development investment. It will be important to revisit the analyses moving forward as more data become available and as material supply and demand change.

Short- and medium-term scores for importance to energy are based on a weighted average of two factors. Short- and medium-term scores for supply risk are based on a weighted average of five factors. For each factor, key materials are assigned qualitative scores of one (least critical) to four (most critical). The factors are described in more detail below.

Importance to Energy

Importance to energy encompasses two factors for each material over the short and medium terms. The weighting factor for each attribute is shown in parentheses.

- **Energy Demand (75%):** Captures the importance of the material in magnets, batteries, solar photovoltaic (PV) coatings, LEDs, lightweighting, and catalytic converters used in energy technologies.
- **Substitutability Limitations (25%):** Addresses constraints on practically substituting for the material and technology within energy technologies. Substitution could occur at any level of the supply chain. This may include using different raw materials, components, or even end-use technologies. This includes substitution by material, such as praseodymium for neodymium in magnets, as well as component technology-based substitutions, such as induction motors for permanent magnet motors.

Supply Risk

The overall supply risk for each material is based on five factors of risk for the short and medium terms. For each factor, key materials are assigned qualitative scores of one (least critical) to four (most critical). The factors are described in more detail below.

- **Basic Availability (40%):** The extent to which global supply will be able to meet demand. Short-term basic availability examines current production relative to demand. Medium-term basic availability examines the potential for increased capacity utilization relative to anticipated increases in demand. The qualitative score is informed by the projections in Chapter 3 (Use of Key Materials in Energy Technologies), but it may also take into account other factors, such as global reserves, mines projected to come online in the near future, and additional supplies from recycling.
- **Competing Technology Demand (10%):** Whether non-energy-sector demand is expected to grow rapidly, thus constraining the supply of the material available to the energy sector.
- **Political, Regulatory, and Social Factors (20%):** Risk associated with political, social, and regulatory factors within major producer countries. This includes the risk that political instability in a country will threaten mining and processing projects; that countries will impose export quotas or other restrictions; or that social pressures or permitting or regulatory processes will threaten sources of new or existing production.
- **Codependence on Other Markets (10%):** Instances when a material is a coproduct or by-product of producing or refining other materials. Codependence can be an advantage or a disadvantage, depending on which material is driving production levels. In general, coproducts with lower revenue streams (*i.e.*, production rate multiplied by price) will have higher scores because they are less likely to drive production than coproducts with higher revenue.
- **Producer Diversity (20%):** Market risks due to the lack of diversity in producing countries or companies (*e.g.*, monopoly or oligopoly).

4.2 Identification of Critical Materials

Figure 4-1 and Figure 4-2 plot criticality ratings for the key materials in the short and medium terms, respectively. Appendix A (Criticality Assessments by Material) provides more detailed assessments. Note that, in general, the criticality of some materials changes over time due to anticipated market response and the emergence of viable substitutes or a dramatic ramp up in demand for the materials.

Figure 4-1 and Figure 4-2 suggest three broad categories of criticality. Materials in the upper quadrant of the matrix—with scores of three or higher on both axes—are characterized as critical. Materials with a score of three or higher on one axis but a two on the other axis are characterized as near critical. While they are not currently judged to be critical, small changes in one or more of the underlying factors could put them at criticality. All other materials are judged to be not critical. However, all of the assessments are based on the best available information, so even materials judged not critical could be at risk due to significant unforeseen circumstances.

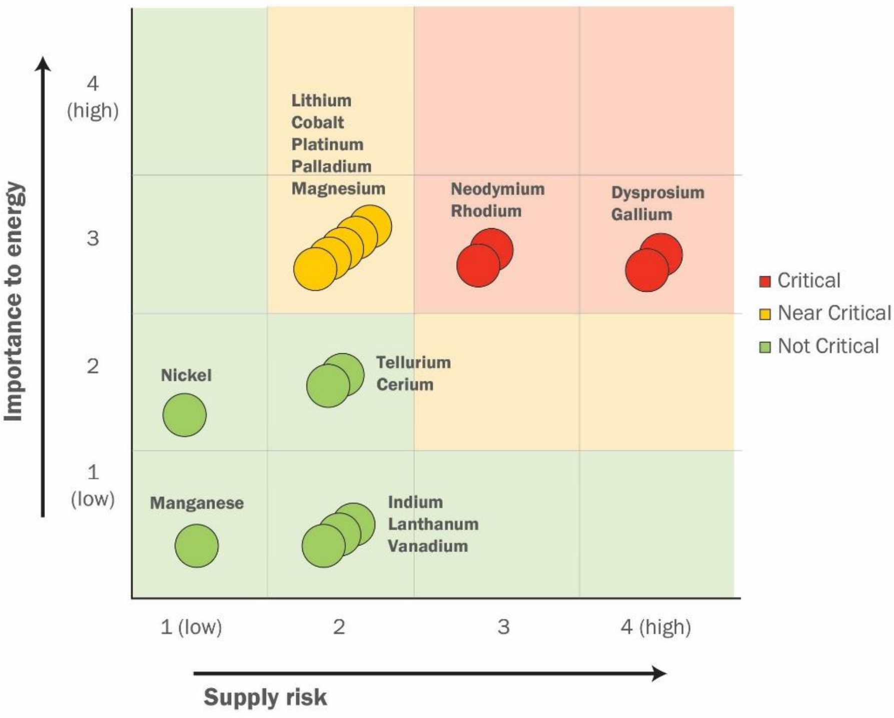

Figure 4-1. Short-term (2015–2020) criticality matrix

Figure 4-2. Medium-term (2020–2030) criticality matrix

According to the analysis, dysprosium, neodymium, gallium, and rhodium are critical in the short term. The uses for these critical materials are spread across magnets, batteries, LEDs, solar PV coatings, and catalytic converters. Cobalt, lithium, magnesium, palladium, and platinum are near critical. Cerium, lanthanum, manganese, nickel, tellurium, and vanadium are not critical. Between the short term and medium term, the importance to energy and supply risk scores shift for some materials (Figure 4-3). For example, importance to energy scores for neodymium, dysprosium, gallium, and nickel increase, while the importance to energy scores for palladium and platinum decrease. In addition, supply risk scores for rhodium and palladium increase, while the supply risk score for gallium decreases. Both factors—importance to energy and supply risk—increase for lithium, cobalt, and magnesium, moving them from the near-critical category in the short term into the critical category in the medium term. All other key materials either remain in the same category or become less critical from the short term to medium term.

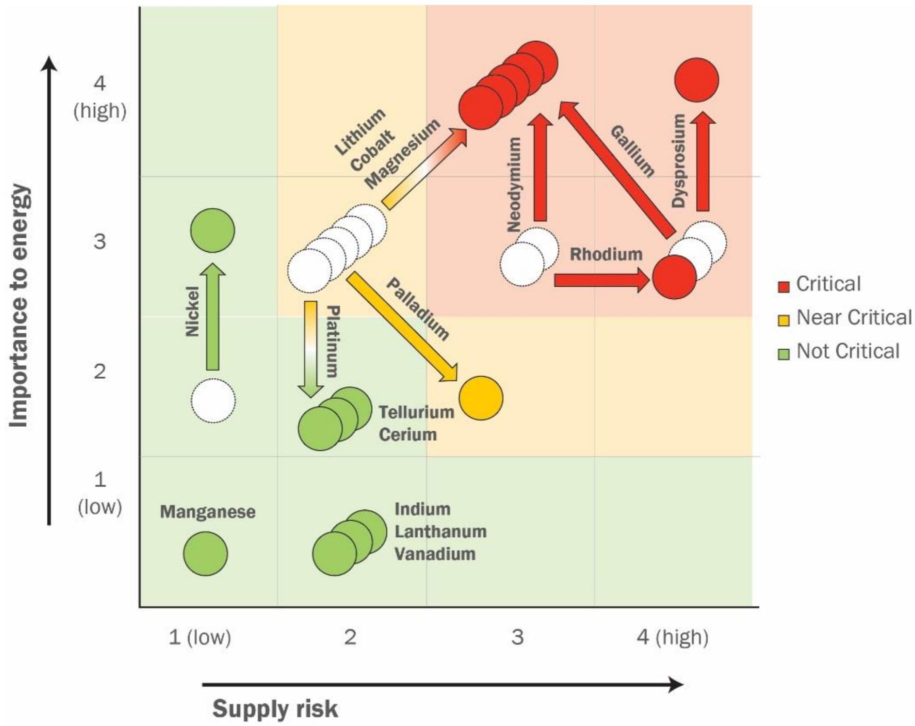

Figure 4-3. Criticality movement between the short term (2015–2020) and medium term (2020–2030)

Market dynamics along the entire supply chain for energy technologies—as described in Chapter 2 (Criticality in the Context of Global Dynamic Supply Chains and Implications for the U.S. Economy) and Chapter 3 (Use of Key Materials in Energy Technologies)—will play a large role in criticality changes. This is clearly demonstrated when examining how the criticality assessment for some materials has changed between the 2011 *Critical Materials Strategy* report and this 2019 *Critical Materials Strategy* report.

Examining shifts in criticality between the 2011 *Critical Materials Strategy* report and this 2019 *Critical Materials Strategy* report for a similar time period reveals how changes in the markets for these materials and the relevant energy technologies can change the outlook for criticality. Figure 4-4 illustrates the shift in criticality ratings from the 2011 *Critical Materials Strategy* report in the medium term (2015–2025) to this 2019 *Critical Materials Strategy* report in the short term (2015–2020). Solid circles represent the criticality ratings in this 2019 *Critical Materials Strategy* report. Dotted circles represent the criticality ratings in the 2011 *Critical Materials Strategy* report for those materials that shifted. Circles marked with an 'X' represent materials that were assessed in the 2011 *Critical Materials Strategy* report but not assessed in this 2019 *Critical Materials Strategy* report. Arrows are used to show the movement of the assessments.

The importance to energy scores for neodymium and dysprosium both decreased as material and component-level substitution has taken hold in wind turbine and electric vehicle technologies. In addition, increased favorability for lithium-ion batteries that require cobalt as opposed to lanthanum-consuming nickel metal hydride batteries in electric vehicles has driven an increase in the importance to energy score for cobalt and a decrease in the importance to energy score for lanthanum. Similarly, increased favorability for crystalline silicon solar PVs as opposed to tellurium- and indium-consuming thin-film solar PV technologies has reduced the importance to energy scores for tellurium and indium. Finally, the rapid shift in lighting technologies from fluorescents to LEDs resulted in the removal of three previously critical materials—yttrium, europium, and terbium—from the assessment altogether because LEDs consume significantly less of these materials. However, this same shift has led to an increase in the importance to energy score for gallium because of its use in LEDs. Not many changes occurred in supply risk scores, reflecting the relatively slow pace at which material supply tends to respond to market conditions. A notable exception is the supply risk score for gallium, which has increased mostly due to the significant increase in supply concentration in China.

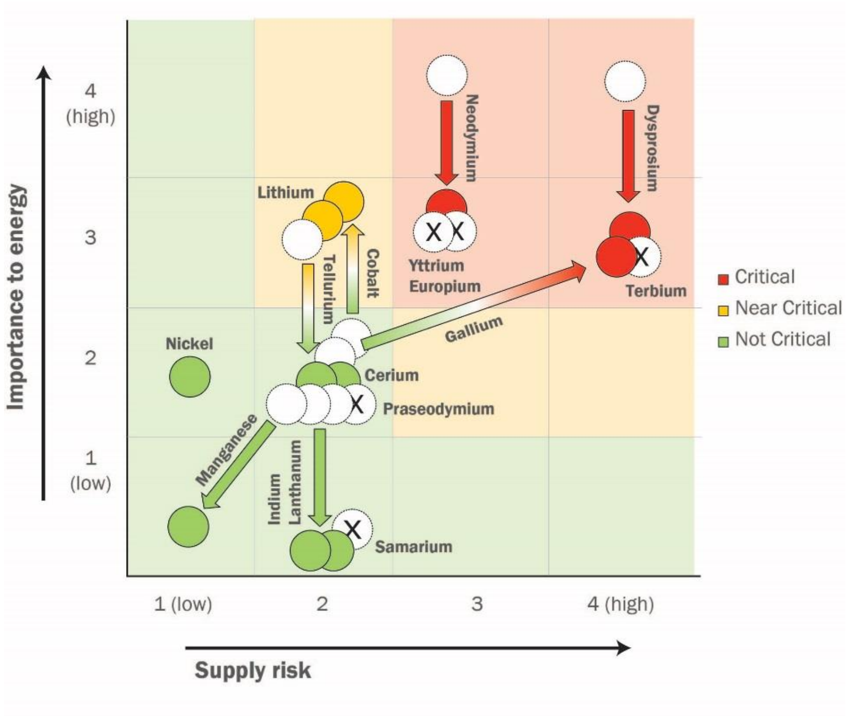

Figure 4-4. Criticality movement between 2019 *Critical Materials Strategy* report short-term (2015–2020) and 2011 *Critical Materials Strategy* report medium-term (2015–2025)

Examining shifts in medium-term criticality between the 2011 *Critical Materials Strategy* report and this 2019 *Critical Materials Strategy* report can inform ongoing efforts by the U.S. Department of Energy and others in terms of which materials and energy technologies to target. It can also suggest a shift in focus between supply-side and demand-side strategies. Figure 4-5 illustrates the shift in criticality ratings from the 2011 *Critical Materials Strategy* report in the medium term (2015–2025) to this 2019 *Critical Materials Strategy* report in the medium term (2020–2030). Solid circles represent the criticality ratings in this 2019 *Critical Materials Strategy* report. Dotted circles represent the criticality ratings in the 2011 *Critical Materials Strategy* report for those materials that shifted. Circles marked with an 'X' represent materials that were assessed in the 2011 *Critical Materials Strategy* report, but not assessed in this 2019 *Critical Materials Strategy* report. Arrows are used to show the movement of the assessments.

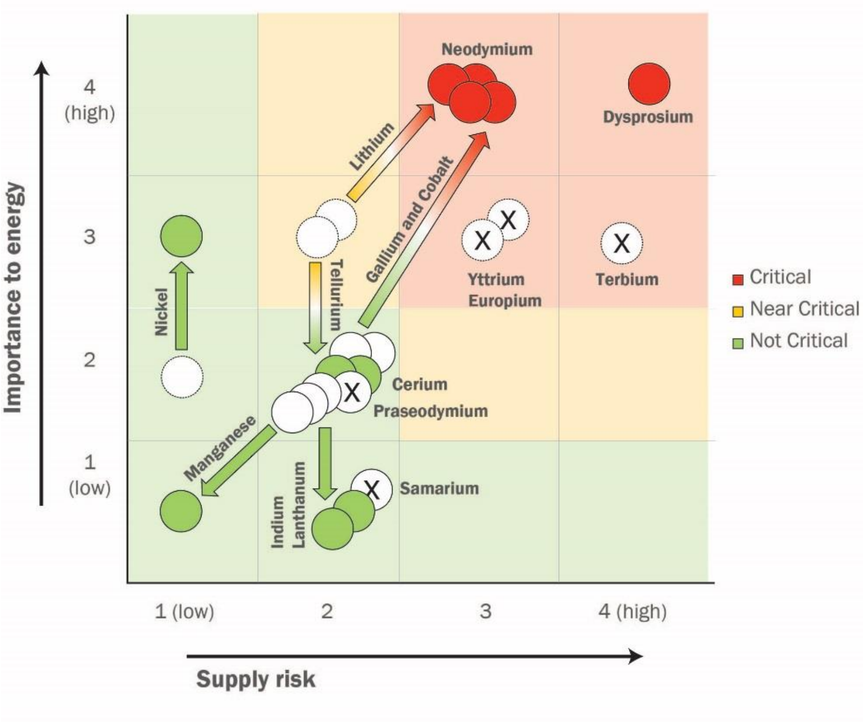

Figure 4-5. Criticality movement between 2019 *Critical Materials Strategy* report medium-term (2020–2030) and 2011 *Critical Materials Strategy* report medium-term (2015–2025)

The importance to energy score and the supply risk score both increased for lithium, cobalt, and gallium. These changes have shifted the criticality outlook for lithium from near critical to critical and for cobalt and gallium from not critical to critical. This suggests that increased attention is warranted for the supply risks of these materials and the energy technologies that may account for a significant share of demand: electric vehicle batteries and LEDs. Tellurium was assessed to be near critical in the 2011 *Critical Materials Strategy* report, but is now considered not critical due to its decreased importance to energy. This is driven by reductions in expected market share for tellurium-consuming thin-film solar PVs. Neodymium and dysprosium used in electric vehicles and wind turbines remain critical and warrant continued attention. Finally, three rare earths used in lighting phosphors (yttrium, europium, and terbium) were deemed critical in the 2011 *Critical Materials Strategy* report, but are no longer considered critical because of a significant decrease in their importance to energy. This is driven by reductions in expected deployment of the type of efficient lighting requiring these materials (*i.e.*, fluorescent lamps).

4.3 Endnotes

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5 Next Steps

The previous chapters examined risks and constraints across energy technology supply chains that have important implications for the U.S. economy and national security. This chapter draws conclusions from the previous chapters, identifies potential opportunities, and discusses potential program and policy directions. There is an opportunity to pursue approaches that can help energy supply chains incorporate innovative technologies and processes to leapfrog over vulnerabilities relating to material supply risk while accommodating and adapting to changes in the global economy.

Since 2011, the U.S. Department of Energy (DOE) has made significant investments in research and development (R&D) to address 1) supply diversification, 2) substitutes, and 3) recycling and efficient use. Important progress has been made, yet significant work remains to be done. Along with R&D, DOE can help address barriers for domestic production, emphasizing non-traditional resources. Mineral production and domestic manufacturing are shaped by global markets and a tableau of domestic and international policies, including trade, intellectual property, material production, and manufacturing policies. Education and workforce training are critical to growth and leadership in material production and manufacturing. Finally, understanding the material and technology flows, supply, and demand are important to informing criticality assessments. Further data improvements will help strengthen our understanding of global market dynamics.

Figure 5-1 brings together multiple key points: risks and constraints across the supply chain discussed throughout this report, opportunities that lie ahead, and DOE and federal government program and policy directions that can enable the United States to seize the identified opportunities. DOE's authorities and historic capabilities with respect to these categories vary widely. Some—such as R&D—relate to DOE's core competencies. Others—such as permitting for domestic production—concern topics on which DOE has little or no jurisdiction, underscoring the value of cross-agency coordination. These program and policy directions align with the Administration's 2017 *National Security Strategy of the United States of America*.

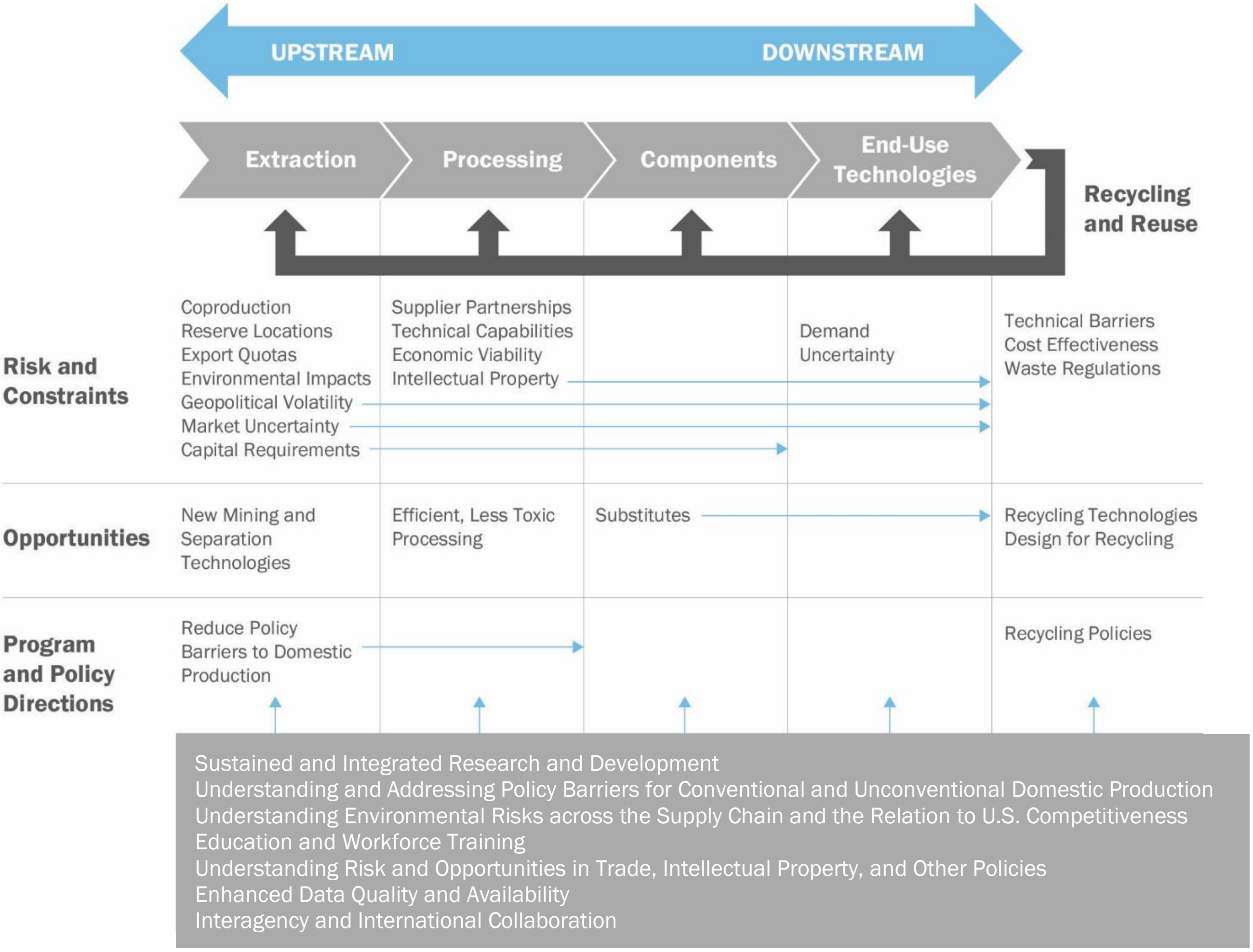

Figure 5-1. Policy and program directions in the critical materials supply chain

5.1 Sustained and Integrated Research and Development

Following the DOE *Critical Materials Strategy* reports of 2010 and 2011, DOE invested nearly $400 million in research underlying three pillars:[a] 1) achieving globally diverse supplies; 2) identifying appropriate substitutes; and 3) improving capacity for recycling, reuse, and more efficient use. DOE's research has yielded a number of significant advances in both the science and technology related to the three pillars. These investments and achievements play an important role in enlarging the range of options available to markets responding to material constraints. The analysis in this report identifies areas for additional work.

Producing material from unconventional sources can help achieve globally diversified supply, but it historically has proven to be technically difficult and less economical than conventional sources. DOE R&D has made progress on both fronts. DOE organizations have contributed significantly to the

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[a] Cumulative Funding Since 2011: Critical Materials Institute: $190 million; Office of Fossil Energy/National Energy Technology Laboratory: $75 million; Advanced Research Projects Agency-Energy: $30 million; Office of Science: $150 million.

advances in supply diversification efforts, yielding new extraction methods and identifying economically viable, nontraditional sources for production of rare earths. For example, as part of work funded by the Office of Fossil Energy and National Energy Technology Laboratory, researchers at the University of Kentucky have created a process that has produced small quantities of materials that are 80% rare earth elements and more than 98% rare earth oxides from coal. The process is set to be scaled up to a small pilot-scale facility. Likewise, at West Virginia University, researchers have been able to recover nearly 100% of rare earth elements from acid mine drainage, and they are currently assessing the economic feasibility at a regional scale with a similar end objective of developing and operating a bench-scale facility.

DOE has also developed new methods for efficient use of materials, which have since been commercialized. For example, Momentum Technologies—a small U.S. startup—licensed patents from both the Critical Materials Institute (CMI) and Oak Ridge National Laboratory, both to recycle rare earths from hard disk drives and to produce 3D-printed rare-earth magnets from recycled materials. The commercialization of these innovations represents new options in source flexibility in early stages of the supply chain. Similarly¸ CMI partnered with Rio Tinto—a metals and mining company with an existing copper mine in Utah—to explore opportunities to recover by-product minerals (*e.g.*, platinum group metals and rare earths) from existing operations. The joint project leverages CMI research in relevant areas and Rio Tinto's expertise in mining and smelting. Another CMI project also targeted the supply side by evaluating phosphate tailings as an alternative source for rare earths.

Identifying substitutes can help reduce the need for materials. Under ARPA-E's REACT (Rare Earth Alternatives in Critical Technologies) program, researchers at Northeast University developed iron-nickel alloys to replace neodymium and dysprosium. Similarly, in 2016, researchers out of Los Alamos National Laboratory, Oak Ridge National Laboratory, and the University of Minnesota invented a permanent magnet made of iron and nitrogen. In addition to these efforts, recent advances in computer science and programming have expanded the universe of material substitutes and can help accelerate moving from discovery to deployment. CMI has invented two new phosphors aimed at reducing the demand for rare earths using advanced theory, computational power, expert insights, and other approaches from the Materials Genome Initiative.

To establish a foundation for future energy technologies, the Office of Science supports fundamental research to advance understanding of the role that critical materials play in the determination of the properties of materials at length scales ranging from electronic interaction distances to atomic and microstructural scales. This research includes the development of novel synthesis techniques that control properties at the atomic level to develop unique capabilities for the preparation, purification, processing, and fabrication of well-characterized materials. The Office of Science also supports the development, validation, and application of models to theoretically and computationally identify compounds that are promising critical material substitutes. This research includes projects aimed at identifying replacements for rare earths in electronic and magnetic applications as well as alternatives to materials such as lithium and cobalt in batteries, and platinum in catalytic reactions.

Looking forward, DOE and partners can build on the strong foundations created over the last 8 years, continuing to invest in and support R&D that leads to material substitutes in components (*e.g.*, magnets, batteries), process innovations for recycling and more efficient material use, and increased production from unconventional sources. As previously mentioned, investment into the three pillars for rare earths identified as critical in the 2011 *Critical Materials Strategy* report have made significant strides. It is essential to sustain this effort for dysprosium and neodymium, which continue to be critical in the short and medium term. Moving forward, focus can expand to emerging critical materials like gallium, magnesium, rhodium, lithium, and cobalt, as well as concentrating on portions of the supply chain that are currently less responsive to market signals. In particular, DOE and partners can encourage research that bolsters the options available to the supply side of materials; specifically, separation and processing of by-product minerals, as well as exploring extraction and economic viability of other unconventional resources.

5.2 Understanding and Addressing Policy Barriers for Conventional and Unconventional Domestic Production

Addressing permitting and other policy barriers can help both conventional and unconventional production in the United States. The United States is endowed with high-quality natural resources. Until 1990, the United States was the world's largest producer of metallic and industrial minerals; however, as world production increased, U.S. production remained flat. This has implications for national security and the economy, which has led the Administration to prioritize ensuring secure and reliable supplies of critical materials. Developing robust supply chains for important energy technologies has long been a U.S. goal that can be supported both through traditional mining and increasing domestic production from unconventional resources.

Despite its promise, production from unconventional sources was slow to respond during the 2011 commodities price spike; this lack of response is mainly attributed to technical barriers, but policy barriers may have also played a role. Policies that influence unconventional production are not well understood. Examples of federal policies that potentially impact unconventional production include regulations governing radioactive materials; coal regulations that influence minor metals from coal/coal by-products; the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation, and Liability Act; water discharge permitting under the Clean Water Act; and permitting for recyclers (*e.g.*, lead-acid battery recyclers). Policies may be federal or at the state level, which may further complicate compliance. It would be valuable to better understand the suite of policies that affect unconventional domestic production and how they may impact new technology deployment.

5.3 Understanding Environmental Risks across the Supply Chain and the Relation to U.S. Competitiveness

The U.S. has strong environmental protections relative to some competing manufacturing and producing countries. This can mean that relatively lax environmental and health protections can contribute to lower production costs for some producing countries. Thus, global standards of environmental protection can be a competitiveness issue, as well as and environmental stewardship issue.

5.4 Education and Workforce Training

In addition to robust investment in R&D, leadership in energy technologies and the mineral resources that underlie and enable performance requires a sufficiently educated and populated workforce, both across the supply chain and from early-stage R&D to commercialization. This includes miners and mining engineers; machinists, mechanics, and electricians; mechanical and electrical engineers; and technical product managers. Areas of academic importance include material science, chemistry, engineering, and physics, as well as specific focal areas such as mineral and mining engineering, mineral economics, manufacturing engineering, and computer science. As market volatility can affect the workforce across energy supply chains, it is valuable for education and training to also support and strengthen job flexibility and resilience among workers.

However, echoing efforts to bolster dynamic product supply chains, supportive actions related to education and training may benefit from increased cognizance of workforce dynamics across the supply chain. For example, price volatility not only affects the status of mines; it also affects human capital. While mines can be placed on care and maintenance when prices are depressed, workers are often laid off. Similarly, there can be a significant lag between price spikes and the available supply of workers. Further, education is not necessarily a substitute for experience, emphasizing that sustaining the workforce may be important. Hence, in looking forward, workforce development efforts can be informed by attention to both the short-term and long-term needs of the economy generally, but also to the specific tiers of energy technology supply chains.

Ultimately, coordinated and sustained investment into education and training in the broader ecosystem of energy and material supply chains will not only help support the country's manufacturing base, but it will also spur innovation in both the short term and long term. There is an opportunity for cross agency collaboration to identify and prioritize needs for education and workforce training. The strength of the U.S. industry in this sector depends on sufficient human capital to support mining and processing operations, as well as later-stage manufacturing. As recent Administration directives have acknowledged, a strong workforce is essential to both national security and robust economic health.[1,2]

5.5 Understanding Risk and Opportunities in Trade, Intellectual Property, and Other Policies

Material production and energy technology production occur in a global market. The United States has active trade policies, as do other countries. As seen for rare earths in 2010 and 2011, other countries' policies—such as trade duties and quotas—can affect U.S. access to materials, as well as U.S. manufacturers' access to global markets, either directly or through prices and market response. Additional geopolitical factors contribute to price volatility and market constraints. This in turn affects the evolution of domestic manufacturing across the supply chain. U.S. competitiveness can be affected by these relationships.

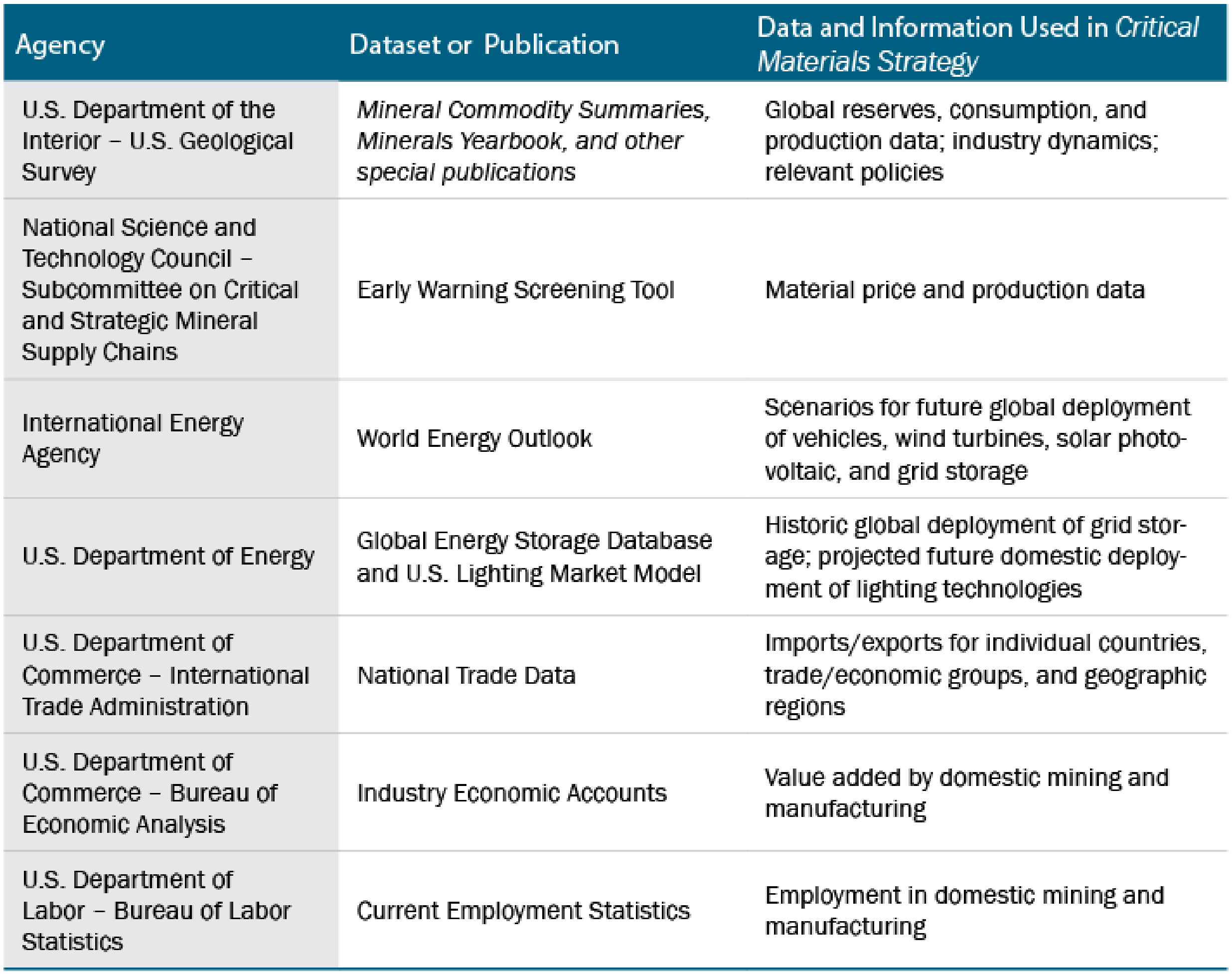
A more in-depth examination of global trade, intellectual property, manufacturing, and resource policies and how they affect material production and energy technology manufacturing could help decision makers navigate this complex landscape. Considering the interactions among these policies domestically and internationally can help inform and strengthen domestic policies addressing trade, intellectual property, manufacturing, and related areas.

5.6 Enhanced Data Quality and Availability

The quantitative assessment of critical materials is inextricably tied to the availability of data on both the supply and demand sides of materials. This includes material resource production and consumption, trade, prices, and recycling, as well as market dynamics of downstream technologies. Furthermore, the precision of such an assessment is highly correlated with the quality of the underlying statistics, stressing the importance of reliable access to uniform, disaggregated, and consistent data.

Table 5-1 shows government datasets that informed this report. Opportunities exist to improve the compatibility of these and other datasets both in terms of timescales and level of aggregation. For example, by-product materials like gallium and tellurium would benefit from greater granularity in the data. In addition, there are a number of additional sources and datasets that could provide a more comprehensive picture addressing trade policies, intellectual property, employment, and other topics.

Table 5-1. Government Data Resources Used in this 2019 *Critical Materials Strategy* report



Agency	Dataset or Publication	Data and Information Used in *Critical Materials Strategy*
U.S. Department of the Interior – U.S. Geological Survey	*Mineral Commodity Summaries, Minerals Yearbook, and other special publications*	Global reserves, consumption, and production data; industry dynamics; relevant policies
National Science and Technology Council – Subcommittee on Critical and Strategic Mineral Supply Chains	Early Warning Screening Tool	Material price and production data
International Energy Agency	World Energy Outlook	Scenarios for future global deployment of vehicles, wind turbines, solar photovoltaic, and grid storage
U.S. Department of Energy	Global Energy Storage Database and U.S. Lighting Market Model	Historic global deployment of grid storage; projected future domestic deployment of lighting technologies
U.S. Department of Commerce – International Trade Administration	National Trade Data	Imports/exports for individual countries, trade/economic groups, and geographic regions
U.S. Department of Commerce – Bureau of Economic Analysis	Industry Economic Accounts	Value added by domestic mining and manufacturing
U.S. Department of Labor – Bureau of Labor Statistics	Current Employment Statistics	Employment in domestic mining and manufacturing

5.7 Interagency and International Collaboration

The complex and crosscutting nature of material criticality and supply chains makes collaboration and integration among the various stakeholders essential. Stakeholders span across the government, private industry, and internationally. Vehicles for collaboration on this scale include the National Science and Technology Council's Subcommittee on Critical and Strategic Mineral Supply Chains (now the Subcommittee on Critical Minerals) and the United States-European Union-Japan Trilateral Conference on Critical Materials.

DOE participates in various collaborative efforts related to critical materials, which strengthens DOE's own work. For example, recent analytical work by the National Science and Technology Council

Subcommittee[3] was heavily utilized for the assessment of material criticality contained in this report. DOE can build on the foundation created over the last 8 years by sustaining these efforts.

In addition, DOE can continue to engage the international community where there are shared interests and values. Through these relationships, DOE and its partners can promote economic growth within fair and free markets.

5.8 Conclusions

This report has identified a number of risks and constraints, which also present opportunities. This chapter identified a number of potential program and policy directions meant to take advantage of those opportunities. Program directions for DOE and its partners include the following:

- Sustained and integrated R&D
- Understanding and addressing policy barriers for conventional and unconventional domestic production
- Understanding environmental risks across the supply chain and the relation to U.S. competitiveness
- Education and workforce training
- Understanding risk and opportunities in trade, intellectual property, and other policies
- Enhanced data quality and availability
- Interagency and international collaboration

Focused and coordinated effort in these areas can help the United States in achieving economic and national security goals.

5.9 Endnotes

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[1] Executive Order No. 13,806, "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," *Code of Federal Regulations*, title 3 (2017), https://www.gpo.gov/fdsys/pkg/FR-2017-07-26/pdf/2017-15860.pdf.

[2] The White House, *National Security Strategy of the United States of America* (Washington, DC: The White House, 2017), https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf.

[3] National Science and Technology Council (NSTC), *Assessment of Critical Minerals: Updated Application of Screening Methodology* (Washington, DC: NSTC, 2018), https://www.whitehouse.gov/wp-content/uploads/2018/02/Assessment-of-Critical-Minerals-Update-2018.pdf.

Appendix A : Criticality Assessment by Material

This appendix provides detailed assessments of criticality for each of the key materials. The methodology used to develop the criticality scores is explained in Chapter 4 (Criticality Assessment). For each material, the scores for “importance to energy” and “supply risk” are based on weighted averages of a number of individual factors. The descriptions of each factor are also presented in Chapter 4.

Table A-1 summarizes the assessment scores for each key material in both the short and medium terms.

Table A-1. Short- and Medium-Term Criticality Scores for Key Materials

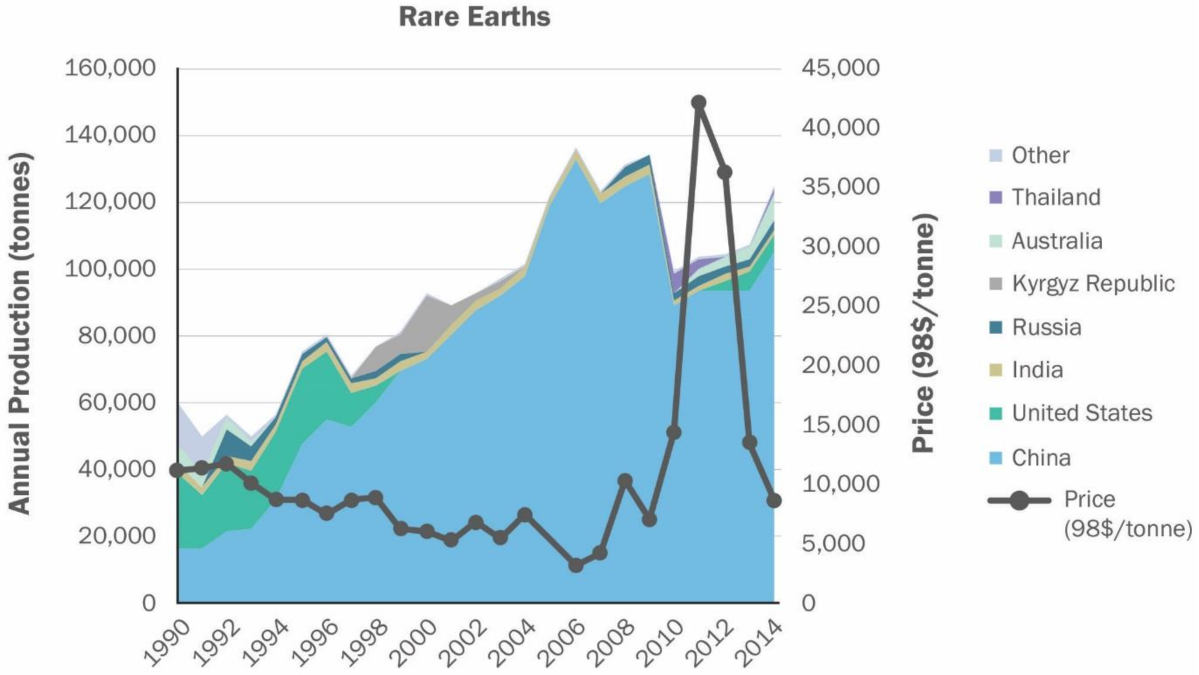
Weight:		**0.75**	**0.25**		**0.40**	**0.10**	**0.20**	**0.10**	**0.20**
Factor:	**Importance to Energy**	Energy Demand	Substitutability Limitations	**Supply Risk**	Basic Availability	Competing Technology Demand	Political, Regulatory, and Social Factors	Codependence on Other Markets	Producer Diversity
Short Term									
Cerium	2	2	1	2	2	2	2	2	4
Cobalt	3	3	3	2	2	3	3	3	2
Dysprosium	3	3	3	4	4	2	3	4	4
Gallium	3	3	3	4	4	4	3	4	4
Indium	1	1	1	2	1	2	2	3	2
Lanthanum	1	1	1	2	2	2	2	2	4
Lithium	3	3	4	2	3	4	1	1	2
Magnesium	3	3	3	2	1	2	3	1	4
Manganese	1	1	1	1	1	1	1	1	1
Neodymium	3	3	3	3	2	2	2	3	4
Nickel	2	1	3	1	1	1	1	1	1
Palladium	3	3	2	2	3	1	2	3	2
Platinum	3	3	2	2	1	1	3	3	3
Rhodium	3	3	4	3	3	1	3	4	4
Tellurium	2	2	1	2	1	2	1	4	2
Vanadium	1	1	2	2	2	2	2	2	3
Medium Term									
Cerium	2	2	1	2	2	2	2	2	4
Cobalt	4	4	3	3	4	2	3	3	2
Dysprosium	4	4	2	4	4	3	3	4	4
Gallium	4	4	3	3	3	3	3	4	4
Indium	1	1	1	2	1	2	2	3	2
Lanthanum	1	1	1	2	2	2	2	2	4
Lithium	4	4	4	3	4	3	1	1	2
Magnesium	4	4	3	3	3	2	3	1	4
Manganese	1	1	1	1	2	1	1	1	1
Neodymium	4	4	3	3	4	3	2	3	4
Nickel	3	3	3	1	2	1	1	1	1
Palladium	2	2	2	3	4	1	2	3	2
Platinum	2	2	2	2	2	1	3	3	3
Rhodium	3	2	4	4	4	1	3	4	4
Tellurium	2	2	1	2	2	2	1	4	2
Vanadium	1	1	2	2	2	2	2	2	3

Below are detailed assessments for each material. The assessments are informed by the information in Chapter 2 (Criticality in the Context of Global Dynamic Supply Chains and Implications for the U.S. Economy) and analysis in Chapter 3 (Use of Key Materials in Energy Technologies), but they also take into account other available information impacting material criticality.

<table>
<tr><th colspan="2">Cerium (Ce) Atomic Number: 58</th></tr>
<tr><td colspan="2">Cerium is a lanthanide metal and one of the light rare earth elements. It is primarily used for glass polishing and glass additives and in auto and refining catalysts and steel and battery alloys.</td></tr>
<tr><th colspan="2">Importance to Energy: <i>Short Term: 2, Medium Term: 2</i></th></tr>
<tr><td colspan="2">Use of cerium in energy applications, driven by demand for catalytic converters and nickel-metal hydride (NiMH) batteries in hybrid electric vehicles, is expected to increase; however, energy demand retains a constant share of total cerium demand as its growth matches that of non-energy applications.</td></tr>
<tr><td>Energy Demand
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• Energy demand for cerium is expected to stay relatively constant at 12%–21% of total cerium demand through 2030, depending on market penetration and material intensity of catalytic converters and NiMH batteries.
• All demand trajectories increase at similar rates, illustrating a tradeoff in cerium demand between the two vehicle deployment scenarios: when cerium demand for NiMH batteries is high, cerium demand for catalytic converters is low, and vice versa.</td></tr>
<tr><td>Substitutability Limitations
<i>Short Term: 1</i>
<i>Medium Term: 1</i></td><td>• Cerium has limited substitutability within NiMH batteries and catalytic converters.
• Lithium-ion batteries, which do not contain cerium, can be used instead of NiMH batteries in hybrid electric vehicles.</td></tr>
<tr><th colspan="2">Supply Risk: <i>Short Term: 2, Medium Term: 2</i></th></tr>
<tr><td colspan="2">The supply risk for cerium is low. Current rare earth production capacity is highly concentrated in China, but cerium is the most abundant material within rare earth deposits where production is typically driven by higher-revenue rare earths.</td></tr>
<tr><td>Basic Availability
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• Production capacity of cerium appears sufficient in the short term, but additional capacity would be needed to cover demand in the medium term if non-energy demand continues to increase.
• Only 40%–50% of the rare earths contained in Chinese iron deposits are recovered.
• Recent market reports expect a 38% increase in supply of rare earths by 2020, which would cover any cerium supply deficits well into the medium term.
• Post-consumer recycling of rare earths in any significant volumes does not take place; however, there is potential to extract cerium from spent catalytic converters, which are already collected for recycling of platinum group metals, but this activity is largely driven by the price of platinum group metals.</td></tr>
<tr><td>Competing Technology Demand
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• Non-energy applications constitute a significant portion of total cerium demand, but these applications are unlikely to create additional demand pressure.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• China is the largest producer of cerium and had imposed export quotas on rare earths until a World Trade Organization ruling forced China to remove the quotas in 2015.
• In 2017, environmental inspections severely disrupted output of rare earths from processing facilities in China, especially in the Sichuan province.</td></tr>
<tr><td>Codependence on Other Markets
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• Most cerium is recovered with other rare earths as a by-product of iron, tin, and titanium mining.
• Cerium is often one of the most abundant materials within a rare earth deposit.</td></tr>
</table>

Producer Diversity *Short Term: 4* *Medium Term: 4*	• China accounted for 84% of rare earth production in 2014, followed by Australia (6%) and the United States (4%). • U.S. production has since halted, but additional capacity has come online, most notably in Australia and India. • Several rare earth deposits outside of China are under development, but the likelihood that they'll reach full capacity in the short term is unclear.

Historical Price and Production



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- National Science and Technology Council (NSTC), *Assessment of Critical Minerals: Updated Application of Screening Methodology* (Washington, DC: NSTC, 2018), https://www.whitehouse.gov/wp-content/uploads/2018/02/Assessment-of-Critical-Minerals-Update-2018.pdf.
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- N.T. Nassar, T.E. Graedel, and E.M. Harper, "By-product metals are technologically essential but have problematic supply," *Science Advances* 1, no. 3 (2015): e1400180, doi:10.1126/sciadv.1400180.

Cobalt (Co) Atomic Number: 27

Cobalt is a transition metal that is primarily used in rechargeable battery electrodes and in superalloys for gas turbine engines.

Importance to Energy: *Short Term: 3, Medium Term: 4*

Use of cobalt in energy applications, driven by demand for electric vehicle (EV) batteries, is expected to increase. EV manufacturers can opt for cobalt-free lithium-ion battery chemistries, but that may result in diminished performance.

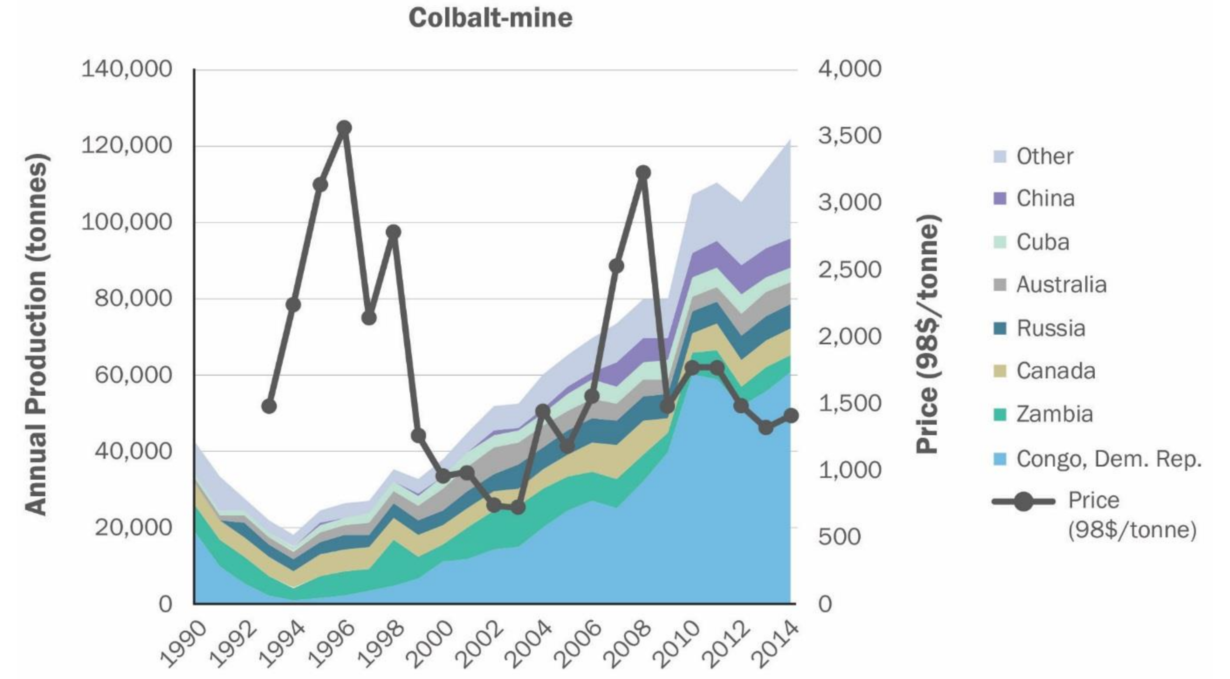
Energy Demand *Short Term: 3* *Medium Term: 4*	• Energy demand currently constitutes a moderate fraction (23%) of total cobalt demand; it could constitute 33%–60% of total cobalt demand in the short term and anywhere from 40% to 91% in the medium term, depending on EV deployment.
Substitutability Limitations *Short Term: 3* *Medium Term: 3*	• EV manufacturers could opt for cobalt-free lithium-ion battery chemistries, and hybrid electric vehicle manufacturers could opt for less cobalt-intense nickel-metal hydride batteries, but both may result in diminished performance. • Reducing cobalt intensities while maintaining battery performance and improving performance of cobalt-free batteries is the subject of ongoing research.

Supply Risk: *Short Term: 2, Medium Term: 3*

The supply risk for cobalt is moderate in the short term, but it has the potential to worsen in the medium term if new production does not come online. The DRC constitutes a large and growing share of global cobalt production capacity.

Basic Availability *Short Term: 2* *Medium Term: 4*	• Current cobalt production appears sufficient to meet demand in the short term under all but the highest demand trajectory (Trajectory D), but additional production capacity would be required in the medium term under the high material intensity scenario (Trajectories B and D). • Although more than 30,000 tonnes of additional cobalt production capacity is expected to come online by 2020, this would still be insufficient to meet demand under the highest demand trajectory (Trajectory D).
Competing Technology Demand *Short Term: 3* *Medium Term: 2*	• Use of cobalt in superalloys for various applications and in lithium-ion batteries for portable electronics may present a significant source of competing demand in the short term before energy demand for cobalt in EV batteries increases dramatically.
Political, Regulatory, and Social Factors *Short Term: 3* *Medium Term: 3*	• Half of global cobalt production occurs in DRC, which ranks below the 10th percentile in all of the World Bank's Worldwide Governance Indicators, including political stability. • DRC has a history of halting exports of cobalt concentrates due to inadequate power supply to process the concentrates.
Codependence on Other Markets *Short Term: 3* *Medium Term: 3*	• Cobalt is rarely mined as a primary product and is most often produced as a by-product of nickel or copper mining. • Global production of cobalt decreased in 2016 due to lower production from nickel operations.
Producer Diversity *Short Term: 2* *Medium Term: 2*	• DRC accounted for 50% of cobalt production in 2014, and the remaining production was evenly distributed between a dozen countries, including Canada (6%) and Australia (5%). • Producer diversity may decrease in the medium term because a large portion of the planned mining projects are in DRC.

Historical Price and Production



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Dysprosium (Dy) Atomic Number: 66

Dysprosium is a lanthanide metal and one of the heavy rare earth elements. It is primarily used in ceramics and as an additive to high-strength permanent magnets for electric vehicles (EVs), wind turbines, and other applications.

Importance to Energy: *Short Term: 3, Medium Term: 4*

Use of dysprosium in energy applications could increase significantly and is driven by deployment of EVs.

Energy Demand *Short Term: 3* *Medium Term: 4*	• Energy demand for dysprosium could surge from 36% in 2015 to 88% in 2030 of total dysprosium demand under the high penetration scenario given current material intensities (Trajectory D). Even with less optimistic market penetration (Trajectory B), energy demand for dysprosium could increase to about 42% of total dysprosium demand by 2030.
Substitutability Limitations *Short Term: 3* *Medium Term: 2*	• Induction motors can be used instead of permanent magnet motors in EVs and gearbox generators can be used instead of permanent magnet generators in wind turbines, but these substitutes have some performance drawbacks. • Terbium can be used instead of dysprosium in permanent magnets, but it is less abundant and more expensive. • Significant research is ongoing to reduce dysprosium content in permanent magnets, with the potential for dysprosium-free permanent magnets in wind turbines.

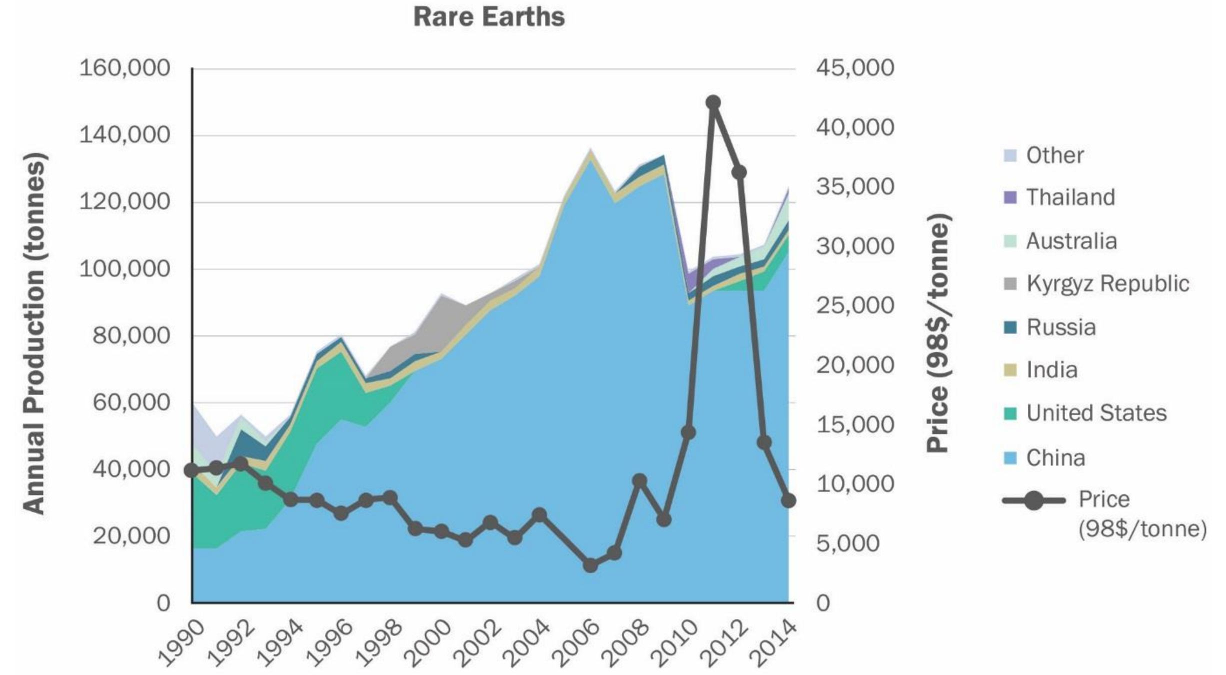
Supply Risk: *Short Term: 4, Medium Term: 4*

The supply risk for dysprosium is moderate. Current production capacity, which is highly concentrated in China and largely recovered as a by-product of iron mining, will likely be insufficient in the medium term.

Basic Availability *Short Term: 4* *Medium Term: 4*	• Production capacity of dysprosium will only be sufficient in the short term if significant reductions in material intensity are achieved (Trajectories A and C). • Only 40%–50% of the rare earths contained in Chinese iron deposits are recovered. • Recent market reports expect a 38% increase in supply of rare earths by 2020, which would cover any dysprosium supply deficits in the short term under all but the highest demand trajectory (Trajectory D), but additional production capacity would be required in the medium term under all but the lowest demand trajectory (Trajectory A). • Post-consumer recycling of rare earths in any significant volumes does not take place.
Competing Technology Demand *Short Term: 2* *Medium Term: 3*	• There is significant competition for high-strength magnets in other applications, which could increase in the medium term.
Political, Regulatory, and Social Factors *Short Term: 3* *Medium Term: 3*	• China is the largest producer of dysprosium and had imposed export quotas on rare earth until a World Trade Organization ruling forced China to remove the quotas in 2015. • In 2017, environmental inspections severely disrupted output of rare earths from processing facilities in China, especially in the Sichuan province.
Codependence on Other Markets *Short Term: 4* *Medium Term: 4*	• Most dysprosium is recovered with other rare earths as a by-product of iron, tin, and titanium mining.

Producer Diversity *Short Term: 4* *Medium Term: 4*	• China accounted for 84% of rare earth production in 2014, followed by Australia (6%) and the United States (4%). • U.S. production has since halted, but additional capacity has come online, most notably in Australia and India. • Several rare earth deposits outside of China are under development, but the likelihood that they'll reach full capacity in the short term is unclear.

Historical Price and Production



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Gallium (Ga) Atomic Number: 31

Gallium is a post-transition metal that is used in wireless communication technologies and in opto semiconductor (LEDs and laser diodes) and power semiconductor devices for both consumer and military applications.

Importance to Energy: *Short Term: 3, Medium Term: 4*

Use of gallium in energy applications, especially LEDs, could increase significantly in the short term.

Energy Demand *Short Term: 3* *Medium Term: 4*	• Demand for LEDs is expected to rise precipitously in the short term and then plateau in the medium term, driving energy demand for gallium from 18% in 2015 to anywhere from 36% to 80% in 2030, depending on material intensity. • Sixty-seven countries have voluntary or mandatory energy-efficient standards for lighting. • The share of global energy consumption for lighting covered by mandatory energy efficiency policies increased from less than 5% to more than 60% between 2000 and 2015.
Substitutability Limitations *Short Term: 3* *Medium Term: 3*	• There is opportunity within LEDs to use alternative package types, such as high-brightness LEDs, which are more expensive but use significantly less gallium. There is also opportunity to use alternative down converters such as quantum dots. • The lighting industry could also revert back to favoring fluorescent lights, but these technologies use significantly more rare earths.

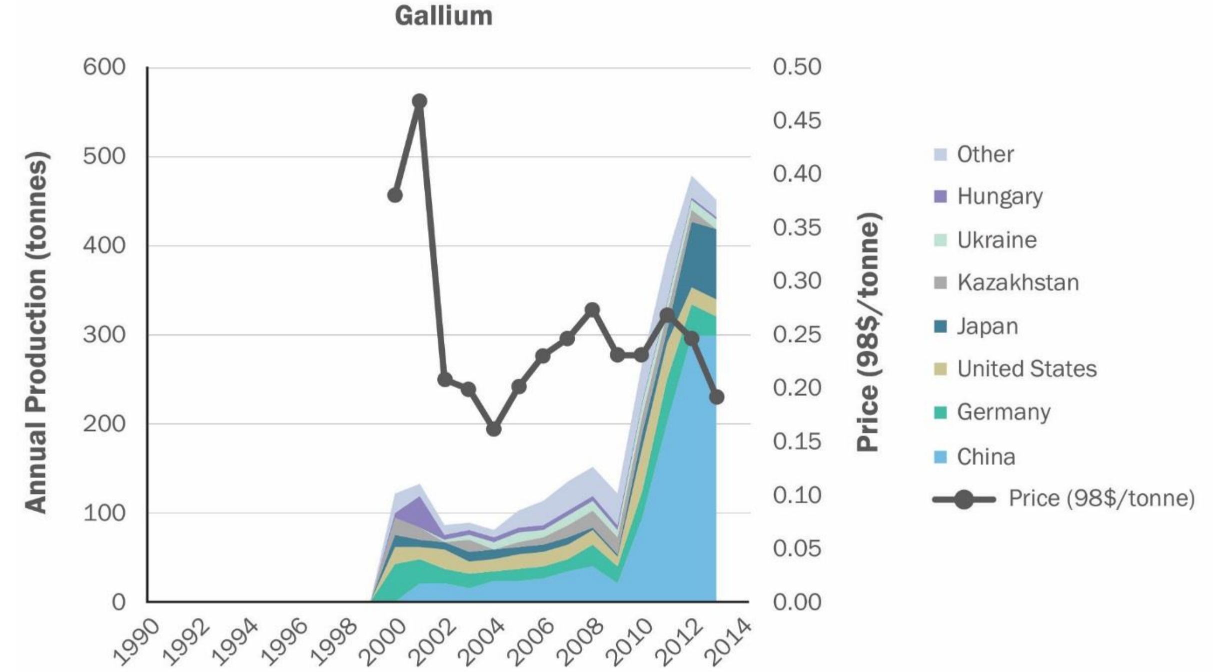
Supply Risk: *Short Term: 4, Medium Term: 3*

The supply risk for gallium is moderate. Production is highly concentrated in China and is somewhat constrained by its by-production with aluminum, but there is significant excess capacity and opportunities to increase gallium recovery rates. There is a high potential for competing technology demand to place additional strains on supply.

Basic Availability *Short Term: 4* *Medium Term: 3*	• Consumption of gallium is less than primary gallium production, which only has a 50% capacity utilization rate. • Current gallium production capacity would cover demand in the medium term if significant reductions in material content were achieved (Trajectories A and C); without these improvements, additional production capacity would be needed in the medium term to meet gallium demand even with meager LED deployment (Trajectory B). • Additional sources would be required in the short term to meet gallium demand under the highest demand trajectory (Trajectory D). • There is opportunity to increase the gallium recovery rates from bauxite and zinc ores—currently, only 2% of the gallium contained in bauxite and 3% of the gallium contained in zinc ores is recovered. • There is also opportunity to extract gallium from coal fly ash. • Post-consumer recycling of gallium in any significant volumes does not take place.
Competing Technology Demand *Short Term: 4* *Medium Term: 3*	• Global demand for gallium in smartphones is likely to increase due to expected growth in sales of 3G and 4G smartphones, which use 10 times more gallium than 2G cellular telephones. • Gallium demand in the defense sector is also likely to increase due to proliferation of gallium arsenide devices in radar, electronic warfare, communications, and other defense applications.
Political, Regulatory, and Social Factors *Short Term: 3* *Medium Term: 3*	• With production highly concentrated in China, gallium supply is susceptible to supply disruption due to political, regulatory, and social factors.
Codependence on Other Markets *Short Term: 4*	• Most primary gallium is recovered as a by-product of aluminum, extracted when processing bauxite into alumina. • The remainder of gallium production is recovered as a by-product of zinc ores.

Medium Term: 4	
Producer Diversity *Short Term: 4* *Medium Term: 4*	• In 2014, 67% of primary gallium production was concentrated in China; preliminary reports indicate China's share of production increased to 93% in 2016. • Adding gallium production capacity to existing bauxite refining operations in Canada, India, Australia, Brazil, and the United States could help diversify supply. • Primary gallium production capacity in China has more than tripled from 140 tonnes in 2010 to approximately 600 tonnes in 2016, which constitutes 83% of global primary production capacity. • Excess supply of primary gallium has driven prices down, prompting producers to reduce output and forcing some to shut down completely, including one plant in Germany. Kazakhstan was a leading producer in 2012 but has not reported any production since. • A planned alumina production facility in Canada may include a separation facility to recover gallium. India's largest aluminum producer is exploring ways to extract gallium from one of its alumina refineries.

Historical Price and Production



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Indium (In) — Atomic Number: 49

Indium is a post-transition metal that is primarily used in thin-film coatings for flat-panel displays, but it is also used in alloys and solders, thin-film solar photovoltaic (PV) cells, and semiconductor materials, such as those used in LEDs.

Importance to Energy: *Short Term: 1, Medium Term: 1*

Use of indium in energy applications could increase if copper-indium-gallium-diselenide (CIGS) solar PV technologies retain a significant market share, but this would constitute a small share of total indium demand.

Energy Demand *Short Term: 1* *Medium Term: 1*	• If CIGS solar PV technologies maintain a significant market share in the high deployment scenario (Trajectories C and D), energy demand for indium could increase by 50%–450% between 2015 and 2030, but this would constitute a small share of total indium demand. • Much of the expected increase in demand for indium will come from non-energy applications.
Substitutability Limitations *Short Term: 1* *Medium Term: 1*	• There are other thin-film solar PV technologies (cadmium telluride) and crystalline silicon solar PV technologies that compete with CIGS. • Crystalline silicon modules are the favored solar PV technology with higher efficiencies and lower manufacturing costs, but some defense and aerospace applications rely on thin-film solar PVs because weight is an important aspect of performance. • Although CIGS formulations have optimized the share of gallium and indium to increase efficiency and bandgap, it is possible for CIGS to use more gallium in place of indium. • Several substitutes for indium in solar PV technologies are being developed, including the use of carbon nanotube coatings instead of indium tin oxide coatings. • Other thin-film solar PV technologies, such as single-junction gallium arsenide, have been developed but are prohibitively expensive to mass produce at this time.

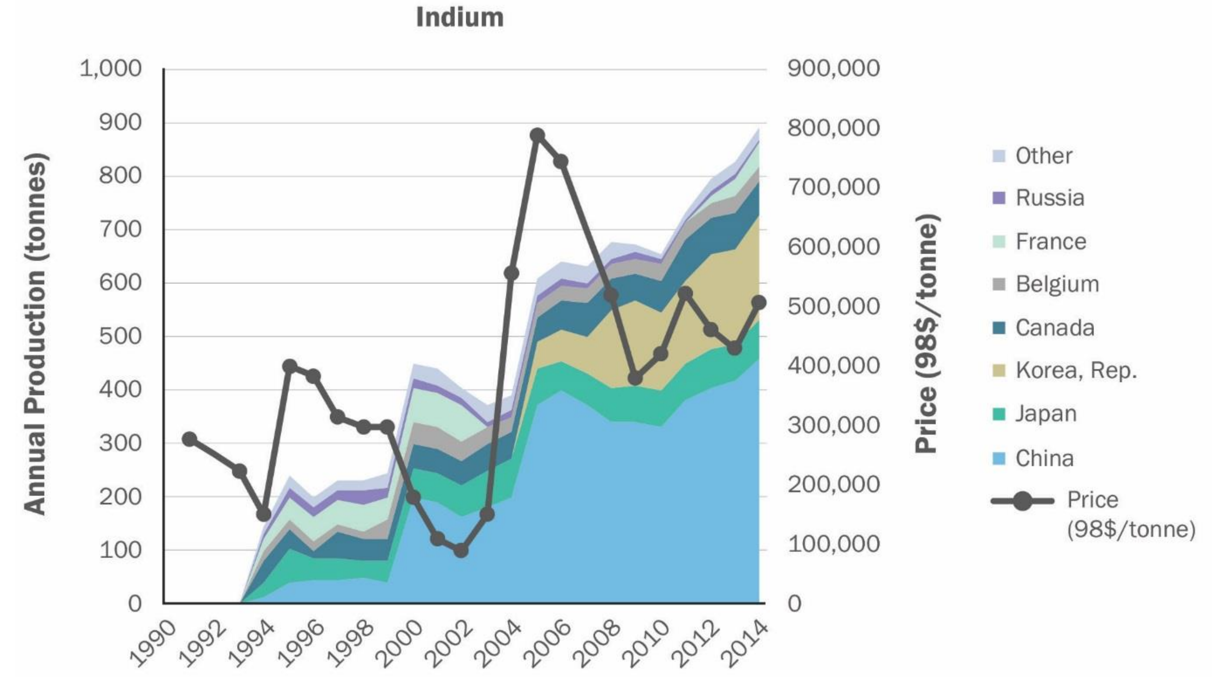
Supply Risk: *Short Term: 2, Medium Term: 2*

The supply risk for indium is moderate. Producer diversity is favorable, but indium is constrained by its by-production with zinc. Significant competing technology demand could place strains on indium supply in the short term, but there is opportunity to increase indium recovery rates.

Basic Availability *Short Term: 1* *Medium Term: 1*	• Production capacity of indium appears sufficient well into the medium term. • There is significant excess indium production capacity because reutilization of indium in the manufacturing of liquid crystal displays has become increasingly common, displacing demand for primary indium. • Several indium-containing exploration or development projects are underway in Canada, South America, and the United States. • There is opportunity to increase the indium recovery rates at zinc production facilities—currently, only 35% of the indium contained in zinc deposits is recovered. • Post-consumer recycling of indium in any significant volumes does not take place.
Competing Technology Demand *Short Term: 2* *Medium Term: 2*	• Indium is primarily used in thin-film coatings for flat-panel displays such as liquid crystal displays, the demand for which is expected to increase as the average screen size of televisions, monitors, and tablets increases. • Several alternative technologies are being developed for flat-panel displays, including antimony tin oxide and zinc oxide nanopowders.
Political, Regulatory, and Social Factors *Short Term: 2* *Medium Term: 2*	• China is the largest producer of indium and has imposed an export quota system to regulate its indium production; in 2015, 16 companies were approved to export indium.

	- Indium is traded on a number of China's metal exchanges, one of which—the Fanya Metal Exchange—collapsed after the Yunnan Securities Regulatory Bureau began a criminal investigation in 2014.
Codependence on Other Markets *Short Term: 3* *Medium Term: 3*	- Most indium is recovered as a by-product of zinc refining, but it is also found in copper, tin, lead, and iron ores.
Producer Diversity *Short Term: 2* *Medium Term: 2*	- Production of indium is fairly diverse, but China accounted for 55% of production in 2014, followed by South Korea (22%), Japan (8%), Canada (8%), and France (5%).

Historical Price and Production



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Lanthanum (La) Atomic Number: 57

Lanthanum is a lanthanide metal and one of the light rare earth elements. It is primarily used in refining catalysts and battery alloys and for glass polishing.

Importance to Energy: *Short Term: 1, Medium Term: 1*

Use of lanthanum in energy applications will increase if nickel-metal hydride (NiMH) batteries retain a large share of the market for batteries in hybrid electric vehicles (HEVs); however, energy demand is expected to remain a small share of total lanthanum demand.

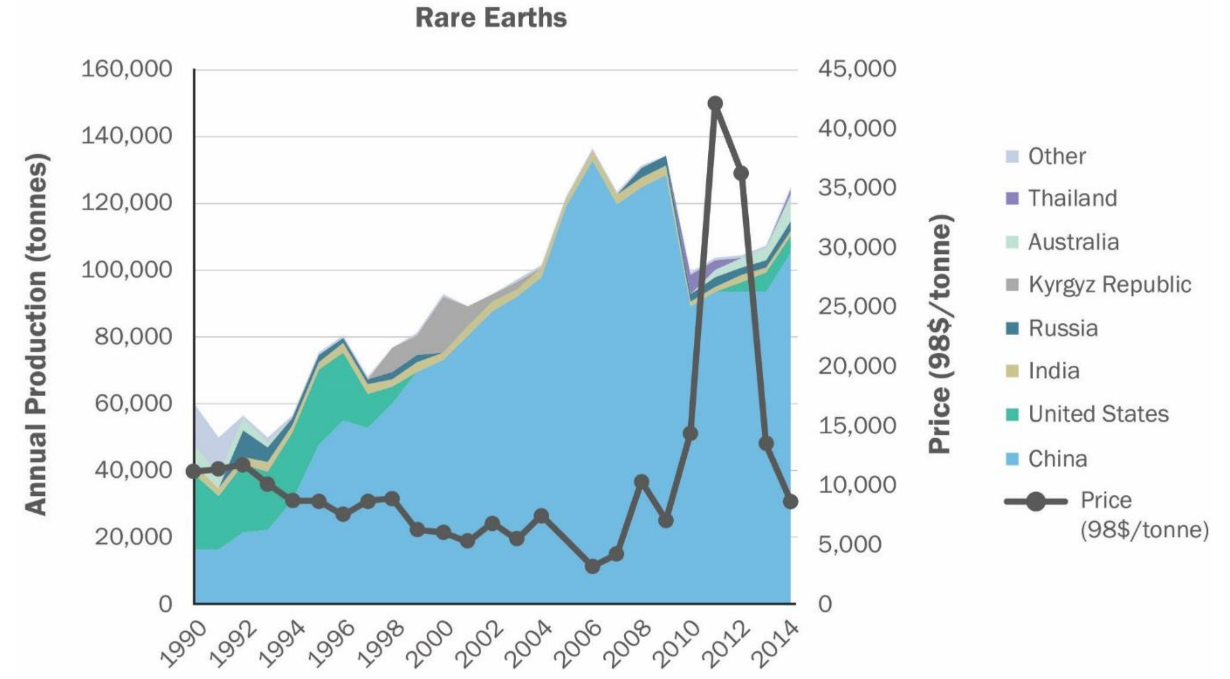
Energy Demand *Short Term: 1* *Medium Term: 1*	• Energy demand for lanthanum could increase under the high penetration scenario (Trajectories C and D), but it would still constitute a small portion of total lanthanum demand. • Even with high penetration rates for NiMH batteries in HEVs, energy demand for lanthanum only reaches 5%–8% of total lanthanum demand in 2030, depending on material intensity.
Substitutability Limitations *Short Term: 1* *Medium Term: 1*	• Lanthanum has limited substitutability within NiMH batteries. • Lithium-ion batteries, which do not contain lanthanum, can be used instead of NiMH batteries in HEVs.

Supply Risk: *Short Term: 2, Medium Term: 2*

The supply risk for lanthanum is low. Current rare earth production capacity is highly concentrated in China, but lanthanum is one of the most abundant materials within rare earth deposits where production is typically driven by higher-revenue rare earths.

Basic Availability *Short Term: 2* *Medium Term: 2*	• Current lanthanum production capacity is nearly adequate to cover demand in the short term, but additional capacity would be needed to cover demand in the medium term if non-energy demand continues to increase. • Only 40%–50% of the rare earths contained in Chinese iron deposits are recovered. • Recent market reports expect a 38% increase in supply of rare earths by 2020, which would cover any lanthanum supply deficits well into the medium term. • Post-consumer recycling of rare earths in any significant volumes does not take place.
Competing Technology Demand *Short Term: 2* *Medium Term: 2*	• Non-energy applications constitute a significant portion of total lanthanum demand, but these applications are unlikely to create additional demand pressure.
Political, Regulatory, and Social Factors *Short Term: 2* *Medium Term: 2*	• China is the largest producer of lanthanum and had imposed export quotas on rare earth until a World Trade Organization ruling forced China to remove the quotas in 2015. • In 2017, environmental inspections severely disrupted output of rare earths from processing facilities in China, especially in the Sichuan province.
Codependence on Other Markets *Short Term: 2* *Medium Term: 2*	• Most lanthanum is recovered with other rare earths as a by-product of iron, tin, and titanium mining. • Lanthanum is often one of the most abundant materials within a rare earth deposit.
Producer Diversity *Short Term: 4* *Medium Term: 4*	• China accounted for 84% of rare earth production in 2014, followed by Australia (6%) and the United States (4%). • U.S. production has since halted, but additional capacity has come online, most notably in Australia and India. • Several rare earth deposits outside of China are under development, but the likelihood that they'll reach full capacity in the short term is unclear.

Historical Price and Production



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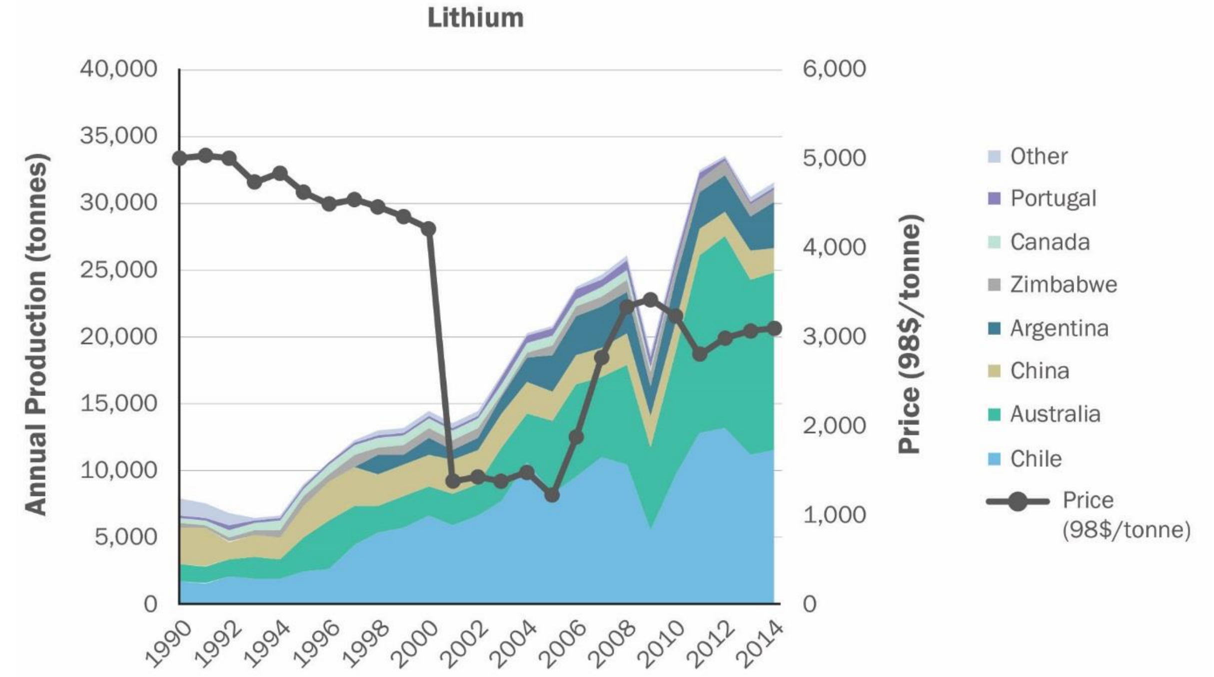
Lithium (Li)	Atomic Number: 3
Lithium is an alkali metal that is primarily used in batteries, ceramics, and glass.	
Importance to Energy: *Short Term: 3, Medium Term: 4*	
Use of lithium in energy applications, driven by demand for electric vehicle (EV) batteries, is expected to increase. There are significant substitutability limitations for lithium in EV batteries, except in hybrid electric vehicles (HEVs) where lithium-free nickel-metal hydride batteries can be used.	
Energy Demand *Short Term: 3* *Medium Term: 4*	• Lithium demand for batteries is expected to increase significantly with increased deployment of lithium-ion (Li-ion) battery-operated vehicles (HEVs, plug-in hybrid electric vehicles, all-electric vehicles). • Energy demand currently constitutes 22% of total lithium demand, which could increase to 30%–58% of total lithium demand in the short term and anywhere from 71%–91% in the medium term under the high penetration scenario (Trajectories C and D). • Although Li-ion batteries are likely to be a large portion of added grid storage battery capacity, lithium's use in grid storage applications will be a small fraction of total energy demand for lithium.
Substitutability Limitations *Short Term: 4* *Medium Term: 4*	• Lithium is an important component in all Li-ion battery chemistries and cannot be substituted easily, except in HEVs where lithium-free nickel-metal hydride batteries can be used. • Zinc-air batteries, sodium-sulfur batteries, fuel cells, and super- or ultra-capacitors could substitute for Li-ion batteries in stationary configurations; however, these technologies currently are not commercially viable and only look to become viable in the long term.
Supply Risk: *Short Term: 2, Medium Term: 3*	
The supply risk for lithium is moderate in the short term, but it has the potential to worsen in the medium term if additional production capacity does not come online.	
Basic Availability *Short Term: 3* *Medium Term: 4*	• Current production capacity of lithium appears adequate to meet demand in the short term but potentially inadequate to meet demand in the medium term, especially under a high penetration scenario for EVs (Trajectories C and D). • New mining operations are under development in a variety of countries, including Argentina, Chile, China, and the United States.
Competing Technology Demand *Short Term: 4* *Medium Term: 3*	• Use of Li-ion batteries for smartphones, tablet computers, and other handheld devices is growing rapidly. • Lithium demand for primary aluminum production, ceramics, and glass is likely to increase during the next decade, but at a slower rate than lithium use for batteries.
Political, Regulatory, and Social Factors *Short Term: 1* *Medium Term: 1*	• With a relatively diverse group of producers, lithium production is unlikely to experience any significant supply risks associated with political, regulatory, or social factors.
Codependence on Other Markets *Short Term: 1* *Medium Term: 1*	• Lithium is mined as a primary product and is unlikely to experience significant issues with codependence on other markets.
Producer Diversity *Short Term: 2* *Medium Term: 2*	• Production of lithium is fairly diverse, with Australia accounting for 42% of production in 2014, followed by Chile (37%), Argentina (11%), and China (6%).

Historical Price and Production



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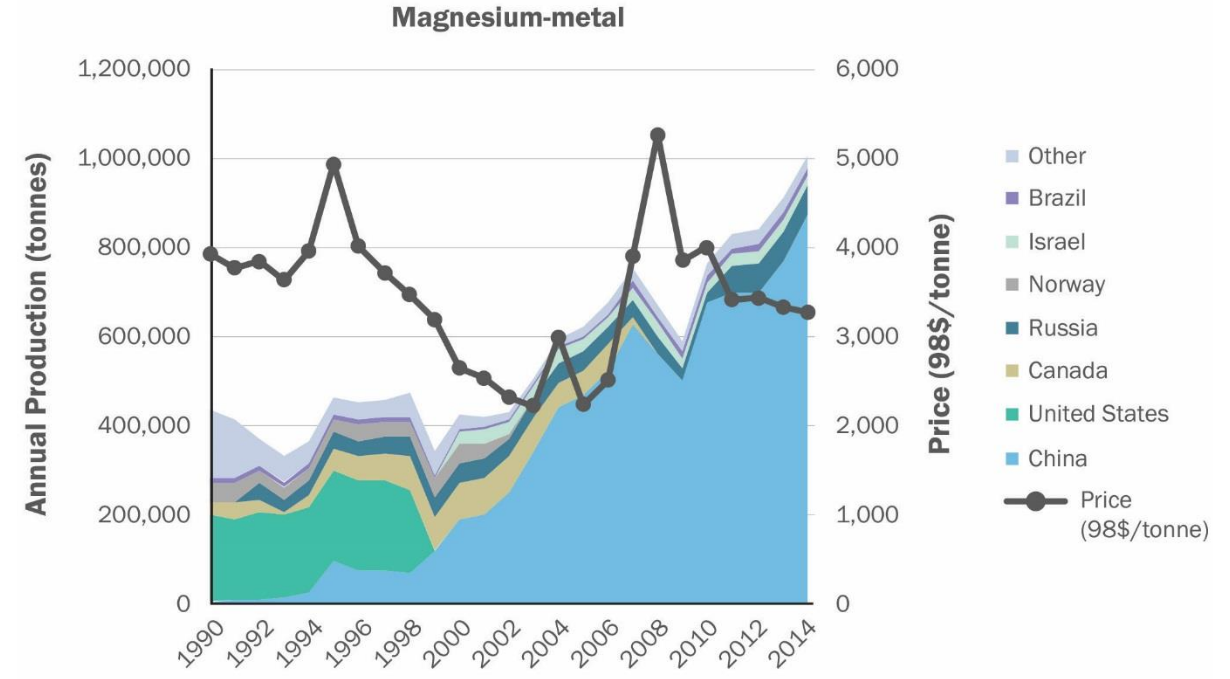
<table>
<tr><th>Magnesium (Mg)</th><th>Atomic Number: 12</th></tr>
<tr><td colspan="2">Magnesium is an alkaline earth metal that is primarily used for transportation products, including aluminum alloys. It is also used to reduce titanium and other metal halides to pure metal.</td></tr>
<tr><th colspan="2">Importance to Energy: Short Term: 3, Medium Term: 4</th></tr>
<tr><td colspan="2">Use of magnesium in energy applications is expected to increase, driven by demand for lightweight materials in vehicles, including aluminum, and magnesium alloys. Substitutes for magnesium in these materials do exist, but they result in reduced performance given magnesium’s high strength-to-weight ratio.</td></tr>
<tr><td>Energy Demand
Short Term: 3
Medium Term: 4</td><td>• Energy demand currently constitutes 28% of total magnesium demand, which could increase to 49%–56% of total magnesium demand in the medium term under the high penetration scenario (Trajectories C and D).</td></tr>
<tr><td>Substitutability Limitations
Short Term: 3
Medium Term: 3</td><td>• The high strength-to-weight ratio of magnesium means aluminum alloys must forego significant performance benefits in order to reduce magnesium content.
• Research is ongoing to make other lightweight materials, such as carbon fiber, more cost competitive; however, they are unlikely to displace magnesium in the short or medium terms.</td></tr>
<tr><th colspan="2">Supply Risk: Short Term: 2, Medium Term: 3</th></tr>
<tr><td colspan="2">The supply risk for magnesium is moderate in the short term, but it has the potential to worsen in the medium term if a more geographically diverse portfolio of additional production capacity does not come online.</td></tr>
<tr><td>Basic Availability
Short Term: 1
Medium Term: 3</td><td>• With significant unutilized magnesium production capacity, current magnesium supply can handle increased demand in the short term under all but the highest demand trajectory (Trajectory D); however, demand under a high penetration scenario (Trajectories C and D) will surpass current production capacity in the medium term.
• Several projects are under development that could increase primary magnesium metal capacity by 255,000 tonnes by 2020, but it would still be insufficient to meet increased magnesium demand under the highest demand trajectory (Trajectory D).
• Magnesium is produced from a variety of sources (dolomite, magnesite, olivine, salt brines, seawater, and recycling) using a variety of processes (pidgeon, electrolytic).</td></tr>
<tr><td>Competing Technology Demand
Short Term: 2
Medium Term: 2</td><td>• Other uses for magnesium, including non-transportation applications of aluminum and magnesium alloys, are unlikely to place significant additional strain on magnesium supply.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short Term: 3
Medium Term: 3</td><td>• With production highly concentrated in China, magnesium supply is susceptible to supply disruption due to political, regulatory, and social factors.
• In Russia, the second-largest supplier of magnesium, political stability can impact mine output.</td></tr>
<tr><td>Codependence on Other Markets
Short Term: 1
Medium Term: 1</td><td>• Magnesium is mined as a primary product and is unlikely to experience significant issues related to codependence on other markets.</td></tr>
<tr><td>Producer Diversity
Short Term: 4
Medium Term: 4</td><td>• China accounted for 87% of magnesium production in 2014, followed by Russia (6%), Israel (3%), and Brazil (2%).</td></tr>
</table>

Historical Price and Production



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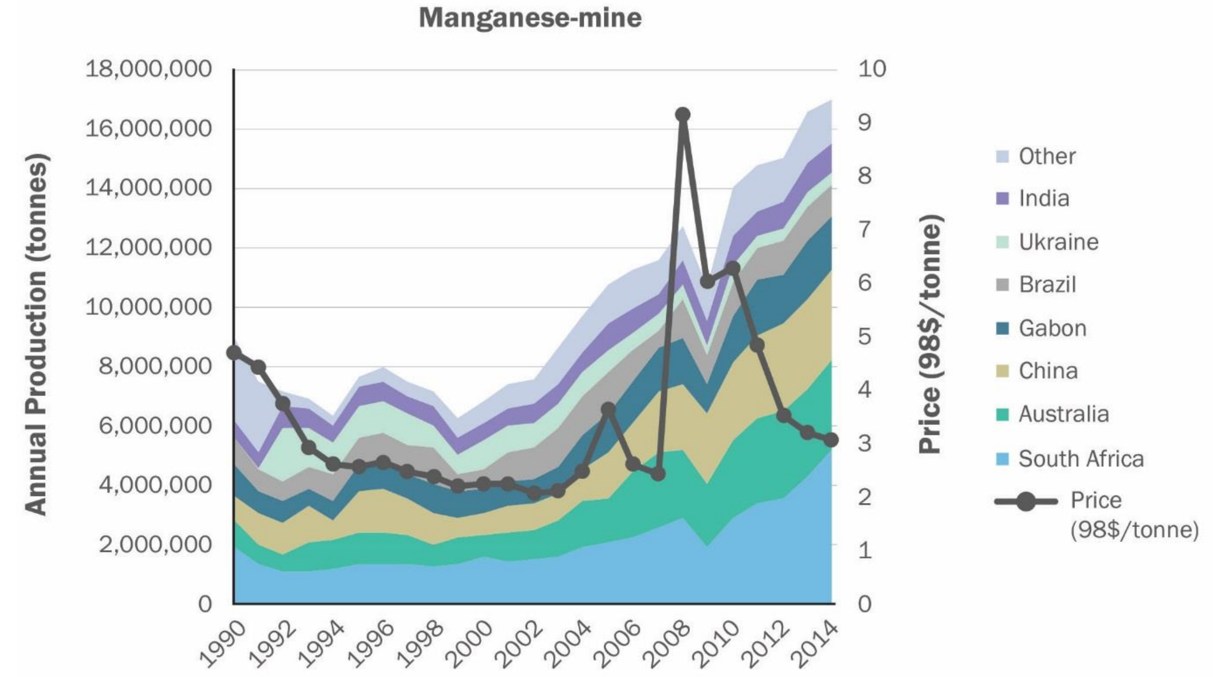
Manganese (Mn)	Atomic Number: 25
Manganese is a transition metal that is primarily used in iron and steel production for its sulfur-fixing, deoxidizing, and alloying properties. It is also commonly used in aluminum alloys and batteries.	
Importance to Energy: *Short Term: 1, Medium Term: 1*	
Use of manganese in energy applications, specifically lightweighting materials and lithium-ion (Li-ion) batteries in vehicles, is expected to increase but maintain a small share of total manganese demand. Several substitutes for manganese in energy applications are available.	
Energy Demand *Short Term: 1* *Medium Term: 1*	• Energy demand for manganese represents 3%–4% of total manganese demand through 2030, except under the highest demand trajectory (Trajectory D) where demand for material-intense Li-ion batteries drives energy demand for manganese to 17% of total manganese demand.
Substitutability Limitations *Short Term: 1* *Medium Term: 1*	• Using alternative lightweighting materials or decreasing manganese content in high-strength steels and aluminum alloys is possible, but it may result in diminished performance and/or significantly higher costs. • Electric vehicle manufacturers could opt for manganese-free Li-ion battery chemistries, such as nickel cobalt aluminum, with minimal impact on performance.
Supply Risk: *Short Term: 1, Medium Term: 1*	
The supply risk for manganese is minimal given its large and geographically diverse production.	
Basic Availability *Short Term: 1* *Medium Term: 2*	• With significant unutilized manganese production capacity, current manganese supply can handle increased demand in the short term; however, additional production capacity would be needed by the middle of the medium term to cover growth in both energy and non-energy demand for manganese. • High stock levels and low ore prices have driven 11.7 million tonnes of capacity cuts in recent years, but production facilities could be restarted in Australia, India, Japan, and South Africa.
Competing Technology Demand *Short Term: 1* *Medium Term: 1*	• Other uses for manganese, including non-transportation applications of high-strength steel and aluminum alloys, are unlikely to place significant additional strain on manganese supply.
Political, Regulatory, and Social Factors *Short Term: 1* *Medium Term: 1*	• With a relatively diverse group of producers, manganese production is unlikely to experience any significant supply risks associated with political, regulatory, or social factors.
Codependence on Other Markets *Short Term: 1* *Medium Term: 1*	• Manganese is often mined as a primary product and is unlikely to experience significant issues related to codependence on other markets.
Producer Diversity *Short Term: 1* *Medium Term: 1*	• Production of manganese is very diverse; South Africa accounted for 31% of production in 2014, followed by Australia (18%), China (18%), Gabon (11%), Brazil (6%), and India (6%).

Historical Price and Production



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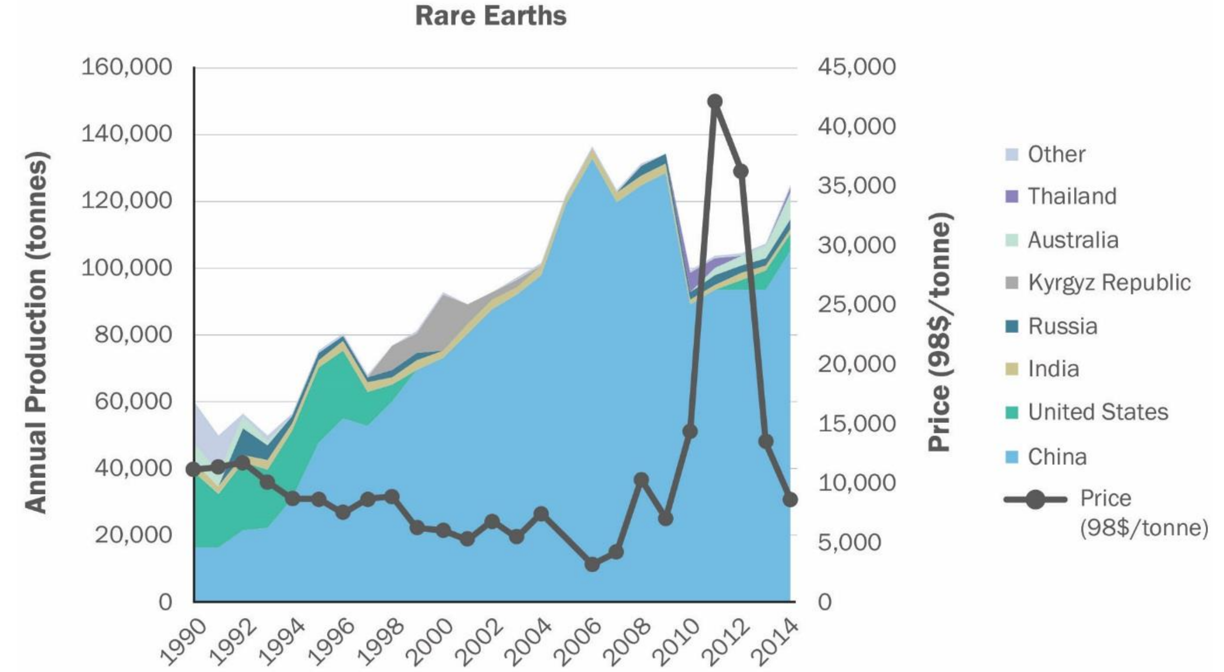
Neodymium (Nd)	Atomic Number: 60
Neodymium is a lanthanide metal and one of the light rare earth elements. It is primarily used in high-strength permanent magnets for electric vehicles (EVs), wind turbines, and other applications. It is also used for coloring glass and ceramics and in batteries for EVs.	
Importance to Energy: *Short Term: 3, Medium Term: 4*	
Use of neodymium in energy applications could increase significantly; it is driven by deployment of wind turbines in the short term and deployment of EVs in the medium term.	
Energy Demand *Short Term: 3* *Medium Term: 4*	• Under the high penetration scenario (Trajectories C and D), energy demand for neodymium surges from 15% of total neodymium demand in 2015 to 25%–61% in 2030, depending on material intensity. • In the low penetration scenario (Trajectories A and B), energy demand increases at the same rate as non-energy demand.
Substitutability Limitations *Short Term: 3* *Medium Term: 3*	• Induction motors can be used instead of permanent magnet motors in EVs and gearbox generators can be used instead of permanent magnet generators in wind turbines, but these substitutes have some performance drawbacks. • Praseodymium can be used instead of neodymium in permanent magnets, but it is less abundant and more expensive. • Significant research is ongoing to reduce neodymium content in permanent magnets.
Supply Risk: *Short Term: 3, Medium Term: 3*	
The supply risk for neodymium is moderate. Current production capacity, which is highly concentrated in China and largely recovered as a by-product of iron mining, will likely be insufficient in the medium term.	
Basic Availability *Short Term: 2* *Medium Term: 4*	• Production capacity of neodymium appears sufficient in the short term under all but the highest demand trajectory (Trajectory D). • Only 40%–50% of the rare earths contained in Chinese iron deposits are recovered. • Recent market reports expect a 38% increase in supply of rare earths by 2020, but that would still be insufficient to cover neodymium supply deficits under the highest demand trajectory (Trajectory D); additional production capacity would be required in the medium term under all but the lowest demand trajectory (Trajectory A). • Post-consumer recycling of rare earths in any significant volumes does not take place.
Competing Technology Demand *Short Term: 2* *Medium Term: 3*	• There is significant competition for high-strength magnets in other applications, which could increase in the medium term.
Political, Regulatory, and Social Factors *Short Term: 2* *Medium Term: 2*	• China is the largest producer of neodymium and had imposed export quotas on rare earth until a World Trade Organization ruling forced China to remove the quotas in 2015. • In 2017, environmental inspections severely disrupted output of rare earths from processing facilities in China, especially in the Sichuan province.
Codependence on Other Markets *Short Term: 3* *Medium Term: 3*	• Most neodymium is recovered with other rare earths as a by-product of iron, tin, and titanium mining. • Neodymium's moderate abundance and prices compared to other coproduced rare earths leads to high revenue streams and tends to drive production of the other rare earths.
Producer Diversity *Short Term: 4* *Medium Term: 4*	• China accounted for 84% of rare earth production in 2014, followed by Australia (6%) and the United States (4%). • U.S. production has since halted, but additional capacity has come online, most notably in Australia and India. • Several rare earth deposits outside of China are under development, but the likelihood that they'll reach full capacity in the short term is unclear.

Historical Price and Production



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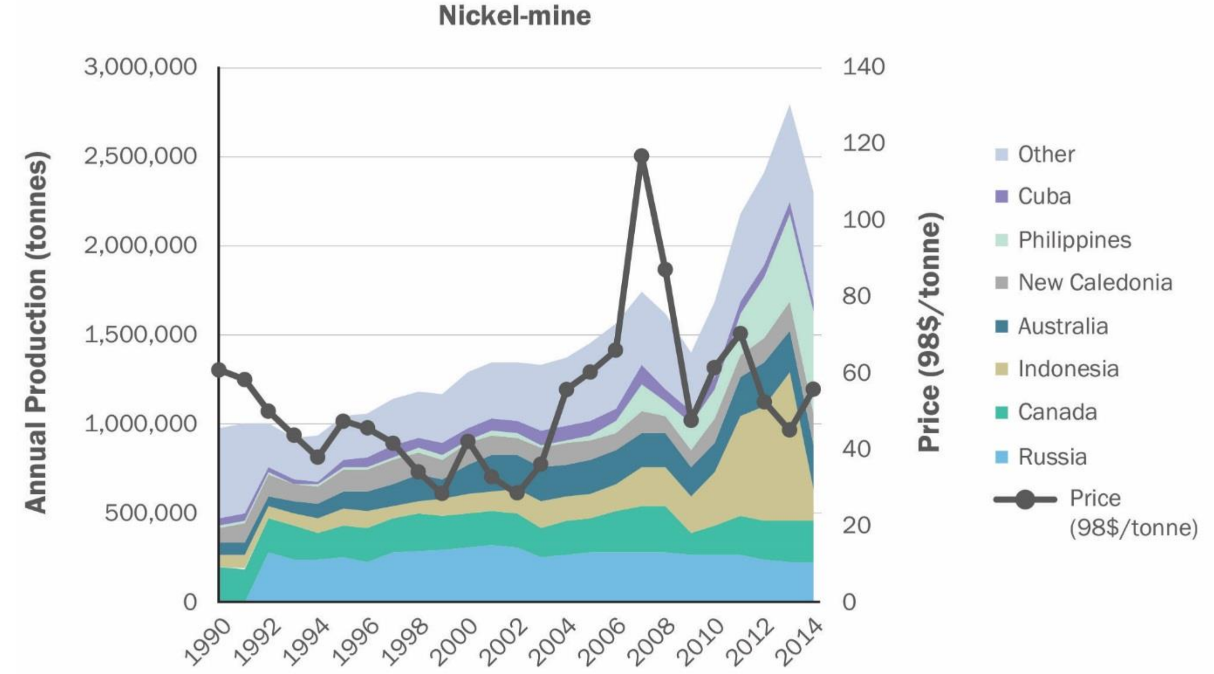
<table>
<tr><th>Nickel (Ni)</th><th>Atomic Number: 28</th></tr>
<tr><td colspan="2">Nickel is a transition metal that is primarily used in stainless steel and superalloys.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short Term: 2, Medium Term: 3</i></td></tr>
<tr><td colspan="2">Use of nickel in energy applications, driven by demand for electric vehicle (EV) batteries, is expected to increase, but it would not constitute a significant portion of total nickel demand unless high penetration rates of materially intense lithium-ion (Li-ion) battery chemistries occur. EV manufacturers can opt for nickel-free Li-ion battery chemistries, but that may result in diminished performance.</td></tr>
<tr><td>Energy Demand
<i>Short Term: 1</i>
<i>Medium Term: 3</i></td><td>• Energy demand currently constitutes 2% of total nickel demand; however, it could constitute 40% of total nickel demand in the medium term under Trajectory D, which combines a high penetration scenario with a high material intensity scenario.</td></tr>
<tr><td>Substitutability Limitations
<i>Short Term: 3</i>
<i>Medium Term: 3</i></td><td>• EV manufacturers could opt for nickel-free Li-ion battery chemistries and hybrid electric vehicle manufacturers could opt for less nickel-intense nickel-metal hydride batteries, but both may result in diminished performance.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short Term: 1, Medium Term: 1</i></td></tr>
<tr><td colspan="2">The supply risk for nickel is minimal given its large and geographically diverse production.</td></tr>
<tr><td>Basic Availability
<i>Short Term: 1</i>
<i>Medium Term: 2</i></td><td>• Current nickel production capacity appears sufficient to meet demand in the short term, but additional production capacity would be required in the medium term under the highest demand trajectory (Trajectory D).
• An additional 770,000 tonnes of nickel production capacity is under development, but this additional supply would still be insufficient to meet demand under the highest demand trajectory (Trajectory D).</td></tr>
<tr><td>Competing Technology Demand
<i>Short Term: 1</i>
<i>Medium Term: 1</i></td><td>• The majority of nickel is consumed in stainless steel production, which is unlikely to place significant additional strain on nickel supply.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
<i>Short Term: 1</i>
<i>Medium Term: 1</i></td><td>• With a relatively diverse group of producers, nickel production is unlikely to experience any significant supply risks associated with political, regulatory, or social factors.</td></tr>
<tr><td>Codependence on Other Markets
<i>Short Term: 1</i>
<i>Medium Term: 1</i></td><td>• Nickel is often mined as a primary product and is unlikely to experience significant issues related to codependence on other markets.</td></tr>
<tr><td>Producer Diversity
<i>Short Term: 1</i>
<i>Medium Term: 1</i></td><td>• Production of nickel is very diverse; the Philippines accounted for 25% of production in 2014, followed by Australia (11%), Canada (10%), and Russia (10%).</td></tr>
</table>

Historical Price and Production



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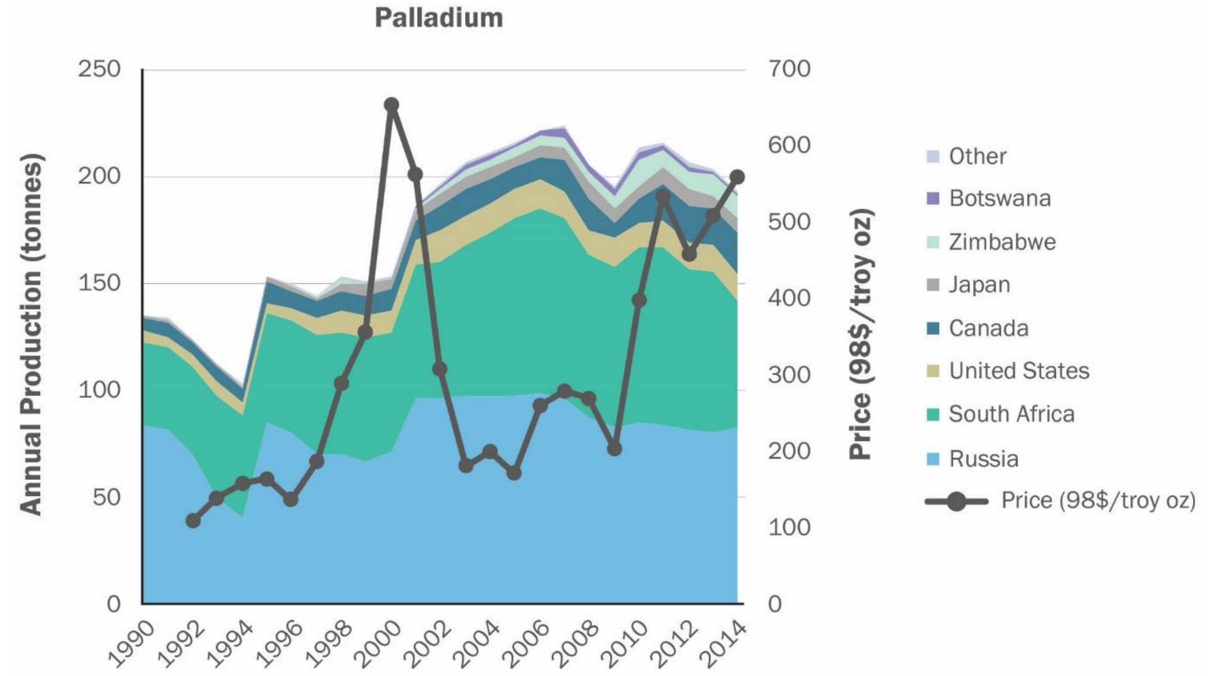
- National Science and Technology Council (NSTC), *Assessment of Critical Minerals: Updated Application of Screening Methodology* (Washington, DC: NSTC, 2018), https://www.whitehouse.gov/wp-content/uploads/2018/02/Assessment-of-Critical-Minerals-Update-2018.pdf.

<table>
<tr><th>Palladium (Pd)</th><th>Atomic Number: 46</th></tr>
<tr><td colspan="2">Palladium is a transition metal that is primarily used in vehicle catalytic converters, with some additional uses in the electronics, dental, and chemical industries.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short Term: 3, Medium Term: 2</i></td></tr>
<tr><td colspan="2">Use of palladium in energy applications constitutes a significant portion of total palladium demand, but this share could decrease as growth in energy demand lags behind potential growth in non-energy demand.</td></tr>
<tr><td>Energy Demand
<i>Short Term: 3</i>
<i>Medium Term: 2</i></td><td>• Energy demand for palladium could decrease from 61%–68% of total palladium demand in 2015 to 52%–65% of total palladium demand in 2030, depending on market penetration and material intensity.</td></tr>
<tr><td>Substitutability Limitations
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• The more expensive platinum can be used in place of palladium in catalytic converters, but it may face similar supply constraints because platinum and palladium are coproduced.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short Term: 2, Medium Term: 3</i></td></tr>
<tr><td colspan="2">The supply risk for palladium is moderate, driven by tightening automobile emissions standards in several countries, as well as political and social instability in the primary palladium-producing countries.</td></tr>
<tr><td>Basic Availability
<i>Short Term: 3</i>
<i>Medium Term: 4</i></td><td>• Tightening automobile emissions standards in China, Europe, and elsewhere will likely drive demand for palladium above current production capacity in the short term.
• Post-consumer recycling of catalytic converters constitutes 28% of palladium supply.</td></tr>
<tr><td>Competing Technology Demand
<i>Short Term: 1</i>
<i>Medium Term: 1</i></td><td>• Palladium use in the electronics, dental, and chemical industries is unlikely to increase demand pressure.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• Forty-three percent of 2014 palladium production was concentrated in Russia where political stability can impact mine output and prices.
• A significant share (30%) of 2014 palladium production also occurred in South Africa, where production is regularly interrupted due to safety failures, labor unrest, and ongoing restructuring of the platinum mining industry.</td></tr>
<tr><td>Codependence on Other Markets
<i>Short Term: 3</i>
<i>Medium Term: 3</i></td><td>• Palladium is mined directly at platinum mines, but about 50% of annual production is also recovered as a by-product of nickel mining.
• Production of palladium is subject to the concentration and prices of the other platinum group metals with which it is coproduced.</td></tr>
<tr><td>Producer Diversity
<i>Short Term: 2</i>
<i>Medium Term: 2</i></td><td>• Russia accounted for 43% of palladium production in 2014, followed by South Africa (30%), Canada (10%), and the United States (6%).</td></tr>
</table>

Historical Price and Production



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- U.S. Geological Survey (USGS), *Mineral Commodity Summaries* (Reston, VA: USGS, 2017), https://minerals.usgs.gov/minerals/pubs/mcs/.
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- N.T. Nassar, T.E. Graedel, and E.M. Harper, “By-product metals are technologically essential but have problematic supply,” *Science Advances* 1, no. 3 (2015): e1400180, doi:10.1126/sciadv.1400180.

Platinum (Pt) Atomic Number: 78

Platinum is a transition metal that is primarily used in vehicle catalytic converters and jewelry, with some additional uses in chemical and petroleum refining and electronics.

Importance to Energy: *Short Term: 3, Medium Term: 2*

Use of platinum in energy applications constitutes a significant portion of total platinum demand, but this share could decrease as growth in energy demand lags behind potential growth in non-energy demand.

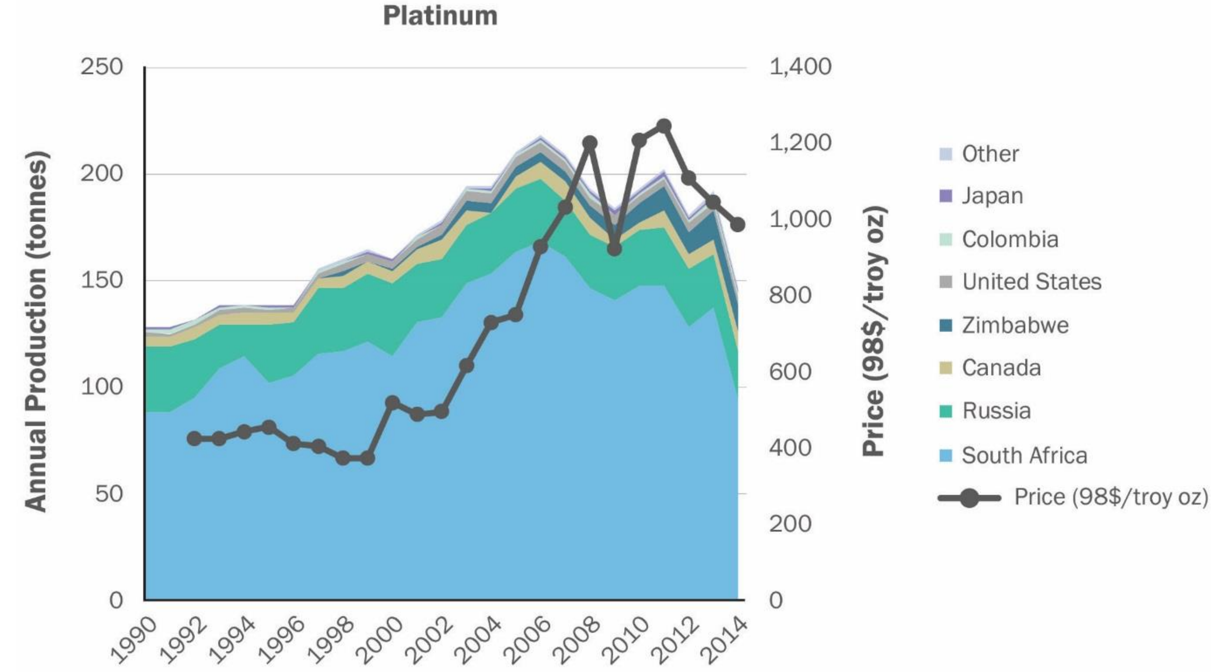
Energy Demand *Short Term: 3* *Medium Term: 2*	• Energy demand for platinum could decrease from 42%–50% of total platinum demand in 2015 to 33%–46% of total platinum demand in 2030, depending on market penetration and material intensity.
Substitutability Limitations *Short Term: 2* *Medium Term: 2*	• The less expensive palladium can be used in place of platinum in catalytic converters, but it may face similar supply constraints because palladium and platinum are coproduced.

Supply Risk: *Short Term: 2, Medium Term: 2*

The supply risk for platinum is low, but it may increase in the medium term if production is increasingly concentrated in South Africa, where mines are regularly faced with safety failures and labor unrest.

Basic Availability *Short Term: 1* *Medium Term: 2*	• Production capacity of platinum will be sufficient in the short term, but additional capacity would be needed in the medium term if any increases in material intensity due to regulatory changes occur. • Post-consumer recycling of catalytic converters constitutes 21% of platinum supply.
Competing Technology Demand *Short Term: 1* *Medium Term: 1*	• Use of platinum in jewelry is the largest competing demand, but it is unlikely to increase demand pressure.
Political, Regulatory, and Social Factors *Short Term: 3* *Medium Term: 3*	• Platinum production is concentrated in South Africa, where production is regularly interrupted due to safety failures, labor unrest, and ongoing restructuring of the platinum mining industry. • Political stability is also a factor for the second- and third-largest platinum-producing countries: Russia and Zimbabwe.
Codependence on Other Markets *Short Term: 3* *Medium Term: 3*	• Most platinum is mined directly, but some is also recovered as a by-product of nickel mining. • Production of platinum is subject to the concentration and prices of the other platinum group metals with which it is coproduced.
Producer Diversity *Short Term: 3* *Medium Term: 3*	• South Africa accounted for 64% of platinum production in 2014, followed by Russia (16%), Zimbabwe (9%), and Canada (6%). • Mine expansions in Zimbabwe are underway, which may increase producer diversity, but South African supply is also expected to increase because the labor strikes that halted production at several mines in 2014 have since ended.

Historical Price and Production



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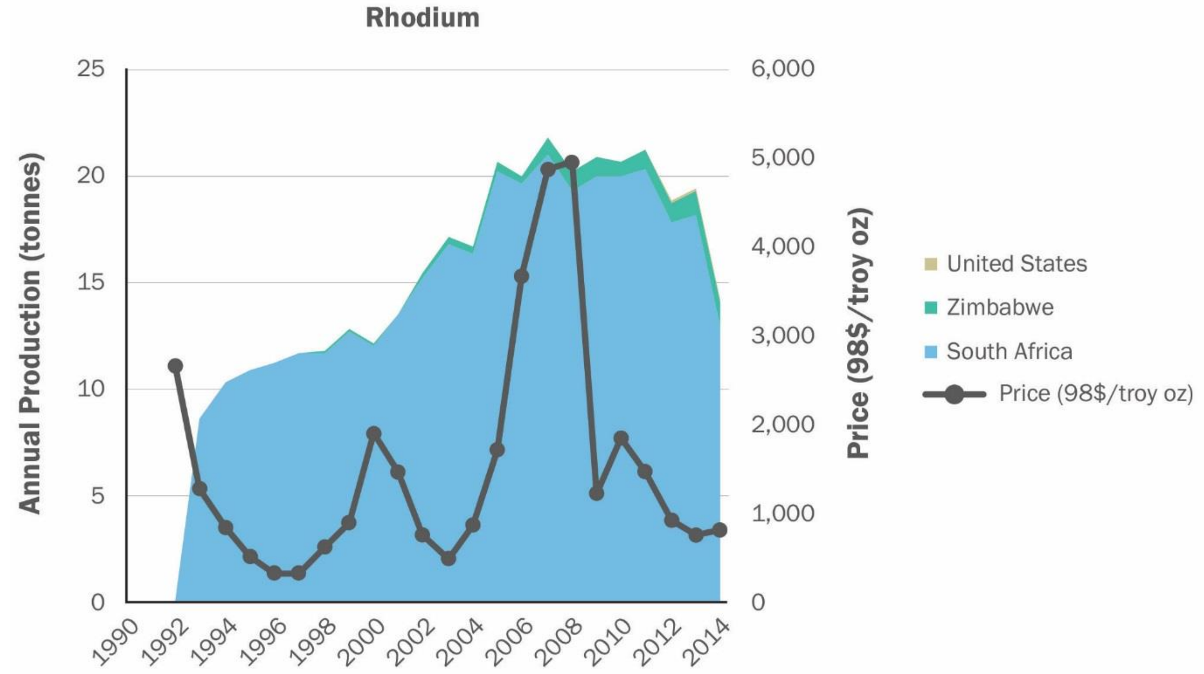
- N.T. Nassar, T.E. Graedel, and E.M. Harper, "By-product metals are technologically essential but have problematic supply," *Science Advances* 1, no. 3 (2015): e1400180, doi:10.1126/sciadv.1400180.

Rhodium (Rh)	Atomic Number: 45
Rhodium is a transition metal that is primarily used in vehicle catalytic converters, with some additional uses in glass manufacturing, chemical production, and electronics.	
Importance to Energy: *Short Term: 3, Medium Term: 3*	
Use of rhodium in energy applications constitutes a significant portion of total rhodium demand, but this share could decrease as growth in energy demand lags behind potential growth in non-energy demand.	
Energy Demand *Short Term: 3* *Medium Term: 2*	• Energy demand for rhodium could decrease from 76%–81% of total rhodium demand in 2015 to 68%–78% of total rhodium demand in 2030, depending on market penetration and material intensity.
Substitutability Limitations *Short Term: 4* *Medium Term: 4*	• Catalytic converters require rhodium for nitrogen oxides reduction, and there are no acceptable substitutes for this purpose.
Supply Risk: *Short Term: 3, Medium Term: 4*	
The supply risk for rhodium is moderate, driven by tightening automobile emissions standards in several countries, as well as political and social instability in the primary rhodium-producing countries.	
Basic Availability *Short Term: 3* *Medium Term: 4*	• Tightening automobile emissions standards in China, Europe, and elsewhere will likely drive demand for rhodium above current production capacity in the short term. • Post-consumer recycling of catalytic converters constitutes 34% of rhodium supply.
Competing Technology Demand *Short Term: 1* *Medium Term: 1*	• Rhodium use in glass manufacturing, chemical production, and electronics is unlikely to increase demand pressure.
Political, Regulatory, and Social Factors *Short Term: 3* *Medium Term: 3*	• Rhodium production is heavily concentrated in South Africa, where production is regularly interrupted due to safety failures, labor unrest, and ongoing restructuring of the platinum mining industry. • Political stability is also a factor for the second-largest rhodium-producing country: Zimbabwe.
Codependence on Other Markets *Short Term: 4* *Medium Term: 4*	• Most rhodium is mined at platinum mines, but some is also recovered as a by-product of nickel mining. • Production of rhodium is subject to the concentration and prices of the other platinum group metals with which it is coproduced.
Producer Diversity *Short Term: 4* *Medium Term: 4*	• South Africa accounted for 91% of rhodium production in 2014, followed by Zimbabwe (8%) and the United States (1%).

Historical Price and Production



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Tellurium (Te) Atomic Number: 52

Tellurium is a metalloid element that is primarily used in solar photovoltaic (PV) cells, thermoelectric applications, and metallurgical uses.

Importance to Energy: *Short Term: 2, Medium Term: 2*

Use of tellurium in energy applications could maintain a significant share of total tellurium demand, but this will depend on the deployment of cadmium telluride (CdTe) solar PV technologies.

Energy Demand *Short Term: 2* *Medium Term: 2*	• Tellurium requirements for solar PVs constitute a significant share of total tellurium demand (19%), but this will likely decrease unless CdTe solar PV technologies maintain market share and continue using material-intense formulations.
Substitutability Limitations *Short Term: 1* *Medium Term: 1*	• There are other thin-film solar PV technologies (copper-indium-gallium-diselenide) and crystalline silicon solar PV technologies that compete with CdTe. • Crystalline silicon modules are the favored solar PV technology with higher efficiencies and lower manufacturing costs, but some defense and aerospace applications rely on thin-film solar PVs because weight is important for performance. • Other thin-film solar PV technologies, such as single-junction gallium arsenide, have been developed but are prohibitively expensive to mass produce at this time.

Supply Risk: *Short Term: 2, Medium Term: 2*

The supply risk for tellurium is low. Producer diversity is favorable, but tellurium is constrained by its by-production with copper. However, there is opportunity to increase tellurium recovery rates.

Basic Availability *Short Term: 1* *Medium Term: 2*	• Production capacity of tellurium appears sufficient in the short term under all but the highest demand trajectory (Trajectory D). • Additional production capacity may be required in the medium term under the high penetration scenario (Trajectories C and D).
Competing Technology Demand *Short Term: 2* *Medium Term: 2*	• Tellurium is also used in thermoelectric production and metallurgy but has many substitutes in these applications.
Political, Regulatory, and Social Factors *Short Term: 1* *Medium Term: 1*	• With a relatively diverse group of producers, tellurium production is unlikely to experience any significant supply risks associated with political, regulatory, or social factors.
Codependence on Other Markets *Short Term: 4* *Medium Term: 4*	• Most tellurium is recovered as a by-product of copper production, but it is also found in lead ores. • Only 4.5% of the tellurium contained in copper deposits is recovered.
Producer Diversity *Short Term: 2* *Medium Term: 2*	• Obtaining precise tellurium production data is difficult, but production is fairly diverse.

Historical Price and Production

Not available.

References

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Vanadium (V) Atomic Number: 23

Vanadium is a transition metal that is primarily used as a hardening agent in steel, with some minor uses in catalysts and batteries.

Importance to Energy: *Short Term: 1, Medium Term: 1*

Use of vanadium in energy applications could increase if vanadium redox flow batteries retain a significant market share, but this would constitute a small share of total vanadium demand.

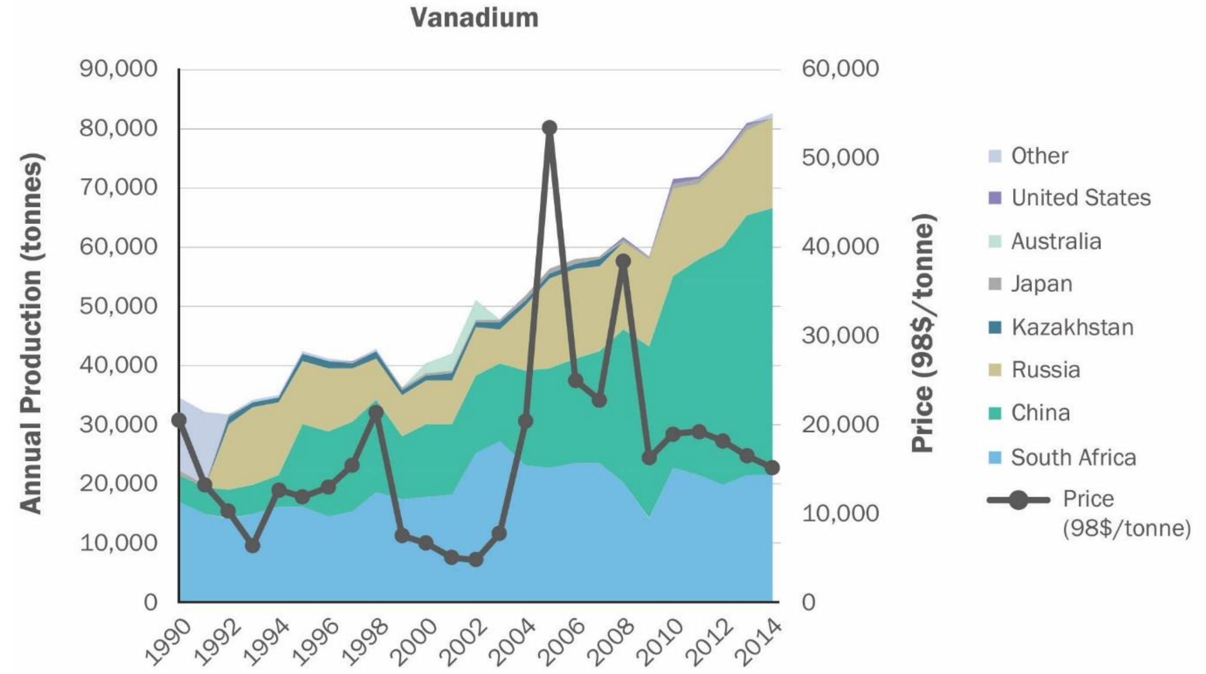
Energy Demand *Short Term: 1* *Medium Term: 1*	• If vanadium redox flow batteries maintain a significant market share in the high deployment scenario (Trajectories C and D), energy demand for vanadium could increase significantly between 2015 and 2030, but this would constitute a small share of total vanadium demand—2%–8%, depending on material intensity. • Much of the expected increase in demand for vanadium will come from non-energy applications.
Substitutability Limitations *Short Term: 2* *Medium Term: 2*	• Although lithium-ion batteries are favored in the electrochemical grid storage market, vanadium-consuming redox flow batteries are apt to provide unique grid services that may be difficult to deliver using other types of batteries. • Other types of redox flow batteries, such as zinc/bromine or iron/chromium, are available substitutes.

Supply Risk: *Short Term: 2, Medium Term: 2*

The supply risk for vanadium is moderate. Production is fairly diverse but concentrated in politically unstable countries. Significant competing technology demand could place strains on vanadium supply in the short term.

Basic Availability *Short Term: 2* *Medium Term: 2*	• Production capacity of vanadium appears insufficient in the short term, mostly due to demand growth in non-energy applications. • Very little vanadium production capacity is under development, but recent growth in demand has been met by expansions at existing production facilities.
Competing Technology Demand *Short Term: 2* *Medium Term: 2*	• Vanadium is primarily used as a hardening agent in steel, the demand for which is expected to follow general economic growth trends. • The use of vanadium in a wider range of steels has increased, but several alternative hardening agents are available.
Political, Regulatory, and Social Factors *Short Term: 2* *Medium Term: 2*	• With production concentrated in China, vanadium supply is susceptible to supply disruption due to political, regulatory, and social factors. • Political stability is also a factor for the second- and third-largest vanadium-producing countries: South Africa and Russia.
Codependence on Other Markets *Short Term: 2* *Medium Term: 2*	• A significant portion of vanadium supply is mined directly, but some is also recovered as a by-product of iron and aluminum mining.
Producer Diversity *Short Term: 3* *Medium Term: 3*	• Production of vanadium is fairly diverse, but China accounted for 54% of production in 2014, followed by South Africa (26%) and Russia (18%).

Historical Price and Production



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- U.S. Geological Survey (USGS), *Mineral Commodity Summaries* (Reston, VA: USGS, 2017), https://minerals.usgs.gov/minerals/pubs/mcs/.
- National Science and Technology Council (NSTC), *Assessment of Critical Minerals: Updated Application of Screening Methodology* (Washington, DC: NSTC, 2018), https://www.whitehouse.gov/wp-content/uploads/2018/02/Assessment-of-Critical-Minerals-Update-2018.pdf.

Appendix B : Material Intensity Calculations

The following sections describe the material intensity calculations and assumptions that underlie the material demand trajectories that appear in Chapter 3 (Use of Key Materials in Energy Technologies).

Solar Photovoltaics

Demand trajectories for key materials in solar photovoltaic (PV) cells consider two thin-film formulations: copper-indium-gallium-diselenide (CIGS) and cadmium telluride (CdTe). Following are the material intensity calculations for indium and gallium in CIGS solar PV cells and tellurium in CdTe solar PV cells. All assumptions used in the calculations were provided by the National Renewable Energy Laboratory.[1]

- **Indium intensity for CIGS:** In the high intensity scenario, indium represents 22% of the 5.75 grams per cubic centimeter (g/cm^3) of thin film included in a 2.0 micrometer (μm) absorber layer with an area-based module power rating of 157 watts per square meter (W/m^2). Assuming a utilization fraction of 55% and a recovery fraction of 25%, the material intensity for indium is 23 tonnes per gigawatt (GW) of solar PV capacity. In the low material intensity scenario, the module efficiency is improved to 20%, the layer thickness is reduced to 1.0 μm, and all of the unspent material on the sputtering or evaporation targets is recovered and recycled. This leads to a material intensity for indium of 6.3 tonnes/GW of solar PV capacity.
- **Gallium intensity for CIGS:** In the high intensity scenario, gallium represents 7% of the 5.75 g/cm^3 of thin film included in a 2.0 μm absorber layer with an area-based module power rating of 157 W/m^2. Assuming a utilization fraction of 55% and a recovery fraction of 25%, the material intensity for gallium is 7.5 tonnes/GW of solar PV capacity. In the low material intensity scenario, the module efficiency is improved to 20%, the layer thickness is reduced to 1.0 μm, and all of the unspent material on the sputtering or evaporation targets is recovered and recycled. This leads to a material intensity for gallium of 2.1 tonnes/GW of solar PV capacity.
- **Tellurium intensity for CdTe:** In the high intensity scenario, tellurium represents 53% of the 5.85 g/cm^3 of thin film included in a 2.5 μm absorber layer with an area-based module power rating of 128 W/m^2. Assuming a utilization fraction of 70% and a recovery fraction of 20%, the material intensity for tellurium is 69 tonnes/GW of solar PV capacity. In the low material intensity scenario, the module efficiency is improved to 18%, the layer thickness is reduced to 1.0 μm, and utilization efficiency is improved. This leads to a material intensity for tellurium of 17 tonnes/GW of solar PV capacity.

Magnets in Wind Turbines and Vehicles

Demand trajectories for key materials in magnets for wind turbines and electric vehicles (EVs) consider neodymium-iron-boron (NdFeB) permanent magnets[a]. Following are the material intensity calculations for neodymium and dysprosium in NdFeB permanent magnets that appear in wind turbines and EVs.

- **Neodymium and dysprosium intensity for magnets in wind turbines:** Material intensity for neodymium and dysprosium in wind turbine magnets is calculated from the estimated weight of

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[a] While some rare earth magnets also contain praseodymium and/or terbium, this analysis is examining neodymium and terbium only.

total NdFeB magnet material per megawatt of turbine capacity. High and low estimates for total magnet weight are 600 kilograms (kg)/megawatt (MW) and 200 kg/MW, respectively, based on a response provided by Arnold Magnetics to a U.S. Department of Energy (DOE) Request for Information.[2] The low range represents average content for a hybrid drive turbine, while the high range represents an average weight for a direct-drive turbine. Neodymium content is estimated to be 32% of magnet weight in the high intensity scenario and 20% of magnet weight in the low intensity scenario. The high intensity scenario represents current state of the art, while the low intensity scenario represents a potential future if stated goals of ongoing research into reducing neodymium content are achieved.[3] Dysprosium content is estimated to be 3% in the high intensity scenario and 0% in the low intensity scenario. The high intensity scenario represents dysprosium content for a typical permanent magnet in a wind turbine, while the low intensity scenario represents the potential to completely eliminate dysprosium from these magnets.[4] Some wind turbine manufacturers have already begun developing such dysprosium-free models.[5]

- **Neodymium and dysprosium intensity for magnets in plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles (AEVs):** Material intensity for neodymium and dysprosium in PHEV and AEV magnets is calculated from the estimated weight of total NdFeB magnet material per vehicle motor. For PHEVs and AEVs, the average weight of a magnet is assumed to be 2 kg/vehicle in the high intensity scenario. Typical permanent magnet motors in PHEVs and AEVs have magnets that weigh 1–2 kg,[6] but some PHEV and AEV manufacturers have successfully reduced the weight of a vehicle magnet by 50% using advanced rotor structures that produce higher torque densities with less magnetic material.[7] Thus, the low intensity scenario assumes an average magnet weight of 0.5 kg/vehicle. Neodymium content is estimated to be 30% of magnet weight in the high intensity scenario and 20% of magnet weight in the low intensity scenario. The high intensity scenario represents current state of the art, while the low intensity scenario represents a potential future if stated goals of ongoing research into reducing neodymium content are achieved.[8] Dysprosium content is estimated to be 7.5% in the high intensity scenario and 2.5% in the low intensity scenario. The high intensity scenario represents dysprosium content for a typical permanent magnet in a PHEV or AEV, while the low intensity scenario represents the potential to significantly reduce dysprosium content using more efficient production processes, such as grain boundary diffusion.[9]
- **Neodymium and dysprosium intensity for magnets in hybrid electric vehicles (HEVs):** Material intensity for neodymium and dysprosium in HEV magnets is calculated from the estimated weight of total NdFeB magnet material per vehicle motor. For HEVs, the average weight of a magnet is assumed to be 0.42 kg/vehicle in the low intensity scenario and 0.84 kg/vehicle in the high intensity scenario. Permanent magnets in HEVs weigh less than those in PHEVs and AEVs because the electric motor is a secondary propulsion source in an HEV and thus requires 58% less magnetic material.[10] Neodymium content is estimated to be 30% of magnet weight in the high intensity scenario and 20% of magnet weight in the low intensity scenario. The high intensity scenario represents current state of the art, while the low intensity scenario represents a potential future if stated goals of ongoing research into reducing neodymium content are achieved.[11] Dysprosium content is estimated to be 7.5% in the high intensity scenario and 0% in the low intensity scenario. The high intensity scenario represents dysprosium content for a typical permanent magnet in an HEV, while the low intensity scenario represents the potential

to completely eliminate dysprosium from these magnets. This is possible in HEVs because temperature requirements are not as high for hybrid motors. Honda has successfully eliminated dysprosium from magnets used in some of its hybrid models.[12]

Batteries in Vehicles

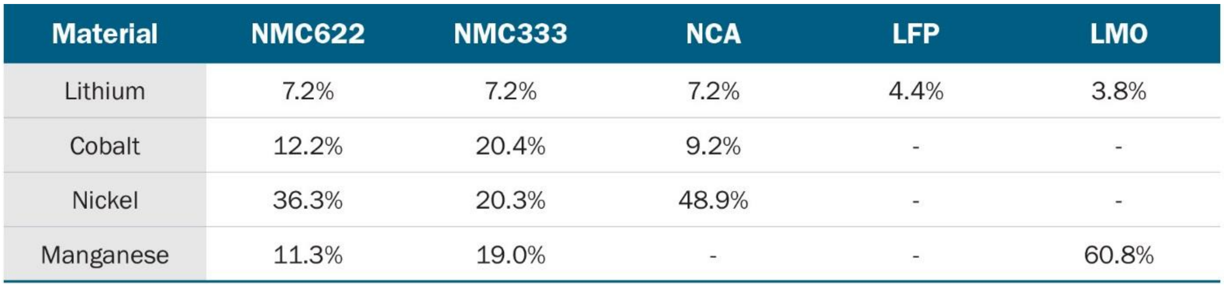
Demand trajectories for key materials in batteries for EVs consider two battery types: lithium-ion (Li-ion) and nickel-metal hydride (NiMH). Following are the material intensity calculations for lithium, cobalt, nickel, and manganese in Li-ion batteries for HEVs, PHEVs, and AEVs, as well as the material intensity calculations for lanthanum, cerium, neodymium, cobalt, nickel, and manganese in NiMH batteries for HEVs.

- **Lithium, cobalt, nickel, and manganese intensity for Li-ion batteries in HEVs, PHEVs, and AEVs:** Material intensity for lithium, cobalt, nickel, and manganese in Li-ion EV batteries is calculated using output from Argonne National Laboratory's Battery Performance and Cost (BatPaC) model.[13] BatPaC is a highly detailed Li-ion battery performance and cost model for electric-drive vehicles. It is used to understand the interplay between materials, design, performance, costs, and integration. Key inputs include battery size (in kilowatt-hours [kWh]), cathode chemistry, and vehicle type (*i.e.*, HEV, PHEV, and AEV). A variety of battery sizes and cathode chemistries were considered. Battery sizes were chosen to reflect vehicle ranges of currently available models for each vehicle type (Table B-1). Five battery chemistries were examined: two nickel manganese cobalt chemistries (NMC622/NMC333), one nickel cobalt aluminum chemistry (NCA-G), one lithium iron phosphate chemistry (LFP-G), and one lithium manganese oxide chemistry (LMO-G). Using these inputs, BatPaC generates the amount of cathode material per cell, the number of cells per battery, and the amount of lithium in the electrolyte. Using these outputs and the stoichiometry ratios for key materials in each cathode chemistry (Table B-2), the total amount of each key material per battery is calculated for each cathode chemistry for a given vehicle type and battery size.

Table B-1. Assumed Li-Ion Battery Sizes and Resulting Vehicle Ranges by Vehicle Type

Vehicle Type	Size (kWh)	Range (miles)
HEV	4	4
PHEV	10	28
	20	56
AEV	30	102
	100	340

Table B-2. Stoichiometric Ratios for Key Materials in Select Li-Ion Battery Cathode Chemistries



Material	NMC622	NMC333	NCA	LFP	LMO
Lithium	7.2%	7.2%	7.2%	4.4%	3.8%
Cobalt	12.2%	20.4%	9.2%	-	-
Nickel	36.3%	20.3%	48.9%	-	-
Manganese	11.3%	19.0%	-	-	60.8%

For each vehicle type, the material requirements for the smaller battery size with the least material-intense chemistry was chosen for the low intensity assumption and the material requirements for the larger battery size with the most material-intense chemistry was chosen for the high intensity assumption (Table B-3).

Table B-3. Material Intensity for Key Materials in Li-Ion Batteries for EVs

Vehicle Type	Low/High Intensity	Battery Size (kWh)	Range (miles)	Material	Material Content (kg)	Cathode Chemistry
HEV	Low	4	4	Lithium	0.4	LFP
				Cobalt	0	LFP/LMO
				Nickel	0	LFP/LMO
				Manganese	0	NCA/LFP
	High	4	4	Lithium	0.5	NMC333
				Cobalt	1.4	NMC333
				Nickel	2.7	NCA
				Manganese	6.2	LMO
PHEV	Low	10	28	Lithium	1.0	LFP
				Cobalt	0	LFP/LMO
				Nickel	0	LFP/LMO
				Manganese	0	NCA/LFP
	High	20	56	Lithium	2.7	NMC333
				Cobalt	7.3	NMC333
				Nickel	13.5	NCA
				Manganese	31.0	LMO
AEV	Low	30	102	Lithium	3.0	LFP
				Cobalt	0	LFP/LMO
				Nickel	0	LFP/LMO
				Manganese	0	NCA/LFP
	High	100	340	Lithium	13.5	NMC333
				Cobalt	36.9	NMC333
				Nickel	68.3	NCA
				Manganese	156.1	LMO

- **Lanthanum, cerium, neodymium, cobalt, nickel, and manganese intensity for NiMH batteries in HEVs:** Material intensity for lanthanum, cerium, neodymium, cobalt, nickel, and manganese in NiMH EV batteries is calculated using several assumptions about capacity and chemistry for a battery with a power rating and cell voltage equivalent to the battery used in a third-generation Toyota Prius. The 2011 *Critical Materials Strategy* report employed the same methodology. A total power rating of 1.3 kWh and 1.2 volts per cell results in a total positive electrode capacity of 1,083 ampere-hours (Ah). Assuming a 1.2–1.8 ratio of negative electrode capacity to positive electrode capacity results in a negative electrode capacity ranging from 1,300 Ah to 1,950 Ah. Assuming 300 Ah of negative electrode capacity per kilogram of negative electrode weight, the negative electrode weight ranges from 4.3 kg in the low intensity scenario to 6.5 kg in the high intensity scenario. The negative electrode alloy is assumed to be AB5, which has the composition shown in Table B-4.

Table B-4. Material Intensity for Key Materials in NiMH Batteries for HEVs

Material	Share of Negative Electrode Alloy (AB5) Weight	Material Content (kg)	
		Low Intensity	High Intensity
Lanthanum	11.2%	0.49	0.73
Cerium	15.9%	0.69	1.03
Neodymium	4.7%	0.20	0.31
Cobalt	10.2%	0.44	0.66
Nickel	49.2%	2.13	3.20
Manganese	5.3%	0.23	0.34
Other	3.5%	0.15	0.23
Total	**100%**	**4.3**	**6.5**

Lightweighting in Vehicles

Demand trajectories for key materials in vehicle lightweighting consider high-strength steel, aluminum alloys, and magnesium alloys. Other plastics and carbon fiber, while important lightweighting materials, were not examined. To estimate the amount of manganese and magnesium per vehicle, three representative lightweighting packages were developed (Table B-5). The standard lightweighting package represents typical amounts of lightweighting material found in many current vehicle models. The two advanced lightweighting packages represent increased use of lightweighting materials and further reductions in weight. The low intensity advanced lightweighting package results in a 10% reduction in vehicle weight and the high intensity advanced lightweighting package results in a 22% reduction in vehicle weight. The weight reductions were applied to a weighted average vehicle mass for the United States and the rest of the world, which were calculated using data on the average mass of a heavy-duty vehicle,[b,14,15] the average mass of a light-duty vehicle by country,[16] and the sales of both light- and heavy-duty vehicles by country.[17]

Table B-5. Vehicle Weight and Material Blend for Assumed Lightweighting Packages[18]

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[b] The average mass of a heavy-duty vehicle is assumed to be the average of the weights of a Class 7 and a Class 8 heavy-duty vehicle.

	Standard Lightweighting	Advanced Lightweighting	
		Low Intensity	High Intensity
Reduction in Weight	0%	10%	22%
Vehicle Weight (U.S.)	2,144 kg	1,930 kg	1,673 kg
Vehicle Weight (rest of world)	2,083 kg	1,875 kg	1,625 kg
Lightweighting Materials (share of vehicle weight)			
High-Strength Steel	14%	17%	31%
Aluminum Alloys	8%	16%	24%
Magnesium Alloys	0%	0.8%	1.3%

The following are the material content calculations for manganese in high-strength steel and aluminum alloys, as well as magnesium in aluminum alloys and magnesium alloys as lightweighting materials for vehicles.

- **Manganese intensity for high-strength steel in vehicles:** Manganese is assumed to constitute 2% of the weight of high-strength steel used in vehicle lightweighting. Some high-strength steels can contain 17%–24% of manganese (by weight),[19] but these are advanced high-strength steels (*e.g.*, twinning-induced plasticity steel) that are less common in vehicle lightweighting applications. Dual phase and transformation-induced plasticity (TRIP) steels are more common and contain roughly 2% manganese (by weight).[20,21]
- **Manganese and magnesium intensity for aluminum alloys in vehicles:** Manganese is assumed to constitute 0.13% of the weight of aluminum alloys used in vehicle lightweighting. Magnesium is assumed to constitute 1.3% of the weight of aluminum alloys used in vehicle lightweighting. These are weighted averages assuming 80% of the aluminum alloys used in vehicle lightweighting (by weight) are a typical 5000 series alloy (5182-O) and 20% of the aluminum alloys used in vehicle lightweighting (by weight) are a typical 6000 series alloy (6022-T4). The magnesium and manganese content for these aluminum alloys are shown in Table B-6. The two primary types of aluminum alloys used in vehicles are 5000 (aluminum/magnesium) series and 6000 (aluminum/magnesium/silicon) series alloys.

Table B-6. Material Content for Key Materials in Aluminum Alloys for Vehicle Lightweighting

Material	Alloy	Share of Alloy Weight
Magnesium	5000 Series (5182-0)	4.5%
	6000 Series (6022-T4)	0.55%
Manganese	5000 Series (5182-0)	0.4%
	6000 Series (6022-T4)	0.06%

- **Magnesium intensity for magnesium alloys in vehicles:** Magnesium is assumed to constitute 100% of the weight of magnesium alloys used in vehicle lightweighting.

The material content of manganese in high-strength steel and aluminum alloys and the material content of magnesium in aluminum alloys and magnesium alloys described above were applied to the lightweighting packages described in Table B-5. The resulting material intensities for manganese and magnesium in vehicle lightweighting are shown in Table B-7.

Table B-7. Material Intensity for Key Materials in Assumed Vehicle Lightweighting Packages (kg per vehicle)

Material	Standard Lightweighting		Advanced Lightweighting			
			Low Intensity		High Intensity	
	United States	Rest of World	United States	Rest of World	United States	Rest of World
Magnesium	2.3	2.2	19.6	19.0	27.1	26.3
Manganese	6.2	6.0	7.0	6.8	10.9	10.6

Catalytic Converters in Vehicles

Demand trajectories for key materials in catalytic converters use current global average platinum group metal and cerium requirements in the low material intensity scenario. These are 1.9 g of palladium, 1.0 g of platinum, 0.26 g of rhodium, and 75 g of cerium per vehicle.[22,23] The high intensity scenario takes into account two potential opposing trends: reductions in engine size (decreasing material intensity) and additional global regulatory stringency (increasing material intensity). The U.S. Environmental Protection Agency estimates that average vehicle engine size has decreased by 1.55% annually since 1975.[24] If this trends continues, average engine size and associated material requirements can be expected to decrease by 20% between 2015 and 2030. Recent analysis by DOE shows that, absent any technological improvements, expected increases in global regulatory stringency could increase material requirements for catalytic converters by 70%.[25] Combining these two potential opposing trends results in a 36% net increase in material intensity and, thus, a high intensity scenario where catalytic converters require 2.6 g of palladium, 1.4 g of platinum, 0.35 g of rhodium, and 100 g of cerium per vehicle.

Light-Emitting Diodes

Demand trajectories for key materials in LEDs use estimates of material requirements for mid-power LEDs, which have been common in non-directional general lighting applications and are expected to continue being the favored package type in the medium term. The high material intensity scenario assumes that sales of LEDs will require 250,000 kg of gallium and 330 kg of indium per teralumen. These are unofficial estimates provided by DOE's Solid-State Lighting Program. Because material intensity is directly linked to efficacy (lumen per watt [lm/W]), the low material intensity scenario assumes that material intensity could potentially improve in concert with the DOE Solid-State Lighting Program's efficacy targets (255 lm/W), which are an 86% improvement over the current state of the art (137 lm/W).[26] This results in a low material intensity scenario that assumes sales of LEDs will require 35,000 kg of gallium and 50 kg of indium per teralumen.

Batteries in Grid Storage

Demand trajectories for key materials in batteries for grid storage consider two battery types: Li-ion batteries and vanadium redox flow batteries (VRBs). Following are the material intensity calculations for lithium, cobalt, nickel, and manganese in Li-ion batteries, as well as vanadium in VRBs.

- **Lithium, cobalt, nickel, and manganese intensity for Li-ion batteries in grid storage:** Material intensity for lithium, cobalt, nickel, and manganese in Li-ion grid storage batteries is calculated using output from Argonne National Laboratory's BatPaC model.[27] Although BatPaC is designed for vehicle batteries, which have different system configurations and power requirements than grid storage batteries, the difference in material intensity between an AEV and a grid storage battery is assumed to be minimal. A variety of cathode chemistries were considered for a battery size of 200 kWh: NMC622, NMC333, NCA-G, LFP-G, and LMO-G. Using these inputs, BatPaC generates the open-circuit voltage at full power, the active material-specific capacity, and the amount of lithium in the electrolyte. Using these outputs and the stoichiometry ratios for key materials in each cathode chemistry (Table B-2), the total amount of each key material per battery is calculated for each cathode chemistry. Assuming a power-to-energy ratio of 0.25 watts per watt-hour, material intensities per gigawatt of grid storage battery capacity were calculated. For each material, the material requirements for the least material-intense cathode chemistry was chosen for the low intensity assumption and the material requirements for the most material-intense cathode chemistry was chosen for the high intensity assumption (Table B-8).

Table B-8. Material Intensity for Key Materials in Li-Ion Batteries for Grid Storage

Material	Low/High Intensity	Material Content (tonnes/GW)	Cathode Chemistry
Lithium	Low	506	NCA
	High	641	NMC333
Cobalt	Low	0	LMO/LFP
	High	1,495	NMC333
Nickel	Low	0	LFP/LMO
	High	2,752	NCA
Manganese	Low	0	NCA/LFP
	High	6,353	LMO

- **Vanadium for VRBs in grid storage:** Material intensity for vanadium in grid-scale VRBs is calculated based on several assumptions about electrolyte solution molarity and a typical VRB size provided by *Linden's Handbook of Batteries*.[28] In the low intensity scenario, a 75 kWh battery is assumed to require 2,500 liters of vanadium electrolyte with a solution molarity of 1 mole per liter. In the high intensity scenario, a 75 kWh battery is assumed to require 4,000 liters of vanadium electrolyte with a solution molarity of 2.4 moles per liter. Using the molecular weight of vanadium, and assuming a power-to-energy ratio of 0.25 watts per watt-hour, low and high material intensities per gigawatt of grid storage battery capacity were calculated. In the low material intensity scenario, each gigawatt of grid storage battery capacity requires 6,365 tonnes of vanadium. In the high material intensity scenario, each gigawatt of grid storage battery capacity requires 24,450 tonnes of vanadium.

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