U.S. DEPARTMENT OF
ENERGY

DRAFT REPORT

Critical Materials Assessment

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Preface

This is a preliminary draft report that compiles core analysis for DOE’s critical materials assessment. The draft report is being issued to solicit public comment on the analysis. The final report will contain additional content that interprets the analysis and presents findings and conclusions.

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1. Introduction

Materials are essential to manufacturing products that maintain our modern lives. Many of these materials are embedded in components and systems of critical infrastructure with national security importance such as energy, communications, transportation, and water. In addition, as the world aims to reach net zero greenhouse gas emissions in 2050 (United Nations, 2022), increased demand for clean energy and decarbonization technologies requires a different set of material supply chains from those powering the fossil fuel economy. Understanding the degree to which certain energy technologies rely on these materials is important for meeting climate policy goals, reducing carbon emissions, and preventing environmental damage. Many of these materials are concentrated in a small number of countries, are produced as by-products, or are associated with small markets and geopolitical challenges that lead to volatile prices and material availability concerns (Mancheri, 2015). As demand for these materials increases to achieve clean energy and decarbonization goals, the need to anticipate their criticality and develop a strategy to mitigate risks to decarbonizing the global economy is growing.

The U.S. Department of Energy (DOE) has an established history of conducting material criticality assessments to inform its critical material strategies. These reports include the 2010 Critical Materials Strategy (CMS) (Bauer et al., 2010), 2011 CMS (Bauer et al., 2011), and 2019 CMS (DOE, 2019). These strategies help DOE prioritize research and development (R&D) efforts to meet the nation’s energy needs while reducing reliance on materials with high supply risk. DOE’s definition of material criticality includes both importance to energy applications and supply risk. DOE’s criticality assessments are forward looking in that they incorporate demand trajectories based on growth scenarios for various energy technologies coupled with assumptions about the material intensity of those technologies. Specifically, these reports have each provided criticality assessments for the short term (0–5 years) and medium term (5–10 years). Meanwhile, the Energy Act of 2020 authorizes the Secretary of Energy to determine critical materials[1]. This Critical Materials (CM) Assessment report continues the DOE's systemic analyses of materials criticality, in part to inform the critical materials determination under the Energy Act of 2020.

Material criticality assessments have also been conducted by other organizations, both within the United States and in other countries. For example, the 2022 Critical Mineral List produced by the U. S. Geological Survey (USGS) evaluates the criticality of minerals based on economic vulnerability and disruption potential from 2018 to 2021 (Nassar and Fortier, 2021), and the critical raw material assessment conducted by the European Union considers non-energy raw materials for economic importance and supply risk for the 2016–2020 period (Grohol and Veeh, 2023). While similar, the DOE assessments differ in that they are focused specifically on the importance of materials to energy and decarbonization technologies and are performed with an eye to the future. The current report also incorporates selected engineered materials in addition to elements.

Like previous reports, this analysis provides a range of possible demands for selected materials based on various deployment scenarios, levels of sub-technology market penetration, and material intensities. To evaluate supply risk, projected demand is compared against current production capacity to estimate the supply

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[1] Section 7002(a)(2) of the Energy Act of 2020 (codified at 30 U.S.C. § 1606(a)(2)) authorizes the Secretary of Energy to determine critical materials according to the following statutory definition of a “critical material”:
Any non-fuel mineral, element, substance, or material that the Secretary of Energy determines: (i) has a high risk of a supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy; or a critical mineral [as designated by the Secretary of the Interior]

gap while also considering social, political, and other market disruption factors. Rather than predicting the future, the goal is to understand potential roadblocks to energy deployment in the short term (2020–2025) and medium term (2025–2035) and help inform R&D investments and policy engagement. By anticipating criticality, DOE can proactively reduce medium- and long-term material criticality by investing in R&D that reduces the reliance of energy technologies on critical materials and promotes the diversification of material supply.

This report has seven chapters, including this introduction. The remaining sections in this chapter include an overview of the scope of this report and brief overviews of the markets for the energy technologies considered herein, with a specific focus on updates that have occurred in the market since drafting of the 2019 version of the CMS. Chapter 2 discusses the method for screening and selecting key materials to be evaluated in the overall material criticality assessment. Chapter 3 details the criticality assessment methodology and discusses the results of the analysis.

The report also includes several appendices with additional information pertaining to the analysis. Appendix A provides detailed information used to conduct the criticality assessment for each key material. Appendix B provides assumptions about material intensities used in the material demand trajectories for the technologies considered. Appendix C provides additional detail about the scores received by materials in the screening process described in Chapter 3. Finally, Appendix D provides the demand trajectories used to conduct the criticality assessment, as well as assumptions used to derive the trajectories for each key material.

1.1 Scope and assessment process

This CM Assessment introduces a number of key differences from previous reports. Namely, it (1) includes a more formal screening process to determine which materials are included in the assessment, (2) considers a number of engineered materials in addition to natural raw materials, and (3) introduces a scoring rubric with defined thresholds and criteria to determine scores for each factor contributing to determine a material’s importance to energy and supply risk.

As in previous reports, this report is global in scope. It presents material criticality assessments for both the short term and the medium term. This report defines the short term as the period from 2020 to 2025 and the medium term as 2025 to 2035.

In 2022, DOE released 11 reports as part of its one-year response to Executive Order 14017 on Securing America’s Supply Chains. These “supply chain deep dive” reports evaluate the potential vulnerabilities to the supply chains that make up the country’s Energy Sector Industrial Base and that contribute toward decarbonizing the U.S. economy. This report leverages the findings of the supply chain deep dives, which serves to expand the scope of this assessment to include a larger set of technologies and materials, including a number of engineered materials.

A list of candidate materials was first derived from these DOE supply chain assessments. These reports cover technologies such as carbon capture (Suter et al., 2022), electric grid including transformers and high-voltage direct current transmission (Nguyen et al., 2022), energy storage (Mann, Putsche, and Shrager, 2022), fuel cells and electrolyzers (Badgett et al., 2022), hydropower including pumped storage hydropower (Uría-Martínez, 2022), rare earth magnets (Smith et al., 2022b), nuclear energy (Finan et al., 2022), platinum group metal catalysts (Smith et al., 2022a), semiconductors (Mann and Putsche, 2022), solar photovoltaics (PVs) (DOE, 2022), and wind energy (Baranowski et al., 2022). The candidate material list is further refined in consultation with experts from various DOE offices. The final candidate list has 37 materials along with their technologies, as shown in Table 1.1. They are aluminum (Al), boron (B), cobalt (Co), copper (Cu), dysprosium (Dy), electrical steel, fluorine (F), gallium (Ga), gallium nitride (GaN), germanium (Ge), indium (In), iridium (Ir), iron (Fe), lanthanum (La), lithium (Li), magnesium (Mg), manganese (Mn), mixed rare earth oxide (MREO), natural graphite, neodymium (Nd), nickel (Ni), palladium (Pd), phosphorous (P), praseodymium (Pr), platinum (Pt), rhodium (Rh), silicon (Si), silicon carbide (SiC), sodium (Na), strontium (Sr), sulfur (S), tellurium (Te), titanium (Ti), uranium (U), vanadium (V), yttrium (Y), zinc (Zn), and zirconium (Zr).

There are four main categories of energy applications considered in this report, including (1) generation, (2) transmission, (3) storage, and (4) end-use applications with a focus on energy efficiency. Regarding materials, there is a minor modification compared to previous reports where some engineered materials such as silicon carbide (SiC) and electrical steel are included alongside minerals as a test case for the assessment framework. If successful, future efforts will include more manufactured materials important for energy applications, and better understanding of the supply risk is needed.

Table 1.1 Candidate technologies and materials considered in this report.

Energy Application Categories	Technology	Components/ Subtechnology	Materials
Transmission	HVDC*	Converters, transformers, breakers, and switches	Cu, Ge, Ni, electrical steel, SiC
	HVAC*	Transformers	Cu, electrical steel
Generation	Nuclear	Fuels[2], moderators	U, Zr, natural graphite, electrical steel
	Solar	PVs	Si, Te, Ga, In
	Wind	Off-shore	Cu, Nd, Pr, Dy, B, electrical steel
		Land-based	Cu, electrical steel
Energy storage	Fuel cells	Stationary hydrogen to electricity conversion	Pt, Graphite, La, Sr, Co, Ni, Y, Zr, Mn
	Batteries	Lithium-ion batteries, zinc air, iron air, sodium air, flow batteries	Li, Co, Ni, graphite, V, Zn, Fe, Al, Na, S, P, F
End-use	Lighting	LED*	Ga
	Consumer electronics	Power electronics	GaN, SiC
	Electric vehicles	Power electronics	SiC
		Lightweighting	Mn, Mg, Al, Ni, Si
		Magnets	Nd, Pr, Dy, B, Fe
		Batteries	Li, Ni, Mn, Co, graphite, Al, Fe, P, LREEs*

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[2] Under section 7002 of the Energy Act of 2020, materials may not be designated as critical materials by the Secretary of Energy based on their fuel uses; however, to provide the public with complete information and to inform relevant DOE decisions making, this report has analyzed uranium, including based on its fuel uses, under the same methodology used for other materials.

Energy Application Categories	Technology	Components/ Subtechnology	Materials
		Motors	Electrical steel, Cu
		Wiring	Cu
	Optoelectronics	Microchips	Ge
	Vehicles	Lightweighting	Mn, Mg, Al, Ni, Si
		Catalysts	Pt, Pd, Rh
		Motors	Electrical steel, Cu
		Fuel cells	Pt, Graphite, La, Sr, Co, Ni, Y, Zr, Mn
		Wiring	Cu
	Hydrogen	Hydrogen electrolyzers	Pt, Ir, Ti, La, Sr, Co, Ni, Y, Zr, Mn

* HVAC = high-voltage alternating current; HVDC = high-voltage direct current; LED = light-emitting diode, LREE = light rare-earth elements.

1.2 Market developments since the 2019 report

Since the last DOE CMS report, several major global events have significantly affected global material supply chains. The Covid-19 pandemic has lengthened the lead time for multiple energy products due to labor shortages (Nguyen et al., 2022; Uría-Martínez, 2022), material shortages (Baranowski et al., 2022; Shih, 2020), reduced capacity (Smith et al., 2022a) or delayed capacity development (Turk & Kamiya, 2020). Additionally, Russia's invasion of Ukraine has limited both the amount of energy and the supply of some materials to the U.S and European countries, including of natural gas, crude oil, coal, palladium, nickel, corn, wheat, timber, and fertilizers (Fyfe, 2022). As a result, pressure on obtaining additional supply from other countries in Asia has increased, leading to higher prices. The International Energy Agency (IEA) reported that increased fuel prices were responsible for 90% of increased average generation costs for electricity on a global basis (IEA, 2022b). While the global pandemic did not affect the growth of certain clean technologies such as electric vehicles (EVs) (Turk & Kamiya, 2020), Russia's invasion of Ukraine has boosted near-term demand for oil and gas and has also changed the way various governments plan for energy security and deploy clean energy in the medium term to meet zero carbon emissions by 2050 (IEA, 2022b). The following sections provide a brief overview of market developments in several energy technologies that are included in this report.

1.2.1 Electric vehicles

EV use has continued to grow rapidly worldwide, with global sales increasing from 716,000 vehicles in 2015 to 10.6 million vehicles in 2022 (IEA, 2023). While growth in EV use has been strong throughout the world, it has been led by China, which accounted for 60% of new EV registrations worldwide in 2022, including sales of cars, trucks, vans, and buses (IEA 2023). These numbers include fully battery-powered electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), which can run on a combination of battery power and gasoline and offer owners the ability to recharge batteries from wall outlets or charging stations. The average range of EVs sold in the U.S. has also grown rapidly, increasing from about 155 miles in 2015 to almost 300 miles in 2021 (Gohlke et al., 2022). The rapid growth in electric vehicle sales has put pressure on key components such as lithium-ion batteries and NdFeB magnets.

1.2.2 Electric vehicle batteries

Lithium-ion batteries continue to be used in almost all plug-in electric vehicles. There have been some developments in the cathode chemistries most commonly used in the last few years. Nickel-manganese-cobalt (NMC) chemistries continue to be popular, with trends toward high nickel chemistries such as NMC 622 and 811 (and possibly 955 in the near future) over NMC 333 or 433. Lithium-iron-phosphate (LFP) batteries have also become increasingly popular, especially in China. Some lithium nickel-cobalt-aluminum oxide (NCA) batteries continue to be used as well, while lithium-ion manganese oxide (LMO) batteries are no longer widely used in vehicles. Key materials used in these batteries include lithium, nickel, cobalt, manganese, aluminum, phosphorous, iron, graphite, silicon, and fluorine.

1.2.3 Vehicle lightweighting alloys

Materials used in the automobile industry are essential to increasing fuel efficiency and utilizing less energy while maintaining the same performance to meet modern demands. To increase the fuel economy of modern vehicles, the automobile industry has been transitioning from cast iron and traditional steel to lightweight materials such as high-strength steels, magnesium alloys, aluminum alloys, carbon fiber, and polymer composites. This replacement can be applied to almost all vehicles, and the automobile industry is pushing to expand the application of the lightweight materials to all vehicle types, including internal combustion engine (ICE), electric, hybrid, and commercial vehicles (Czerwinski, 2021). In particular, aluminum alloys offer a number of advantages over traditional materials, such as steel, including their lighter weight, high strength, and corrosion resistance. Since 2010, aluminum usage in the automotive industry has grown from 340 pounds per vehicle to 459 pounds per vehicle in 2020 and is expected to grow 12% by 2026 (Czerwinski, 2021). Additionally, high-strength steel alloys increasingly are becoming an integral part of lightweighting of vehicles. In 2021, the average vehicle contained 65% steel, up 5% since 2010 (Hu and Feng, 2021). With such a high percentage of the car containing steel, the utilization of high-strength, low-weight steel is looking to be more widely implemented in vehicles.

With EV sales projected to increase 30–35% among passenger vehicles by 2030 as consumer preferences are expected to shift from internal combustion engine (ICE) to EVs, the need for EV lightweighting is expected to grow over the coming years (Czerwinski, 2021). Lightweighting has a substantial impact on the cost of BEVs due to the frame architecture of the cars. As the industry begins to lightweight both ICE and EVs, the materials required to do so are projected to reach a value of $99.3 billion in 2025 (Czerwinski, 2021). By 2025, weight reduction from design optimization, material selection, and part-count reduction for EVs is expected to reach 10–15% by 2025 and 20–30% by 2035 (Czerwinski, 2021).

The EV industry has been adopting and will continue to adopt these technologies, but recent circumstances have forced the industry to consider other focus points on the manufacturing of their vehicles. In electric vehicles produced with both an ICE and electric option, the weight of the EV version is approximately 1,000 pounds heavier than the ICE version (Halonen, 2022). This weight issue also extends to commercial trucking, where a class 8 commercial truck can be 3,000–6,000 pounds heavier than an ICE model (Halonen, 2022). To combat the EV's extra weight, many manufacturers are turning to aluminum due to its strength-to-weight ratio. However, lightweighting materials are more costly than steel, and the new capital cost of equipment, tooling, and ease of manufacturing sometimes does not justify the cost. In the fourth quarter (Q4) of 2021, the cost of raw materials increased around $7,000 per vehicle, shifting cost and profit considerations to the forefront of manufacturing decision-making (Halonen, 2022). Therefore, materials such as polymer composites or carbon fiber have yet to play a strong role in lightweighting (Czerwinski, 2021).

1.2.4 Rare earth magnets in electric vehicles and wind turbines

The vast majority of EVs being produced today also rely on neodymium iron boron (NdFeB) magnets. While Tesla has announced plans to move away from NdFeB magnets in its next-generation motors (Adamas Intelligence, 2023), the top-selling EV brands all currently use NdFeB magnet motors. With the rapid growth in EV demand, production of this magnet has become one of the largest users of the key rare earth metals neodymium, praseodymium, and dysprosium. Other materials used in these magnets include gallium, cobalt, boron, and iron.

Wind power continues to be a key source of renewable energy, with new installations increasing from 53.5 GW in 2017 to 93.6 GW in 2021 (GWEC, 2022a). Global production of offshore wind farms has also increased in the last few years, with a jump in new capacity additions to 17.4 GW in 2021, up from 4.5 GW in 2017 (Musial et al., 2022; GWEC, 2022a). New approaches, such as floating wind farms, have begun to come online as well (Musial et al., 2022). About 30% of all new wind turbines in 2020 were either direct drive or hybrid turbines that use NdFeB magnets. These technologies are more popular for offshore wind farms due to their lower maintenance requirements and lower weight (GWEC, 2022b).

1.2.5 Fuel cells in vehicles

Manufacturing and demand for fuel-cell electric vehicles (FCEVs) has also been steadily increasing since 2019. While BEVs and PHEVs are powered by electricity stored in batteries, FCEVs are powered by electricity generated in fuel cells from onboard hydrogen. Like EVs, FCEVs produce no tailpipe emissions and are classified as zero-emission vehicles. Historically, however, demand for FCEVs has been lower than for EVs and PHEVs. By the end of 2020, approximately 35,000 FCEVs were operational across the globe (Samsun et al., 2022). The majority of these vehicles were on the road in Korea, followed by the United States, China, and Japan (Samsun et al., 2022).

FCEVs considered in this analysis are cars, vans, buses, and trucks (E4Tech, 2022). Other FCEVs include forklifts, watercraft, locomotives, and tractors (EPA, n.d.). With higher energy density per weight than batteries, FCEVs can provide longer distances between fueling and faster fueling times than EVs of comparable vehicle type. Several countries (e.g., United States, Korea Japan, European Union [EU] countries) (Ko and Shin, 2023; Asif and Schmidt, 2021) have announced incentives and policies to spur adoption of FCEVs and to build out the hydrogen fueling station infrastructure required to operate them.

Regardless of where they are built, all FCEVs are powered by polymer electrolyte membrane fuel cells (PEMFCs). Advantages of this fuel cell technology for transportation applications include low operating temperature, high stack power, fast start, and corrosion resistance (Luo et al., 2021). Significant PEMFC R&D has been focused on reducing the platinum content in the PEMFC anode and cathode, thereby reducing system cost. Safety standards for FCEV design and testing have also been promulgated.

1.2.6 Energy storage

Global installed grid-scale battery storage capacity increased from 6 GW in 2019 to 16 GW in 2021, with the United States adding 2.9 GW of new capacity in 2021 (IEA, 2022c). The market will expand at an average annual rate of 29% in the short to medium term, up to 2030 (IEA, 2022b; Colthorpe 2022). However, to meet the ambitious net-zero carbon emission goals, stationary storage will need to grow by more than 40-fold globally, or up to 680 GW by 2030 (IEA, 2022c), requiring average annual additions of about 80 GW (IEA, 2022b). The primary stationary battery storage technologies include lithium-ion batteries, flow batteries, metal-air batteries, and other emerging technologies (DOE, 2020). Of these technology options, lithium-ion batteries (particularly lithium iron phosphate) will still dominate the stationary storage market in the medium term up to

2030, given energy density and cost advantages (DOE 2020; Blair et al., 2022). Flow batteries have the potential to become competitive as the technology matures in the medium to long term and may approach 50% of demand capacity by 2030 driven in part by their suitability for peaking and energy shifting grid services (DOE, 2020). The first large-scale (>100 MW) vanadium redox flow battery was recently commissioned in 2022 in China (China Energy Storage Alliance, 2022). The primary bottleneck for the current battery technology mix remains lithium supply, expected to grow by an order of magnitude for the combined EV and stationary storage market by 2030 (IEA, 2022b). However, this dependence would become less of an issue for stationary storage as redox flow batteries and alternative technologies gain traction.

1.2.7 Hydrogen

Historically, hydrogen use has been concentrated in the chemical, refining, and steel industries. In 2021, global hydrogen consumption was 94 million tonnes (Mt) (IEA, 2022b). Ammonia production was the largest consumer of hydrogen, followed by methanol production, and direct reduction of iron (DRI). Today, most hydrogen is produced by steam methane reforming (SMR). In refineries, hydrogen may also be produced as a by-product and used to remove impurities, such as sulfur, from oil and to upgrade heavy oil feeds. Hydrogen can also be produced with electricity and water through electrolysis. Some electrolyzer technologies rely on platinum group metals for catalysts.

To meet decarbonization goals, hydrogen demand is expected to increase, particularly for sectors that are difficult to decarbonize, such as long-distance heavy- and medium-duty trucks; synthetic fuels for air and marine transport; energy storage; and high-temperature heat. Hydrogen demand is also expected to increase for other applications, including electricity and chemicals. Additionally, hydrogen used to produce low-carbon ammonia, methanol, and other chemicals is expected to increase.

1.2.8 LED lighting

Over the past several years, the global lighting market has undergone rapid change and development. Conventional lighting sources such as fluorescent, incandescent, and high-intensity discharge lamps are being displaced by light-emitting diodes (LEDs) (Lee et al., 2021). The displacement is largely due to increased performance such as better energy efficiency, lifetime, versatility, and color quality when compared to conventional lighting sources (Lee et al., 2021) in parallel with decreased LED production costs (TechSi Research, 2022). Globally, LEDs accounted for more than 50% of the lighting market share in 2020 and 2021 (IEA, 2022a). Smart or connected lighting systems in buildings such as business offices, hospitality venues, and industrial sites are growing (TechSi Research, 2022). In addition to general lighting, LED grow lights for indoor farming and advanced lighting systems in automobiles to improve safety and riding experience are gaining in popularity (Mishra, 2022). Emerging technology such as Light Fidelity (Li-Fi) that transmits data through LEDs is also driving the LED market due to its better speed, security, and efficiency compared to Wi-Fi (TechSi Research, 2022). In the United States, installations of LED products have been increasing, roughly doubling from ~1.1 billion to ~2.3 billion units from 2016 to 2018, accounting for 30% of the U.S. lighting market share (Elliott & Lee, 2020). In 2020, 47% of residential energy consumption survey respondents reported usage of LEDs for most or all of their indoor lighting (EIA, 2022).

1.2.9 Solar energy

Solar photovoltaics (PV) contributed 3.6% of global electricity generation (Bojek, 2022) and 4.5% of U.S. electrical generation (Solar Energy Industries Association, 2022). However, with ambitious goals to achieve net-zero carbon emissions, the solar energy supply share will need to reach 23% globally (IEA, 2022b) and ~45% in the United States by 2050 (DOE, 2021). Crystalline silicon is still dominating the PV market due to its well-established technology with lower production costs. In 2021, ~88% of the PV market share was crystalline silicon, followed by thin-film PV (9% market share), and others (3% market share) (BCC Publishing Staff, 2022). Despite early market growth in the early 2000s of thin-film solar technologies such as cadmium-indium-gallium-selenide (CIGS) and cadmium telluride (CdTe) solar cells, thin-film solar cells have seen a decline in market share since that time period (Lee and Ebong, 2017). By 2009, thin-film technology represented 17% of the global solar market, then decreased to 7–8% by 2014 (Lee and Ebong, 2017), and finally plateaued in the ~5–10% range by 2021 (Chowdhury et al., 2020; Efaz et al., 2021; Kim, Quy, and Bark, 2021). Of the latest total global solar market, CIGS represented only ~2% of the total solar market (Efaz et al., 2021; Kim, Quy, and Bark, 2021). Recent information has indicated that the market share of CIGS may be even lower due to the abandonment of CIGS production by one of the last major CIGS manufacturers, Solar Frontier (Bellini, 2021; Solar Energy Technologies Office, 2023).

Cadmium Telluride (CdTe) thin-film PVs have gained popularity in recent years. Globally, the market share of this technology in the solar PV realm has remained relatively steady at 5% of new installations. However, in the last 5 years, the industry has experienced a year-over-year increase in the amount of newly installed CdTe solar capacity globally (US-MAC Consortium, 2022). In the United States, CdTe today accounts for ~ 90% of new U.S. utility-scale projects and 40% of the utility-scale market (Kennedy, 2022). This result is partially due to the antidumping investigation led by the U.S. Department of Commerce that caused solar adopters to switch to non-crystalline PV technologies. It was determined that China avoided U.S. tariffs on silicon PV by exporting to non-tariffed countries like Thailand, Cambodia, and Vietnam (Swanson and Plumer, 2022) before subsequent import to the United States.

1.2.10 Electrical steel

Electrical steel, also known as iron-silicon alloys, is widely used in transformers, generators, motors, and inverters. While grain-oriented electrical steel (GOES) is mostly used for transformers, non-grain-nongrain-oriented steel (NOES) is typically used for motor applications, with quantities in greater demand than for GOES (Eckard, 2020). The automotive sector has been a major driver for the NOES market in recent years. In a conventional vehicle, there are 20 to 80 low-power auxiliary motors found in components, such as electric power steering, oil pumps, fuel pumps, electric seat adjustment, and sunroof motors (Vittori, Evans, and Fini, 2021). EVs and hybrid vehicles use much higher quantities of NOES per vehicle compared to conventional vehicles and also require the highest grade called xEV NOES. In 2020, only about 4% of more than 11 million tons of produced NOES were xEV grade, which caused concern for the automotive sector as EV demand is expected to grow significantly until 2030 (Vittori, Evans, and Fini, 2021). A steady driver for electrical steel demand in transformers is grid modernization in growing economies due to the construction of metro stations, charging stations, industrial buildings, storage units, and warehouses (Fortune Business Insights, 2022). In the United States, concerns about GOES have been identified as a major bottleneck for the large power transformer supply chain (Nguyen et al., 2022). As a result, electrical steel is included in this report as an engineered material to assess its criticality. It has not been included in previous assessments.

1.2.11 Power electronics

Global decarbonization efforts have facilitated the growth of power electronics in recent years. The largest demand sectors are automotive, consumer, industrial motors, and home appliances (Rosina and Villamor, 2022). The EV sector is fast-growing but has not dominated this market yet. By material, there are three power electronics categories including silicon, gallium nitride (GaN), and silicon carbide (SiC). Like the solar PV sector, silicon power electronics are well-established and are the most used form, accounting for 96% of the market in 2022 due to its lower production costs for low-voltage components (Rosina and Villamor, 2022). This technology is expected to decline in the future but will continue to be the dominant choice. By 2028, its market share is projected to shrink to 80%.

Silicon carbide (SiC) and gallium nitride (GaN) are used in wide-bandgap electronics that can offer higher voltages and power, higher operating temperatures, faster switching, better efficiency, and a smaller form factor (Wolf Speed, 2019). SiC is the next preferred option with a 4% market share in 2022 and is projected to reach a 17% market share by 2028 (Rosina and Villamor, 2022). GaN use in consumer electronics and communications is growing, although the projected market share is only 3% by 2028. Although GaN power electronics have higher switching frequencies compared to SiC, their high cost limits them to niche applications of power supply (Ayari and Chiu, 2022).

The EV market is the primary driver for SiC, especially inverters, along with charging infrastructure for 800 V battery systems, to increase range and decrease charging time (ACM Resarch, 2022). Using SiC inverters also enables a smaller battery in EVs, which reduces supply chain concerns for battery materials. SiC has been used in both residential and commercial EV charging and energy storage. Other applications of SiC include in photovoltaic converters; power supply for consumer electronics; rail; uninterrupted power supply (UPS) applications; motor drive for robotic arms; servo motors; high voltage alternating current (HVAC); and wind (Chiu and Dogmus, 2022).

Efforts have been made by manufacturers to increase performance and costs of GaN and SiC at the component and system/application levels to increase their adoption. SiC manufacturing is more challenging both from technical and environmental standpoints. The manufacturing of SiC boule (the starting material) is energy intensive, takes weeks to grow, and incurs high yield losses due to its brittleness and transparency (ACM Resarch, 2022). It was estimated that SiC is 2.5 times more energy intensive than silicon power electronics per cm^2 basis while GaN has a footprint similar to silicon in the material and manufacturing phase (Warren et al., 2015). Manufacturers have started to lower the carbon footprint of GaN such that it will be four to 10 times lower than a silicon field-effect transistor (Navitas, 2022). For SiC, Smarter Cut^{TM} technology has been used in SiC wafer manufacturing to improve yield (Rosina and Villamor, 2022). This challenge in manufacturing potentially creates a supply chain bottleneck for wide-bandgap power electronics. As a result, both GaN and SiC are considered in the criticality assessment in this report.

2. Screening of Materials and Technologies

The periodic table includes 118 specific elements, a large number of which are used to some extent in energy technologies. Similarly, a comprehensive list of energy technologies ranges from specific power generation and storage technologies to wide-ranging end use and efficiency-enhancing technologies. To complicate matters further, each broad technology class contains a range of available nascent and mature sub-technologies, as well as specific sub-component requirements. Performing a criticality assessment of all of the elements in the periodic table (plus a variety of engineered materials) being used at present in all energy technologies is a nearly impossible task and would provide vague utility to DOE in pursuing a coordinated strategy. Thus, in an attempt to objectively identify a more targeted list of key materials and clean energy technologies, this assessment introduces a formal screening methodology to determine which materials to evaluate in more detail.

The purpose of the screening methodology is to provide a simple and replicable method for categorizing materials into two groups: (1) key materials and (2) lower-risk materials. Key materials are those that have some specific concern to clean energy and decarbonization technologies in the short to medium term and are thus included in the broader material criticality assessment described in more detail in Chapter 3. Lower-risk materials in the second group contribute to technologies that are anticipated to be less important over the next 5 to 15 years (due, for example, to decreasing demand for a mature technology or lack of demand for a more nascent or noncompetitive technology). They may also be characterized by relatively large commodity markets that have broad applications in the overall economy or may be used in minute amounts in relevant technologies, such that any additional demand would be inconsequential. While these materials are deemed lower risk by this assessment, the intent is not to declare them unimportant for energy applications. As such, these lower-risk materials are placed on a watch list that could provide input for future analyses.

Before conducting the screening process to identify key materials, an initial inclusive list of specific technologies, sub-technologies and components, and candidate materials of interest was compiled through consultation with DOE technology offices, subject matter experts, and a review of the various reports that DOE compiled in its one-year response to Executive Order 14017. The various sub-technologies were classified according to their broader technology class (e.g., various electrolysis technologies within hydrogen production, various Li-ion battery cathode chemistries within batteries for EVs, various PV technologies within solar energy, and so on), and relevant materials were assigned to each sub-technology (e.g., catalyst materials for polymer exchange membrane electrolyzers, cathode and anode materials for specific Li-ion battery chemistries, and so on). This process yielded a taxonomy of broad technology classes (e.g., wind energy), sub-technologies/components (e.g., direct-drive generators and rare-earth magnets), and materials (e.g., Nd, Pr, Dy, etc.).

2.1 Screening metrics

The screening method is a scoring system based on a weighted sum of three factors. The three factors were developed to rate (1) the importance of the broader technology class to the energy system, (2) the relative importance of the specific sub-technology or component under consideration within its technology class, and (3) the importance of the specific material. For example, to score neodymium for its use in wind turbines, the importance of wind energy was considered first, followed by the importance of turbines with direct-drive generators, and finally the additional neodymium demand growth implied by the growth of this specific technology.

Table 2.1 shows a summary of the metrics selected to measure each of the three factors, along with their relative weights and scoring determinations. These metrics were developed to be relatively simple to quantify quickly for individual material/technology pairings and do not replace the more intensive metrics used for the criticality assessment described in Chapter 3. Each metric was assigned a threshold such that each material/technology pair could be assigned a score of 1, 2, or 3 based on the value of each respective metric. Each metric was also given a weight from 2 to 4 out of 9 total points to emphasize their relative importance. For each material/technology pair, the score for each metric was then multiplied by its associated weight to derive a total weighted score.

Table 2.1 Metrics used for screening materials associated with specific technologies, their definitions, and scoring thresholds.

Metrics	Definition	Weight (out of 9)	Scores		
			1	2	3
I. Technology importance	Projected growth to 2030 in the International Energy Agency's net-zero (or highest available) scenario, evaluated based on Compound Annual Growth Rate (CAGR)	x 2	Low (CAGR<3%/yr)	Medium (CAGR: 3–5%/yr)	High (CAGR >5%/yr)
II. Sub-technology/ component importance	Market share of specific sub-technology using the material in 2030	x 4	Low (<5%)	Medium (5–9%)	High (>=10%)
III. Material importance	Additional material demand share of technology in 2030 relative to current total supply	x 3	Low (<5%)	Medium (5–24%)	High (>=25%)

The maximum total score possible in this framework is 27, with a minimum score of 9. The screening methodology was developed precisely to screen out materials that are characterized by particularly large commodity markets or those that are used in negligible quantities in individual applications (e.g., iron used in NdFeB magnets or the nickel used to coat them). Such materials may receive high scores for technology importance and sub-technology/component importance, but the lowest score for material importance to the technology (each would receive scores of 21 in this example). For this reason, a threshold value of 22 was selected for inclusion in the overall criticality assessment. Because this assessment is concerned primarily with the criticality of materials and not of technologies, each material under consideration was assigned the maximum value it received across all of the material/technology pairings that include it. Thus, if a material appears across several material/technology pairs and one pair received a score above 22, that material was screened for inclusion in the criticality assessment and for its use across all energy applications.

2.1.1 Technology importance

Technology importance is the first metric in the screening methodology because technology demand plays an important role in determining material criticality issues. Technology importance was evaluated by using the compound annual growth rate (CAGR) of the overall technology until 2030. Due to large variances in projections regarding CAGR, this analysis prioritizes scenarios developed by the IEA that are associated with rapid reductions in carbon dioxide emissions. Where demand scenarios were not available from the IEA for certain technologies, 5-year projections and CAGRs were taken from market reports and used to project demand until 2030. When CAGRs could not be obtained all the way until 2030, estimated CAGRs were used as a proxy.

This analysis relies on several scenarios from the IEA, including the Net-Zero Emission Scenario (NZE), Sustainable Development Scenario (SDS), and the Announced Pledged Scenarios (APS). For example, IEA's most aggressive scenario for HVDC is the SDS, while that for solar energy is the NZE. In addition, most IEA projections are available for the years 2030, 2040, and 2050. While the overall material criticality assessment evaluates materials through 2035, most market projections (from non-IEA sources) have estimates only to 2030. As a result, 2030 serves as the base year for calculations within the screening methodology unless otherwise stated.

As shown in Table 3.1, if a technology has a CAGR of less than 3%, it received the lowest score of 1. This threshold was chosen because the IEA assumes global economic growth will occur at a CAGR of 3% per year from 2021 to 2030 (IEA, 2022a). If a technology is not projected to exceed global economic growth, its demand growth is rated as relatively underwhelming. The second threshold of 5% was chosen because the world's gross domestic product (GDP) growth over the last 20 years has not exceeded 6% (The World Bank, 2022). Therefore, a technology that was projected to grow faster than 5% would earn a score of 3 as it is indicative of high demand growth relative to the broader global economy.

Technology importance received a weight of 2 (the lowest weight of the three metrics) to prevent the overscoring of material/sub-component technologies with smaller market shares. In other words, if a technology has multiple sub-technologies with different adoption rates, a large weight for this metric might overemphasize the material concern of low-adoption technologies.

2.1.2 Sub-technology/component importance

Sub-technology or component importance considers the actual adoption of a particular technology of interest that relies on a specific material or component. For example, CdTe solar panels rely on tellurium, and offshore wind relies on direct-drive wind turbines and rare-earth magnets. This metric clarifies the specific sub-technology importance within the overall technology.

All materials evaluated for a given sub-technology/component receive the same score for the sub-technology/component importance metric. Sub-technology importance is determined by examining the projected market share of the sub-technology/component in the year 2030. As shown in Table 3.1, a sub-technology with a projected market share of less than 5% in 2030 in its respective technology sector is considered low and receives a score of 1. A score of 2 is given for sub-technologies with a market share between 5% and 9%, and a score of 3 is given for a sub-technology with market share of 10% or greater.

This metric receives a weight of 4, the most highly weighted among the three metrics, to emphasize the significance of a sub-technology within an overarching technology sector. Due to the varying levels of importance of specific sub-technologies, materials required for relatively more important sub-technologies should be treated accordingly. For example, the three main solar PV technologies (silicon, CdTe, and CIGS) do not have the same level of importance. Currently, silicon PV has a market share of ~88% (BCC Publishing Staff, 2022) compared to CdTe at 5% (US-MAC Consortium, 2022) and CIGS at less than 1%. While CdTe PV technology relies on tellurium and CIGS PV technology relies on indium and gallium, these three elements do not have the same level of importance to solar technologies overall based on their market adoption. For example, if CdTe demand were to increase more quickly, that technology together with silicon PV could meet clean energy goals. In that case, only silicon and tellurium would be considered in the criticality assessment.

2.1.3 Material importance

Material importance considers the impact that growth of the use of a specific sub-technology/component will have on individual material markets. It is measured by the growth in material demand that might cause concerns for material supply. Specifically, it is measured as the ratio of the additional demand between now and 2030 relative to current supply. For example, if (a) the current total supply of a material is 100 tonnes, (b) a specific energy application accounts for 20 tonnes of demand, and (c) is currently projected to account for 80 tonnes in 2030, then (d) the additional demand share is 60%. The growth of 60% from the current demand share of 20% creates additional pressure for supply to meet the demand of the energy sector. To meet the demand of other sectors, supply will be required to scale up significantly.

Materials all receive a unique score for the material importance score within a given sub-technology/component. As shown in Table 3.1, a score of 1 is given for an additional demand share of less than 5%, demand shares between 5% and 24% receive a score of 2, and a material with an additional demand share of 25% or greater receives a score of 3. To calculate this metric, input data requires relevant energy scenarios as mentioned in Section 2.1.1, market share of sub-technologies as mentioned in Section 2.1.2, material intensities, current and projected material demand, and current material supply. Material intensities were compiled from various sources or calculated based on material density, component dimensions, etc., as summarized in Appendix B. Data sources of material supply were obtained from USGS, technical documents, and conversations with experts.

This metric receives a weight of 3 in the screening methodology, higher than the technology importance metric but lower than the sub-technology importance metric. This weight reflects that the material importance level is more important than the overall technology importance level but material importance receives a lower weight than the sub-technology importance metric because the projected demand is calculated based on both sub-technology importance and material intensity.

2.2 Screening results

Figure 2.1 summarizes the screening scores received by 37 candidate materials. Some materials (such as aluminum, cobalt, graphite, germanium, lithium, magnesium, platinum, and silicon) are used in several applications, and their scores cover a wide range. Others are evaluated for their usage in only one or two technologies and receive a single score, such as dysprosium or uranium. In total, 22 materials were selected for further evaluation in the criticality assessment. In the figure, all materials to the left of iron meet the threshold to be considered key materials, while the remainder are lower-risk materials.

Table 2.2 lists key materials with their associated technologies and the primary factors contributing to their scores. Note that although the technology with the highest score is used for the screening process, all energy technologies are evaluated for key materials in the criticality assessment described in the next chapter. Lower-risk materials with associated technologies and factors contributing to their lower scores are listed in Table 2.3. Scores shown in both tables are the highest scores for each material.

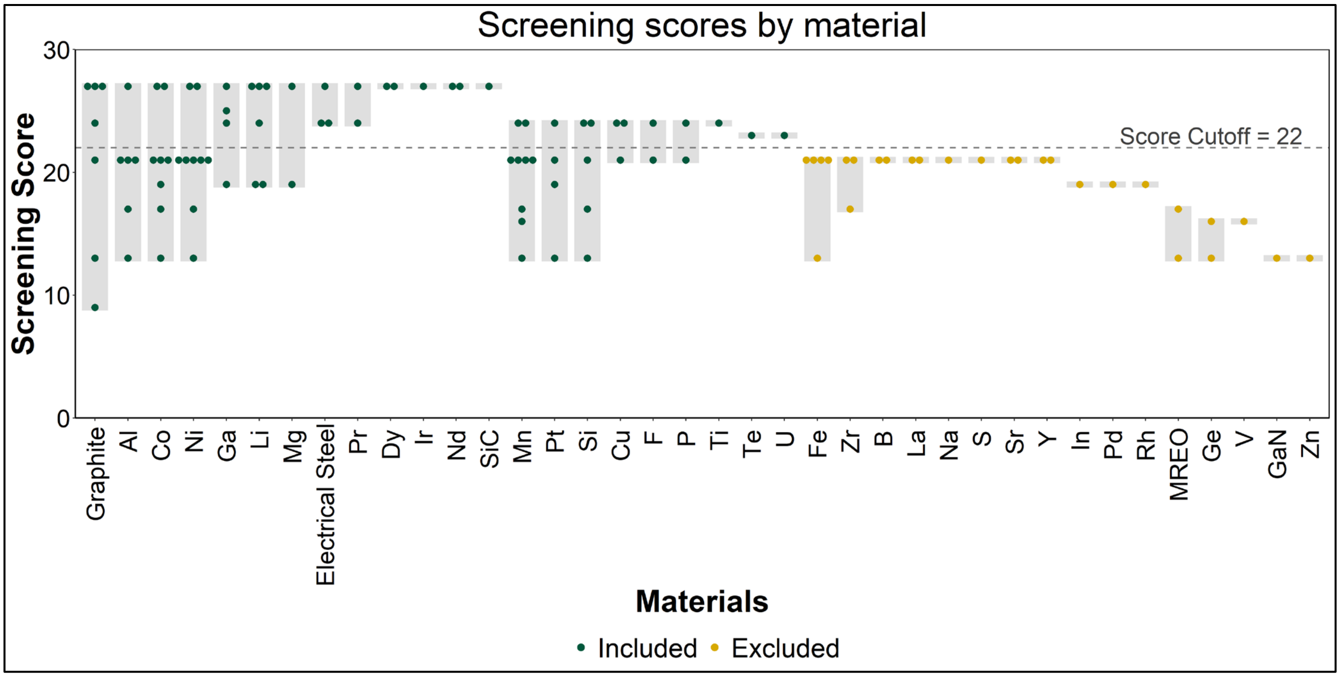

Figure 2.1 Summary scores of 37 materials. Materials with scores above the cutoff line are key materials.

Table 2.2 List of key materials with technologies and factors contributing to high scores, sorted alphabetically by highest score.

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Aluminum	Lightweighting alloys	27	CAGR 7%, 43% additional material demand, 43% market share for Al alloys in vehicles
Cobalt	Various batteries (EVs and storage)	27	CAGR 40%, high component adoption for some cathodes (47%), and high additional demand (218%)
Dysprosium	Wind turbines Electric vehicles	27	CAGR 13–40%; high adoption and additional demand due to current small market size
Electrical steel	Transformers	27	CAGR 6.3% (Markets and Markets, 2021) – 8.5% (Fact.MR, 2022), 46% additional material demand (Markets and Markets, 2021), electrical market share is ~68% when considering market values of electrical steels, FeNi alloys and amorphous nanocrystalline alloys in 2018 and 2019 (Eckard, 2020), 46% additional demand
Germanium	Infrared	27	CAGR 6.8–10.9% (Markets and Markets, 2023), (Intelligence, 2018) high adoption

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
	Fiber optics		due to limited substitutions, increase demand by 27% - 265%
Graphite	Various LIBs* (EVs and storage)	27	CAGR 40% for EVs, large market share of LIBs in EVs; high additional demand relative to natural + synthetic graphite supply
Iridium	PEM* electrolyzers	27	CAGR 87% of H2; high adoption of electrolysis and substantial additional demand (710%)
Lithium	Various batteries (EVs and storage)	27	CAGR 40%, large market share of LIBs in EVs, significant additional demand (>200%)
Magnesium	Lightweighting alloys	27	CAGR 7%, 78% additional material demand, 43% market share for Al alloys in vehicles
Neodymium	Wind turbines Electric Vehicles	27	CAGR 13–40%; high adoption of offshore turbines and EVs, and high additional demand
Nickel	Various LIBs (EVs and storage)	27	CAGR 40% for EVs, large market share of LIBs using Ni, and high additional demand (>50%)
Phosphorous	Li-ion batteries (EVs and storage)	24	CAGR 40% for EVs; 28% market share of LFP chemistry for EV batteries (Xu et al., 2020); 7% additional material demand
Praseodymium	Wind turbines Electric Vehicles	27	CAGR 13 – 40%; high adoption of offshore turbines and EVs, and high additional demand
Silicon carbide	Power electronics	27	CAGR >30%, 16.8% market share in 2027 (Rosina and Villamor, 2022)
Gallium	LED lighting	25	CAGR 4.7% (Navigant Consulting Inc., 2019), 41% additional demand, 100% LED semiconductor
Copper	Vehicles Wind	24	12% CAGR – wind (Modor Intelligence, 2022), 18% (Allied Market Research, 2022) to 24% (Fortune Business Insights, 2021) electric vehicles, 7–15% additional demand
Fluorine	Li-ion batteries	24	Broad usage in electrolyte across all Li-ion battery chemistries; 40% CAGR of BEV+PHEV vehicles; 19% additional material demand for EVs

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Manganese	Various batteries Lightweighting alloys	24	High CAGR for EVs (40%); large market share of NMC LIB chemistry in EVs High adoption of AHSS* with medium impact on additional demand
Platinum	PEM electrolyzers	24	CAGR 87% of H2, high adoption of electrolysis
Silicon	Solar Lightweighting alloys	24	CAGR 14.1% (BCC Publishing Staff, 2022), 5.55% additional demand, 70% solar market share (Weckend, Wade, and Heath, 2016) CAGR 7%, 39% Al alloy market share, 18% additional material demand
Titanium	PEM electrolyzers	24	CAGR 87%; 51% market share of PEM electrolyzers (DOE, 2021); 17% additional demand
Tellurium	Solar	23	CAGR 10% (IEA, 2022), 133% additional Te demand 4–5% share in global solar market, 30–40% in U.S. solar market (Kennedy, 2022), (DOE, 2022)
Uranium	Nuclear	23	110% additional demand in NZE, 100% of nuclear fuel uses uranium

[*] AHSS = advanced high-strength steel; LIB = lithium-ion battery; PEM = polymer electrolyte membrane.

Table 2.3 Lower-risk materials by alphabetical and decreasing score order, their scores, and factors contributing to scores.

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Boron	Wind turbines Electric vehicles	21	Low additional material demand (<0.5%)
Iron	Wind turbines (magnets) Electric vehicles (magnets)	21	Low additional material demand (<0.1%)
Lanthanum	SO fuel cells and electrolyzers	21	87% CAGR, <1% additional demand
Strontium	SO fuel cells and electrolyzers	21	87% CAGR, <1% additional demand
Yttrium	SO fuel cells and electrolyzers	21	87% CAGR, <1% additional demand

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Zirconium	SO fuel cells and electrolyzers	21	87% CAGR in NZE, <1% additional demand
Indium	Solar	19	Low adoption, 9% market share (BCC Publishing Staff, 2022)
Palladium	Catalytic converters	19	4% CAGR for ICE vehicles; 3% additional demand
Rhodium	Catalytic converters	19	4% CAGR for ICE vehicles; 3% additional demand
Sodium	Energy storage (NaS batteries)	17	30% CAGR, <1% additional demand
Sulfur	Energy storage (NaS batteries)	17	30% CAGR, <1% additional demand
Vanadium	Energy storage (flow batteries)	16	21% CAGR, 19% additional demand, 4% market share
Zinc	Energy storage (flow batteries)	13	21% CAGR, <1% additional demand, 1% market share

3. Criticality Assessment

This chapter details the criticality assessment methodology and presents criticality results for both short and medium term. The assessments address two dimensions—importance to energy and supply risk. The basic premise is that rapidly increasing demand for key materials could hamper the ability to manufacture energy technologies by outpacing new production and causing supply–demand mismatches due to (constrained) availability, geopolitical sensitivities, and other concerns. Appendix A (Criticality Assessment by Material) presents detailed material-by-material assessments.

3.1 Assessment Methodology

The basic methodology used to assess the criticality of materials in this report is the same as that used in the 2010, 2011, and 2019 DOE *Critical Materials Strategy* (CMS) reports, which adapted a methodology developed by the National Academy of Sciences (NAS) (National Research Council, 2008). 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.

This assessment adapts the NAS methodology to address particular concerns for energy technologies. First, the DOE assessments recast "impact of supply restriction" to "importance to energy." Second, they define five specific factors to characterize a material's "supply risk." Third, the assessments are forward-looking in that they apply demand scenarios to evaluate the supply and demand profiles for both the short and medium terms, which may elicit different policy response options. For the 2023 assessment, the "short term" is defined as the period from 2020 to 2025 and the "medium term" is defined as the period from 2025 to 2035. Analogous to the NAS methodology (and the previous CMS reports), the two-dimensional criticality ratings are plotted on a matrix to enable comparison across materials for both the short and medium terms. The matrices provide stakeholders with a comparison between materials that informs R&D investment decisions and policy action. Each matrix has three regions: critical (red), near critical (yellow), and not critical (green).

"Importance to energy" and "supply risk" are defined as weighted averages of several factors, each of which receives a score on a scale of 1 to 4. Short- and medium-term scores for importance to energy are based on a weighted average of two factors, while those for supply risk are based on a weighted average of five factors. For each factor, key materials are assigned qualitative scores of 1 (least critical) to 4 (most critical). The following sections describe each factor in greater detail.

3.1.1 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. (Note: for the 2023 version, the weights for energy demand and substitutability limitations were changed from 75% to 70% and from 25% to 30%, respectively.)

- **Energy Demand (70%):** Captures the overall importance of both materials and the technologies that use them to the future of energy, including technologies that produce, transmit, store, and conserve energy. As such, this metric measures two aspects.
    - The first aspect evaluates the use of a material in energy applications as measured by the amount of the material's market share accounted for by energy applications. The higher the market share of energy applications for a given material, the higher the score. This value is calculated for both 2025 and 2035 to account for the short and medium terms, respectively, based on demand

  projections for energy technologies and non-energy technologies. Non-energy (and out-of-scope) applications are assumed to grow at a 3% compound annual growth rate (CAGR) to reflect average global economic growth as discussed in Section 2.1.1(IEA, 2022; The World Bank, 2022).
  - The second aspect evaluates the importance of the specific sub-technology that uses the material to the overall energy technology class, typically reflected by the adoption or penetration rate of the sub-technology. Because materials may be used widely in multiple energy applications, sub-technology adoption is assessed for the energy technology that makes up the largest use of the material.
- **Substitutability Limitations (30%):** Captures the ability to reduce the use of the material in energy applications through material substitution or substitutions in the energy system itself, such as through the use of an alternate technology that does not use the material. Substitution could occur at any level of the supply chain up to the energy technology system level and may include using different raw materials, components, or even end-use technologies (Smith and Eggert, 2018). For example, a system-level substitution could be the adoption of a hydrogen electrolysis technology that does not use iridium as a catalyst, where material substitution refers to the ability to reduce the amount of iridium in the same electrolysis technology. Note that because a material can be used in multiple energy applications, substitution limitations are evaluated broadly across those applications. Substitutability considers limitations in performance as well as environmental factors and actual deployment of substituted technologies and materials.

3.1.2 Supply Risk

The overall risk of supply chain disruption for each material is based on five risk factors for the short and medium terms. The weighting factor for each attribute is shown in parentheses.

- **Basic Availability (40%):** Evaluates the extent to which global supply (including recycling) will be able to meet demand. Short-term and medium-term basic availability examines the gap between current production capacity and projected demands in 2025 and 2035, respectively. Four demand trajectories are considered as a combination of low and high deployment scenarios (based on the IEA's projections or market reports) and low and high material intensities as shown in Appendix B. Other factors are also taken into account where information is available, including sufficiency of projects or capacity additions within the considered timeframe, and environmental or capacity constraints such as declining ore grade or access to water. In general, basic availability scores are guided by the demand trajectories shown in Appendix D. For example, a score of:
  - 1 implies that <u>all</u> demand trajectories for a given material are <u>near or do not exceed</u> current capacity estimate;
  - 2 implies that <u>some</u> demand trajectories <u>slightly exceeded</u> (less than 50%) the current capacity estimate;
  - 3 implies that the <u>high</u> demand trajectories <u>vastly exceeded</u> (> 80%) the current capacity estimate; and
  - 4 implies that <u>all</u> demand projections <u>vastly exceeded</u> the current capacity estimate. For example, even the lowest demand trajectory in 2035 may be upwards of 70% higher than current production capacity.
- **Competing Technology Demand (10%):** Evaluates whether non-energy sector demand is expected to grow rapidly, thus constraining the supply of the material available to the energy sector. The scoring of this metric relies on CAGRs of non-energy applications relative to energy applications. Scores higher than 1 imply that there is at least one major non-energy technology using the material that is anticipated to grow more quickly than the default assumption of 3% used in the demand trajectories.
- **Political, Regulatory, and Social Factors (20%):** Assesses supply risks associated with political, social, and regulatory factors within producing countries based on market concentration. This includes

the risk that political instability in a country will threaten mining and processing projects or production; 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. In addition, other factors can also affect supply risks such as the use of child labor or forced labor, improper occupational health and safety, political instability, and environmental concerns caused by a country's regulations. This metric uses the average country rank from measures of political stability, regulatory quality, and rule of law from the World Bank's World Governance Indicators (WGIs) and Yale University's Environmental Performance Index. A weighted score of producing countries is calculated based on their production share and percentile ranking.

- **Co-dependence on Other Markets (10%):** Captures the reliance of a material on the production of other products. Co-product and by-product materials are produced along with or as a result of the production of other materials. In some instances, a lower-value product may actually benefit from its by-product relationship with higher-value products if it is in excess supply (cerium, for example); however, in most cases, co-dependence is disadvantageous to minor metals because co-products with lower revenue streams cannot drive production of higher revenue streams even if demand is high. Thus, in general, the more dependent a material is on the production of other products, the riskier its supply.
- **Producer Diversity (20%):** Measures market concentration and the ability of producing countries to exert market power over a particular material market due to the lack of diversity in producing countries (e.g., monopoly or oligopoly). Highly concentrated markets are more likely to have one or a small number of countries with the ability to manipulate the market via noncompetitive market practices. This metric uses the Herfindahl-Hirschman Index (HHI), a common measure of market concentration, which is calculated as the sum of squared market share for all producing countries multiplied by 10,000. For mergers and acquisitions within the United States, the U.S. Department of Justice considers scores above 2500 to be highly concentrated. Scores of 1, 2, 3, or 4 are assigned to materials with HHI values of less than 2500, between 2500 and 3332, between 3333 and 4999, and 5000 or greater, respectively. These cutoffs reflect situations where market concentration is worse than one with four countries with equal market share, three countries with equal market share, and two countries with equal market share, although these values may be reached in different ways.

3.1.3 Scoring rubric

As with previous CMS reports, this report is based on qualitative assessments informed by quantitative analysis. While this version adopts the same hybrid scoring approach as previous versions, it introduces the use of a formal scoring rubric with explicit thresholds for each category to ensure consistent scores across all key materials with various applications and supply chain configurations. Individual criteria used for each categorical score from one to four are shown in Table 3.1. Although a more quantitative approach is applied for some factors, the scores for medium-term criticality have higher uncertainties than those of the short term because technology trends and country policies can change radically over a period of 15 years compared to the next one to five years. Nonetheless, the collection of assessments is valuable to inform policy priorities and R&D investment. It will be important to revisit the analyses more often moving forward as more data become available and as material supply and demand change.

Table 3.1 Scoring metrics and thresholds for criticality assessment.

Factor	Metrics	Score = 1	Score = 2	Score = 3	Score = 4
Importance to Energy	Energy Demand (70%)	Meets one of the criteria below: (1) Market share of the material for energy applications <10% (2) Market share of the most dominant specific sub-technology < 10%	Must meet both criteria below: (1) Market share of the material for energy applications ≥10% (2) Market share of the most dominant specific sub-technology ≥ 10%	Must meet both criteria below: (1) Market share of the material for energy applications ≥40% (2) Market share of the most dominant specific sub-technology ≥ 25%	Must meet both criteria below: (1) Market share of the material for energy applications ≥ 70% (2) Market share of the most dominant specific sub-technology ≥ 50%
	Substitutability Limitations (30%)	**Perfect or near-perfect** substitutes are available at material and system levels with **little to no limitations or concerns.**	Substitutes are available at either material or system levels with **minor limitations or concerns.**	Substitutes are available either at the material level or systems level with **major limitations or concerns.**	**No substitutes** are available at either the material or system levels.
Supply risk	Basic Availability (40%)	**No concerns** about existing capacity to meet near- and medium-term demand	**Minor concerns** about capacity to meet near- and medium-term demand	**Major concerns** about capacity to meet near- and medium-term demand	**Grave concerns** about capacity to meet near- and medium-term demand
	Competing Technology Demand (10%)	CAGR of any non-energy application ≤ 3%	CAGR of any non-energy application ≤ 5%	CAGR of any non-energy application ≤ 10%	CAGR of any non-energy application >10%
	Political, Regulatory, and Social Factors (20%)	Weighted average percentile of Governance Indicators and Environmental Performance Index is greater than 60.	Weighted average percentile of Governance Indicators and Environmental Performance Index is from 45 to 60.	Weighted average percentile of Governance Indicators and Environmental Performance Index is from 30 to 45.	Weighted average percentile of Governance Indicators and Environmental Performance Index is less than 30.
	Co-dependence on Other Markets (10%)	Must meet both criteria below: (1) May or may not be produced as a co-product of other metals (2) **Produced** as a main product in **most circumstances**	Must meet both criteria below: (1) Most (>50%) production is as a co-product or as a by-product of other metals (2) **Produced** as a main product in **some circumstances** OR there is excess by-product supply in the market	Must meet both criteria below: (1) Significant (>75%) production as a co-product or by-product of other metals (2) **May be produced** as a main product in **some circumstances** AND there is not excess by-product supply in the market	Must meet both criteria below: (1) 100% of production is as a co-product or as a by-product of other metals (2) **Not produced** as a main product anywhere in the world AND there is no excess by-product supply in the market
	Producer Diversity (20%)	Herfindahl-Hirschman Index (HHI) less than 2500	HHI from 2500 to 3332	HHI from 3333 to 4999	HHI greater than or equal to 5000

3.2 Identification of Critical Materials

Figure 3.1 and Figure 3.2 plot criticality ratings for the key materials in the short and medium terms, respectively. Appendix A (Criticality Assessments by Material) provides more detailed assessment and scoring. In general, the criticality of most 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 3.1 and Figure 3.2 show three broad categories of criticality. Materials in the upper quadrant of the matrix—with scores of 3 or higher on both axes—are characterized as critical. Materials with a score of 3 or higher on one axis but a 2 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 as being not critical. However, this assessment is based on the best available information, so even materials judged as not being critical could be at risk due to significant unforeseen circumstances.

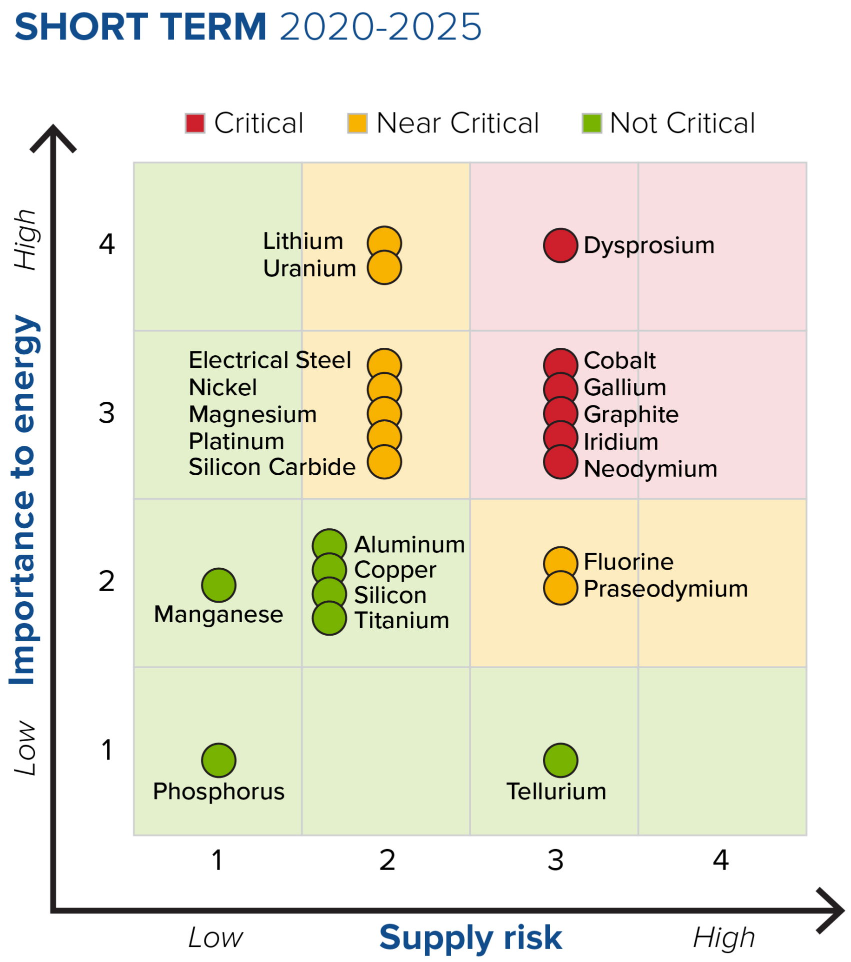

Figure 3.1 Short-term (2020–2025) criticality matrix

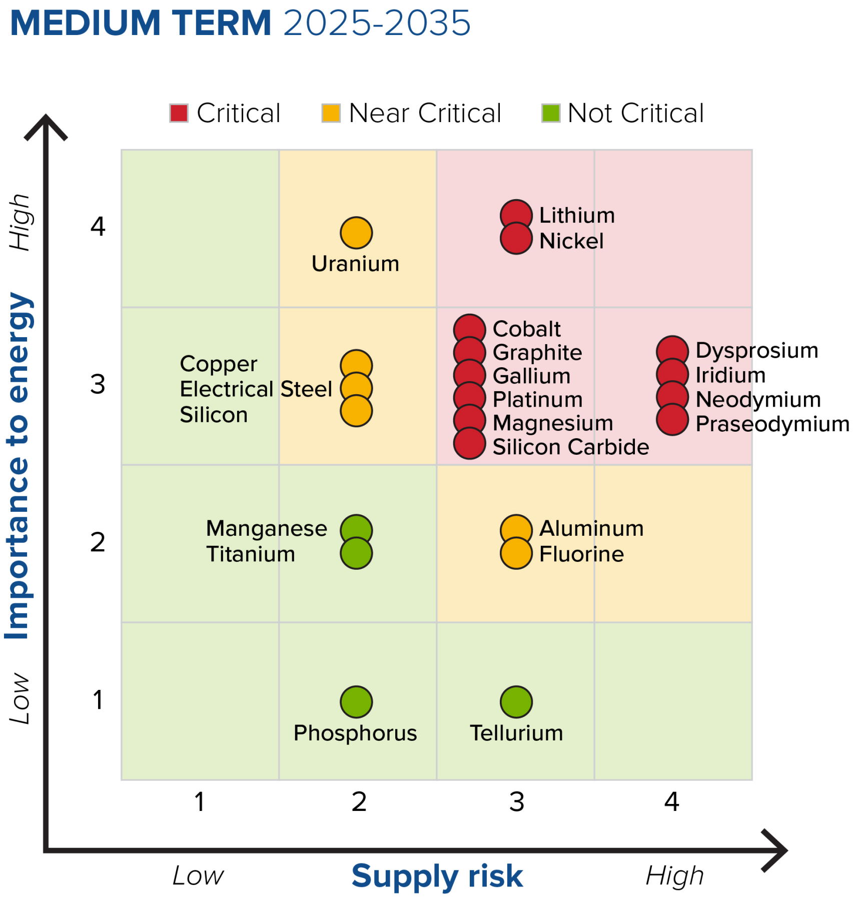

Figure 3.2 Medium-term (2025–2035) criticality matrix

According to the analysis, there are six critical materials in the short term, which include cobalt, dysprosium, gallium, natural graphite, iridium, and neodymium. The uses for these critical materials are spread across rare-earth magnets, batteries, LEDs, and hydrogen electrolyzers. There are nine near-critical materials, which include electrical steel, fluorine, lithium, magnesium, nickel, platinum, praseodymium, silicon carbide (SiC), and uranium. Finally, there are seven noncritical materials including aluminum, copper, manganese, phosphorous, silicon, tellurium, and titanium.

Between the short term and medium term, the importance to energy and supply risk scores shifts for most materials. There are 12 critical, six near-critical, and four noncritical materials in the medium term. For example, the importance to energy scores for copper and silicon increase while their supply risks remain the same. In addition, supply risk scores for aluminum, iridium, manganese, neodymium, phosphorous, platinum, and SiC increase, while their importance to energy stays constant. Nickel increases in both importance to energy and supply risk. Dysprosium, on the other hand, falls in energy importance due to potential substitutions in the medium term but increases in supply risk, remaining a critical material. All other key materials remain in the same category from the short term to medium term.

Market dynamics along the entire supply chain for energy technologies will play a large role in changes to assessed criticality. This is clearly demonstrated when examining how the criticality assessment for some materials has changed between the 2019 CMS report and this 2023 report. Critical and near-critical materials in the 2019 assessment, such as rhodium and palladium, were screened out due to the decreased importance of catalytic converters and their low additional demand share. On the other hand, some materials were noncritical or not considered in 2019 but have become critical in the current assessment. For example, iridium and natural graphite were not considered critical previously but are determined to be critical in this analysis due to their increased demand in hydrogen electrolyzers and batteries, respectively. Platinum was near-critical in the 2019 analysis but it is critical in the current analysis due to increased fuel cell demand. Increased demand for EVs, energy storage, and wind has caused nickel and praseodymium to be more critical in this analysis. In addition, engineered materials such as electrical steel and SiC were not considered previously and have become near critical and critical, respectively, in this report. Note that engineered products are geared toward specific end-uses, which can make them more important than upstream materials. Another aspect worth noting is that as new technologies are developed, the list of candidate materials will continue to grow. In this analysis, 37 candidate materials were considered, and 22 were evaluated for criticality after the screening process. The 2019 assessment considered 16 materials.

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Appendix A: Criticality Assessment by Material

This appendix provides detailed assessments of criticality for each of the key materials that passed the screening in Chapter 2. The methodology used to develop the criticality scores is explained in Chapter 3 (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 3. Table A.1 summarizes the assessment scores for each key material in both the short and medium terms.

Table A.1 Summary scores of assessed key materials.

Weight		**0.75**	**0.25**		**0.40**	**0.10**	**0.20**	**0.10**	**0.20**
Factor	**Importance to Energy**	Energy Demand	Substitutability	**Supply risk**	Basic availability	Competing Technology Demand	Political, Regulatory, and Social Factors	Codependence on Other Markets	Producer Diversity
Short term									
Aluminum	**2.3**	2	3	**2.3**	2	2	3	1	3
Cobalt	**3.4**	4	2	**3.2**	3	1	4	3	4
Copper	**2.3**	2	3	**1.8**	2	3	2	1	1
Dysprosium	**3.7**	4	3	**3.2**	3	3	3	3	4
Electrical steel	**3.0**	3	3	**1.7**	2	2	2	1	1
Fluorine	**1.6**	1	3	**2.5**	2	4	3	1	3
Gallium	**3.4**	4	2	**2.9**	2	3	3	4	4
Graphite	**2.7**	3	2	**2.7**	3	2	3	1	3
Iridium	**2.0**	2	2	**2.7**	2	1	3	4	4
Lithium	**4.0**	4	4	**2.4**	3	1	2	1	3
Magnesium	**3.0**	3	3	**2.1**	1	2	3	1	4
Manganese	**2.3**	2	3	**1.2**	1	1	2	1	1
Neodymium	**3.0**	3	3	**3.2**	3	3	3	3	4
Nickel	**2.7**	3	2	**2.1**	2	1	3	2	2
Phosphorous	**1.3**	1	2	**1.4**	1	1	3	1	1
Platinum	**2.0**	2	2	**2.8**	3	1	3	1	4
Praseodymium	**2.0**	2	2	**3.2**	3	3	3	3	4
Silicon	**2.3**	2	3	**1.8**	1	3	2	1	3
Silicon carbide	**2.7**	3	2	**1.9**	2	4	1	1	2
Tellurium	**1.0**	1	1	**2.9**	3	3	2	4	3
Titanium	**2.0**	2	2	**1.6**	1	1	2	1	3
Uranium	**4.0**	4	4	**1.9**	2	2	2	1	2

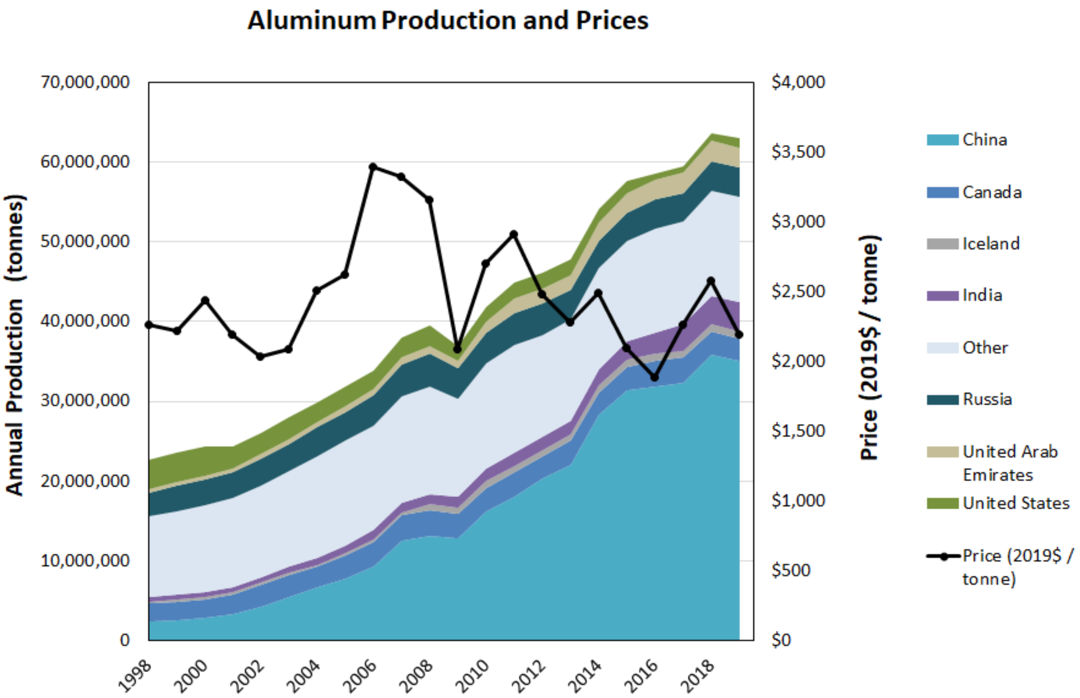
Weight		**0.75**	**0.25**		**0.40**	**0.10**	**0.20**	**0.10**	**0.20**
Factor	**Importance to Energy**	Energy Demand	Substitutability	**Supply risk**	Basic availability	Competing Technology Demand	Political, Regulatory, and Social Factors	Codependence on Other Markets	Producer Diversity
Medium term									
Aluminum	**2.3**	2	3	**2.7**	3	2	3	1	3
Cobalt	**3.4**	4	2	**3.2**	3	1	4	3	4
Copper	**3.0**	3	3	**2.2**	3	3	2	1	1
Dysprosium	**3.4**	4	2	**3.6**	4	3	3	3	4
Electrical steel	**2.7**	3	2	**2.1**	3	2	2	1	1
Fluorine	**2.3**	2	3	**2.9**	3	4	3	1	3
Gallium	**3.4**	4	2	**3.3**	3	3	3	4	4
Graphite	**3.4**	4	2	**2.6**	3	1	3	1	3
Iridium	**2.7**	3	2	**3.5**	4	1	3	4	4
Lithium	**4.0**	4	4	**2.8**	4	1	2	1	3
Magnesium	**2.7**	3	2	**2.5**	2	2	3	1	4
Manganese	**2.3**	2	3	**1.6**	2	1	2	1	1
Neodymium	**3.0**	3	3	**3.6**	4	3	3	3	4
Nickel	**3.7**	4	3	**2.5**	3	1	3	2	2
Phosphorous	**1.3**	1	2	**1.8**	2	1	3	1	1
Platinum	**2.7**	3	2	**2.8**	3	1	3	1	4
Praseodymium	**2.7**	3	2	**3.6**	4	3	3	3	4
Silicon	**3.0**	3	3	**2.2**	2	3	2	1	3
Silicon carbide	**3.0**	3	3	**2.7**	4	4	1	1	2
Tellurium	**1.0**	1	1	**3.3**	4	3	2	4	3
Titanium	**2.0**	2	2	**2.0**	2	1	2	1	3
Uranium	**4.0**	4	4	**2.0**	3	1	2	1	1

Element: Aluminum (Al)	Atomic number: 13
Aluminum is a metal element primarily used as an alloy in the transportation sector. Aluminum alloys offer light weight, high strength, and corrosion resistance, making it particularly useful for automobile and airplane construction.	
Importance to Energy: *Short term: 2, medium term: 2*	
Usage of aluminum in clean energy applications is primarily driven by lightweighting of vehicles through the use of aluminum and magnesium alloys, as well as in electric vehicle (EV) batteries. Energy demand for aluminum is projected to be high across the lightweighting and EV battery landscape, with substitutability being limited across the time frame of this report.	
Energy Demand Short term: 2 Medium term: 2	• Market share for energy applications of aluminum will be 27% in the short term, increasing to 36% in the medium term for the highest intensity demand trajectory. • The highest level of sub-technology adoption within aluminum technologies is 45% in the short term for lithium-ion nickel-cobalt-aluminum oxide (NCA) batteries and decreases slightly to 39% in the medium term for aluminum alloy applications in lightweighting.
Substitutability Limitations Short term: 3 Medium term: 3	• Replacing aluminum alloys with magnesium or polymer composites is unlikely in the near term due to the manufacturing, in-service performance, and costs of the substitutable materials. • Ferrous steel metals contain the majority share of the automotive market, and efforts to lower their weight must contain aluminum as an essential alloying element in density reduction. • The heavy extension of advanced high-strength steel (AHSS) materials utilized in the lightweighting of vehicles may contain aluminum as an alloying material but can be replaced by silicon in certain composites. • The development of lightweighting material composition is very complex, and material selection optimization methods are being developed that can replace aluminum with other materials. However, the replacement of aluminum with other materials, such as magnesium alloys, still results in aluminum content within the lightweighted vehicle as aluminum is an essential material in magnesium alloys. • Future application of other materials besides aluminum alloys is being investigated, as magnesium alloys provide 30% lighter application to automobiles. This substitution would drastically reduce the amount of aluminum in the vehicle if aluminum alloys can be replaced by magnesium alloys or carbon fiber composites. Currently, magnesium is not widely applied to replace aluminum alloys, as magnesium lacks weldability — and trying to improve that weldability requires high temperatures which raises costs. Carbon fiber composites will also raise costs if replacing aluminum entirely. • Aluminum cannot easily be substituted out of lithium-ion batteries, as it is present in all battery chemistries being analyzed, although reductions in aluminum use could be achieved by replacing lithium iron phosphate (LFP) cathodes with nickel-manganese-cobalt (NMC). • Aluminum used in cathode current collectors may be particularly hard to substitute out because no promising candidate has been identified that can offer comparable performance in terms of conductivity, light weight, and cost. • Aluminum used in both cathode current collectors and structural parts can be replaced with cheaper yet heavier stainless steel. Doing so will reduce the battery energy density, but it is not a big concern for energy storage system (ESS) batteries.
Supply Risk: *Short term: 2, medium term: 3*	
The supply risk for aluminum is mild in the short term with production capacity of aluminum meeting all demand trajectories until 2025. By the medium term, availability concerns alongside high production shares in China bring risk in producer diversity as well as political, regulatory, and social factors.	
Basic Availability Short term: 2 Medium term: 3	• In the short term, the production capacity of aluminum in 2020 can meet all aluminum application trajectories, creating no concerns about material availability. By the end of the medium term in 2035, all demand projections vastly exceed 2020 production capacities, creating major concern about availability of aluminum in the medium term. • The end-of-life recycling rate for aluminum is very good at a rate greater than 50%. However, recycled aluminum often contains significant impurities, which can make it

	unsuitable for uses that require high purity. Production of aluminum for certain technologies and products may be restricted toward primary aluminum. • With more than 60% of aluminum refining and conversion production coming from Russia and China, aluminum shortages have been experienced during China's COVID-19 lockdowns and Russia's war against Ukraine. • The global amount of bauxite available for aluminum production is estimated to be around 55 to 75 billion tons. While domestic resources of bauxite are not sufficient to meet long-term U.S demand, aluminum demand can be met with resources containing aluminum other than bauxite. • Clay resources are a potential alternative as a source of alumina and can reduce bottlenecks of bauxite reserves, as approximately 70% of bauxite mining, from which alumina and then aluminum are produced, occurs in Australia or China. Aluminum refining and processing that takes from bauxite resources are therefore subject to two major exporters, causing bottleneck concerns. Clay resources, however, are not currently economically competitive with bauxite but may become so in the future. • Aluminum production requires an extensive amount of electric energy to convert alumina into aluminum with up to 40% of production costs going toward electricity. Recent energy shortages caused by the COVID-19 pandemic and Russia's war with Ukraine have caused aluminum production facilities to curb output in recent years. • Production of aluminum is an energy-intensive process, with refining processing sites located based on the geographic availability of cheap energy. This approach creates a bottleneck in aluminum refining if the supply chain moves from aluminum mining to constrained refining areas. Additionally, new capacity aluminum refining will be limited to areas that have low power costs such as the Middle East and Russia. China has recently expanded aluminum capacity and production, as reduced restrictions on electricity use, along with new capacity resources in Inner Mongolia and the Guangxi and Yunnan provinces, begin production. • The move toward a green energy future through carbon pricing of aluminum production may limit opportunities for new aluminum smelters. Aluminum manufacturing contributes to approximately 2% of global greenhouse gases, which is equivalent to approximately 1.1 billion tons of carbon dioxide. Production may be restricted to existing production in China, Russia, or India, which maintains supply constraints, or may result in higher production costs if moved to carbon-priced areas. Research is being conducted that will decarbonize the aluminum production process through alternative anodes in aluminum smelting, CCUS, hydrogen, or mechanical vapor recompression. Use of these technologies is still not widespread, and most electricity that is used in aluminum manufacturing is form nonrenewable sources.
Competing Technology Demand Short term: 2 Medium term: 2	• In the short term, competing aluminum demand from the construction sector could strain aluminum supply for energy application. Post-pandemic building and the opening of supply chains are projected to create an average compound annual growth rate (CAGR) of 4.8% across the different construction subsectors (construction, housing, nonhousing, and infrastructure) from 2020 to 2025. By 2030, the demand should subside to an average CAGR of 3.6%. • The electrical sector is projected to have the highest growth of aluminum use in the medium term, projected to have a CAGR of 4.1% by 2030. If this rate continues to 2035, this should only a mild strain on supply availability due to competing technology demand.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• The majority of production for aluminum can be found in China (58%). India and Russia have the next-highest production shares at 6% and 5%, respectively. Low political stability and regulatory quality rankings for the top three producers, alongside poor environmental health rankings from India, create mild concern on potential supply disruptions and environmental issues.
Codependence on Other Markets Short term: 1 Medium term: 1	• Aluminum is mined from bauxite, which is the only commercial ore of aluminum. Therefore, it is mined as the main product and is unlikely to become dependent on other markets.

Producer Diversity Short term: 3 Medium term: 3	• China accounts for approximately 58% of market share in the production of aluminum, followed by India (6%), Russia (5%), Canada (4%), and the United Arab Emirates (4%). One country controlling more than 50% of the market means that only a limited range of producers can supply aluminum.

Historical Price and Production



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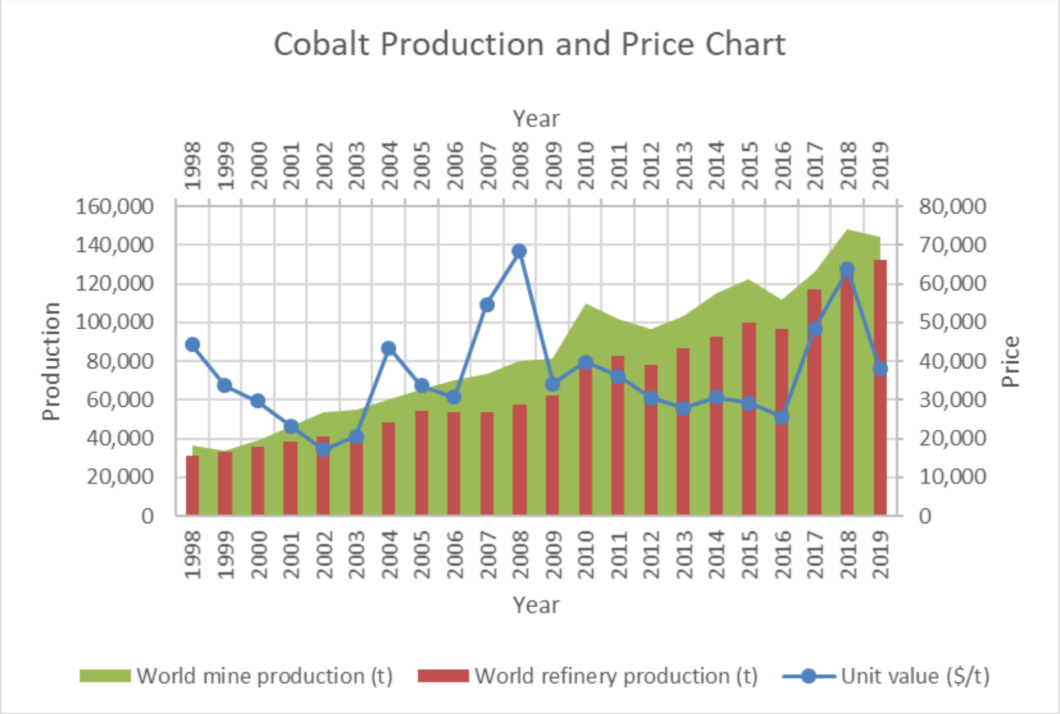
<table>
<tr><th>Element: Cobalt (Co)</th><th>Atomic number: 27</th></tr>
<tr><td colspan="2">Cobalt is a transition metal that is widely used in various industrial and technological applications, such as rechargeable battery electrodes, and in superalloys for gas turbine engine blades and other critical components, as catalysts in chemical and petrochemical processes, and in Samarium Cobalt high-strength permanent magnets.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 3, medium term: 3</i></td></tr>
<tr><td colspan="2">The demand for cobalt is expected to rise in the short to medium term due to the increasing demand for lithium-ion batteries, particularly in the EV industry. Cobalt is a key component in the cathode of most lithium-ion batteries, and its use has been driven by its ability to enhance the battery's energy density and overall performance. However, some EV manufacturers are exploring cobalt-free alternatives to lithium-ion batteries, although these alternatives may result in slightly lower battery performance.</td></tr>
<tr><td>Energy Demand
Short term: 4
Medium term: 4</td><td>• In 2025, about 71% of Co demand is expected to be from EV batteries and stationary storage batteries.
• In 2035, about 93% of Co demand is expected to be from EV batteries and stationary storage batteries.
• In high adoption scenarios, about 98% of vehicle batteries could use cobalt.</td></tr>
<tr><td>Substitutability Limitations
Short term: 2
Medium term: 2</td><td>• Co is the most expensive mineral, and cost is a particularly big concern for use in stationary storage batteries.
• In the short term, the industry is moving toward high-Ni low-Co chemistries, primarily driven by ethical, environmental, and supply security concerns.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term:3, medium term: 3</i></td></tr>
<tr><td colspan="2">The supply risk for cobalt is considered moderate to high in the short and long term. Democratic Republic of Congo (DRC) and Australia account for more than 65% of global cobalt reserves, and 60% of global production is concentrated in DRC. This concentration creates a risk of supply disruption due to geopolitical sensitivity, especially as demand for cobalt is expected to increase with demand for lithium-ion batteries in EVs. A move to alternative battery chemistries that use less or no cobalt can mitigate some of these supply risks.</td></tr>
<tr><td>Basic Availability
Short term: 3
Medium term: 3</td><td>• All trajectories exceed current production capacity by 2025, by nearly 60% for the lowest trajectory and by more than 200% for the highest trajectory.
• All trajectories exceed current production capacity by larger amounts by 2035 (170%–1600%).
• However, supply is expected to increase in the short term, with new projects such as those by Glencore, China Molybdenum and Indonesian Nickel and Cobalt expected to ramp up production capacity.</td></tr>
<tr><td>Competing Technology Demand
Short term: 2
Medium term: 1</td><td>• Other uses for Co include: in jet engine, gas turbine, and rocket nozzle materials in the aerospace and defense industries; in medical devices such as pacemakers and prosthetic joints; in high-performance magnets in electric motors and generators; as catalysts in chemicals and petrochemicals industry pigments; and in some consumer rechargeable batteries.
• The market for non-energy applications for cobalt is expected to grow in the range of about 5% per year in the near term and by 3% in the medium term.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 4
Medium term: 4</td><td>• Cobalt receives a weighted average of 19.38 based on 2022 production data.
• The largest producer, Congo, receives an average rating of 8.3.
• The second- and third-largest producers, Indonesia and Russia, increase the political, regulatory, and social (PRS) score with weighted averages, respectively, of 36.7 and 40.6.</td></tr>
<tr><td>Codependence on Other Markets
Short term: 3
Medium term: 3</td><td>• Roughly 90% of cobalt is produced in conjunction with copper and/or nickel.</td></tr>
<tr><td>Producer Diversity
Short term: 4
Medium term: 4</td><td>• Most of the cobalt (about 70%) comes from Congo, which contributes to the HHI producer diversity score of 5280 for all cobalt mining. Indonesia and Russia each account for about 5%.</td></tr>
</table>

Historical Price and Production



Source: USGS Cobalt historical statistics

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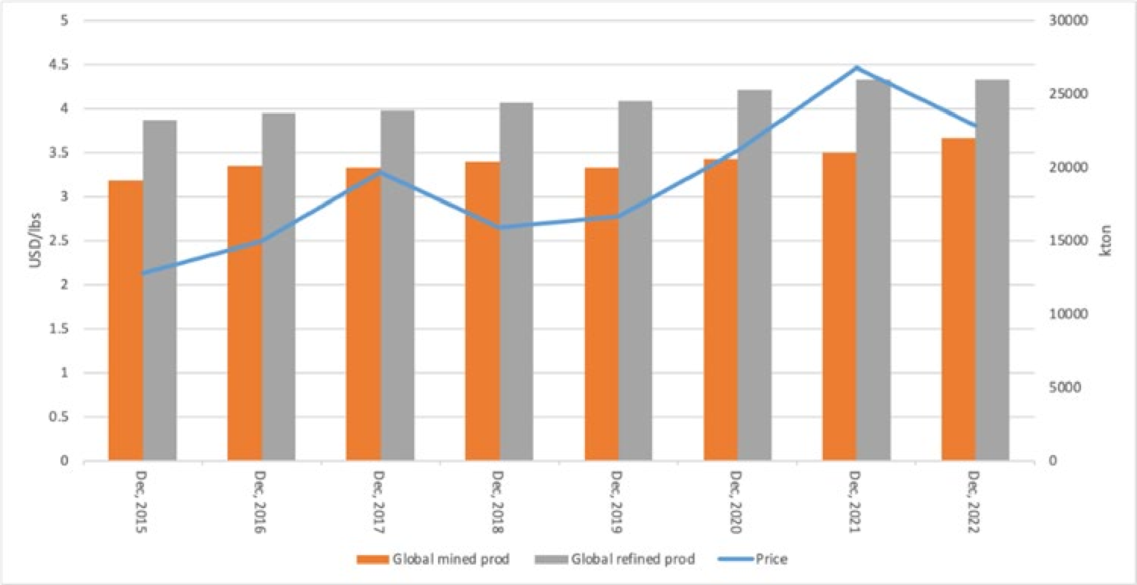
<table>
<tr><th>Copper (Cu)</th><th>Atomic number: 29</th></tr>
<tr><td colspan="2">Cu is generally found in nature in association with sulfur and is extracted as copper sulfides from large open pit mines in porphyry copper deposits (Craig and Leonard, 2019). Copper is the third most-used metal in industry after iron and aluminum due to its high ductility, malleability, thermal and electrical conductivity, and corrosion resistance.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 2, medium term: 3</i></td></tr>
<tr><td colspan="2">Cu needs vary widely across technologies. With growing demand for clean energy technologies such as solar photovoltaic (PV) (5.5 tons Cu per MW), wind (4.7 tons of Cu per 3-MW system), energy storage (20–520 lbs. Cu/MW depending on battery types), power grid, and EVs (88–183 lbs. Cu/vehicle) (Copper Development Association Inc., n.d.), Cu is essential to them. Hydro, concentrating solar power (CSP), and nuclear applications will continue to experience growth, which, although moderate, would require a considerable amount of Cu (IEA, 2021).</td></tr>
<tr><td>Energy Demand
Short term: 2
Medium term: 3</td><td>The demand for Cu is increasing significantly, given the predicted rise of EVs (IEA, 2022a). The aggressive vision of the U.S. Department of Energy (DOE) for wind (~230 GW [IEA, 2022d2022c]) and high-voltage direct current (HVDC) (~39 GW [Baig, 2019]) deployment by 2030 is also a factor. In the International Energy Agency's (IEA's) Net-Zero Emission Scenario (NZE), Sustainable Development Scenario (SDS), and Stated Policies Scenario (STEPS), EV shares are tipped to reach 89%, 76%, and 31%, respectively, by 2040 (IEA, 2022b).
In 2021, global refined Cu production was estimated to be 26 million metric tons. Given the technologies under consideration, including electric grid, conventional vehicles, EVs, and wind, the energy demand share is 36% and 45% in the short term and medium term, respectively. Of those technologies, Cu is a dominant technology choice over other materials. Therefore, a score of 2 and 3 were given for the short and medium terms, respectively.</td></tr>
<tr><td>Substitutability Limitations
Short term: 3
Medium term: 3</td><td>Aluminum (Al) may be used as substitutes in automobile radiators, the cooling and refrigeration tubes, electrical equipment, and power cables. Titanium and steel are used in heat exchangers (USGS, 2022a). Net Cu substitution was at 1.32% of total global copper usage in 2021 and is projected to be the same until 2026 (DMM Advisory Group, 2022). Despite operational limitations, Al constitutes the least costly option. Considering a higher share of Al in underground and subsea cables, which account for 50% and 30% for distribution and transmission lines, respectively, by 2040, Cu demand could be reduced by more than one-third (IEA, 2021).</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 2, medium term: 2</i></td></tr>
<tr><td colspan="2">Copper has a low supply risk thanks to diverse producing countries and to its being a major metal. There are some concerns regarding declining ore grade that reduces production output, as well as competing demand from the construction sector.</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>Despite growth in Cu demand, it is unlikely that Cu reserves will run out anytime soon. In 2022, the supply demand balance was achieved, with refined production able to cover consumption (25.3 vs. 25.1 million mt, respectively) (Nornickel, 2021). In the medium and long terms, if no new discoveries are made and production rates remain unchanged, it would take more than 100 years to mine all current deposits, not including supplies restored through recycling (Trilogy Metals, 2021).

Globally, recycling can meet > 30% of total Cu demand, and the recycling rate of end-of-life Cu is 40% (International Copper Alliance, 2021).

There are some copper mine projects under development or evaluation with annual production capacities > 100,000 tons, which can produce 10 Mt of Cu altogether (International Copper Study Group, 2022). However, globally, the ore quality is degrading. There were only two projects that came online between 2017 and 2021 in the DRC and Peru. Their ramping-up rate has been slow. Chile, the largest copper producer in the world, reported a 7% year-over-year decline in November of 2022. Peru, the second-largest mining country for Cu, observed a decline in output of 5.8% this year (Mills, 2023). In addition, multiple</td></tr>
</table>

	sources have predicted copper shortages of 10 Mt in 2035 and 14 Mt in 2040 (Mills, 2023). Based on projected demand trajectories in Appendix D, in the short term, only trajectory D exceeds current production capacity. In the medium term, three out of four trajectories exceed the current capacity. Combined with the facts listed above, scores of 2 and 3 were given for the short term and medium term, respectively.
Competing Technology Demand Short term: 3 Medium term: 3	The use of Cu in building construction has grown from 44% in 2015 to 46% in 2021 in the United States (USGS, 2015, 2022d) and remains the leading end-use market globally at 29% in 2021 (Business Wire, 2022). Its CAGR is expected to be between 5.3% (Report Linker, 2022) and 6% by 2027 (The Business Research Company, 2023a). Therefore, a score of 3 was given for the short term and medium term, respectively.
Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	Chile, the Democratic Republic of Congo (DRC), Peru, and China are the biggest producers of mined Cu, with Chile leading (USGS, 2023). Although a new relationship was marked in April 2019 with DRC with the announcement of the “Privileged Partnership for Peace and Prosperity” (PP4PP), the country is still prone to instability, with the phenomenon of child/underage labor still rife (Niarchos, 2021). Over the medium/long term, Chile remains dominant, with Australia and Peru (USGS, 2023), which are also friendly (U.S. State Department, 2022a, 2022b). Additionally, in both Peru and the Philippines, maintaining good relationships with indigenous communities is key to maintaining production (International Copper Study Group, 2022). Over the past 2 years, a political conflict in Peru impacted this country’s Cu output, as well as shipment to international markets (Mills, 2023). In addition, the water supply is an issue in dry mining districts, and coal is the main fuel for power to Cu mines (International Copper Study Group, 2022). If coal is phased out, the production cost of Cu would increase and impact production. Regarding refining, China is the leading country with ~39% global market share, followed by Chile at 8% and Japan and DRC at 6%. Other countries have a market share of < 3%. Calculation of the PRS factor is in the 52nd percentile, which yields a score of 2.
Codependence on Other Markets Short term: 1 Medium term: 1	Cu is a major metal, although it can also be a co-product of other metals. Molybdenum, nickel, and cobalt are commonly found with Cu, although it is generally a by-product of these metals and not the primary product (Ayres et al., 2003). Cu can be considered the principal product for selenium and tellurium (Nassar et al., 2015).
Producer Diversity Short term: 1 Medium term: 1	Just five countries, including Chile, Australia, Peru, Mexico, and the United States, hold ~65% of the world’s discovered resources (Trilogy Metals, 2021). In 2022, Cu was mined in more than 13 countries and refined in more than 16 countries (USGS, 2023). Chile and Peru accounted for 37% of global output while China accounted for 35% of refining output in 2021. The HHI indices for mining and refining countries are 1096 and 1684, respectively, showing a competitive market.

Historical Price and Production



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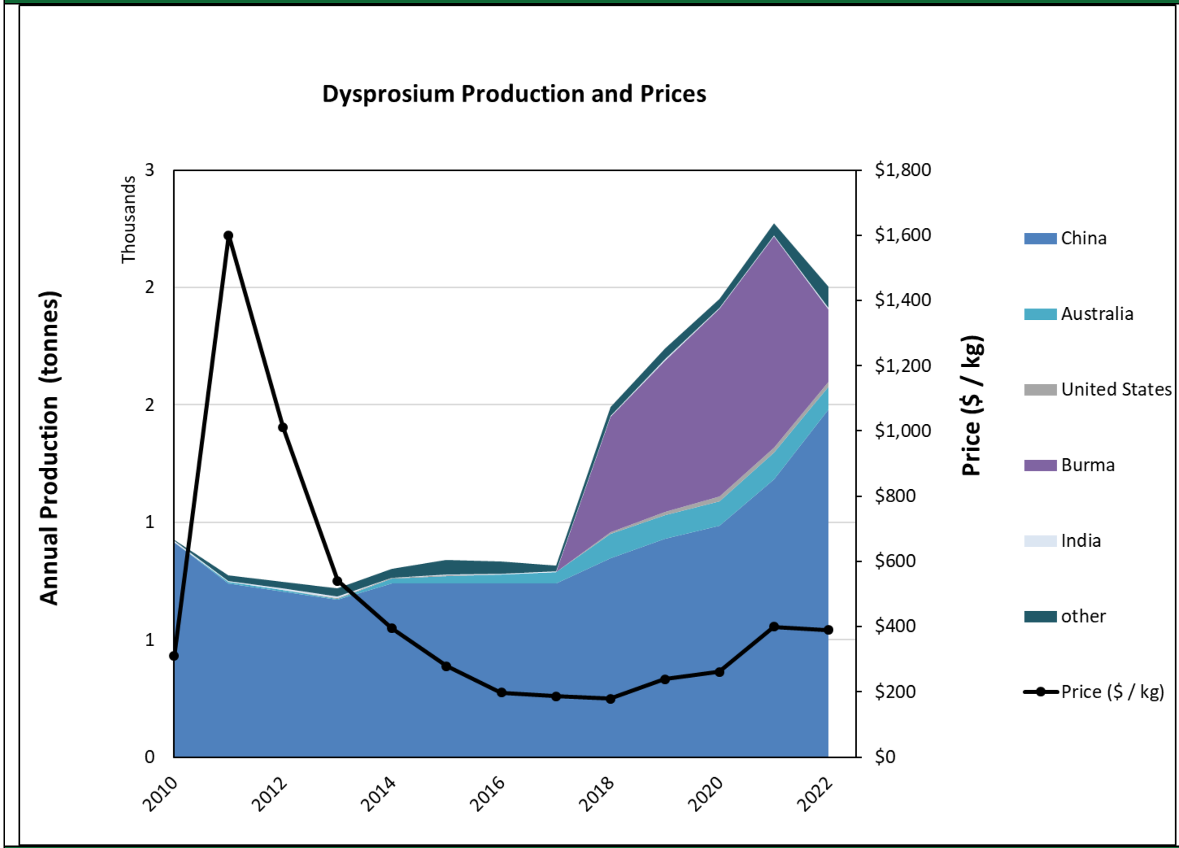
Element: Dysprosium (Dy)	Atomic number: 66
Dysprosium is a rare earth metal that is used in the production of powerful NdFeB magnets, which are used in applications such as electric vehicle motors, wind turbine generators, consumer electronics, industrial motors, and in other non-drivetrain uses in vehicles. In addition, Dy oxide is used in terfenol-D and other alloys.	
Importance to Energy: *Short term: 4, medium term: 3*	
Electric vehicles and wind turbines are both key drivers of dysprosium demand, with vehicles being the more important source of growth, especially in the medium term and beyond. Dysprosium is very important to clean energy in the short term, where its high share of use is driven by key clean energy applications; while in the medium term, the potential for more substitution away from dysprosium reduces its importance slightly.	
Energy Demand Short term: 4 Medium term: 4	• In 2025, about 83% of Dy demand is expected to be from magnets in EVs and wind turbines. • In 2035, 94% of Dy demand is expected to be from EVs and wind turbines. • Component share of permanent magnet motors in electric vehicles is estimated to be 98%, with percentages likely to stay above 50% through 2040.
Substitutability Limitations Short term: 3 Medium term: 2	• NdFeB magnets have alternatives in electric vehicles, including induction motors and electrically excited brushed motors, which have been used in vehicles such as early versions of Tesla and some BMW EVs. However, alternatives have disadvantages, such as lower efficiency for induction motors, and as a result, alternative sources represent a small share of the total market. • NdFeB magnets are used in a relatively small portion of onshore wind turbines; however, they have significant advantages for offshore wind turbines and would be more difficult to replace. • Tesla has announced plans to switch away from NdFeB magnets, likely to use ferrite magnets instead, suggesting some increase in substitutability in the medium term. • Dy use in magnets can be reduced or eliminated through techniques such as grain boundary diffusion, as well as reengineering them to reduce the temperatures at which they operate.
Supply Risk: *Short term: 3, medium term: 4*	
Supply risk for dysprosium is high in the short term and especially in the medium term. Dy is largely produced in China, and there are significant challenges to diversifying the supply, even more so than for Nd and Pr due to the limited number of deposits that are rich in heavy rare earths that can compete with China's ionic clays.	
Basic Availability Short term: 3 Medium term: 4	• Demand for Dy is projected to exceed current capacity by 2025 in three of the four trajectories. • Demand for Dy is projected to significantly exceed current supply by 2035 in all four trajectories. • While many rare-earth deposits have been under development since the early 2010s, a limited number have been able to advance to the construction stage. • The projects that have been most successful at producing heavy rare earths, such as Dy, economically have largely been ionic clays, which are not very common outside of China. • While there are sufficient rare-earth resources to meet the projected increases in demand, new types of rare-earth minerals may need to be developed, which could lead to cost increases.
Competing Technology Demand Short term: 3 Medium term: 3	• Other uses for Dy include: as magnets in consumer electronics, industrial motors, and non-drivetrain automotive motors, as well as terfenol-D and other alloys. • Adamas Intelligence (2020) projects that magnet use in industrial applications and in consumer electronics will grow at rates between 5% and 10% per year.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• The largest producer, China, receives an average rating of 41.3, while the second-largest producer, Burma, brings it down, leading to a weighted average rating of 38.0 for Dy mining. • The scores for separation and metal refining are slightly higher due to the smaller role played by Burma at these stages.
Codependence on Other Markets Short term: 3 Medium term: 3	• Dy is the largest source of revenues for heavy rare-earth deposits such as ionic clays, but these deposits also receive significant revenues from other rare-earth co-products. • Some Dy is produced from deposits where light rare-earth elements (LREEs) such as Nd and Pr are expected to be the primary revenue source.
Producer Diversity Short term: 4 Medium term: 4	• About 93% of Dy separation happens in China, leading to an HHI score of 8634 for Dy separation by country. • The current HHI score for metal refining is estimated to be 8125, and for mining it is 6004.

	• Additional separation capacity outside of China may lower these scores somewhat, but not enough to reduce the risk rating.

Historical Price and Production



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<table>
<tr><th colspan="2">Material: Electrical Steel Atomic number: N/A</th></tr>
<tr><td colspan="2">Electrical steel is an iron-silicon alloy having varying amounts of silicon (Si) ranging from 1% to 6.5% (Eckard, 2020). It is used as the core of electromagnetic devices such as transformers, motors, and generators due to its superior magnetic properties including low coercivity, high permeability, and ductility.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 3, medium term: 3</i></td></tr>
<tr><td colspan="2">Electrical steel applications in the automotive industry (especially electric vehicles) and appliances such as commercial refrigerators, air conditioners, power coolers, and washing machines are the major driving force for market growth (Fact.MR, 2022). Grain-oriented electrical steel (GOES) growth is due to high-power generators and transformers. Non-grain oriented electrical steel (NOES) is used for electric motors, small generators, and appliances. By market value, NOES accounted for ~70% market share in 2021 (Fact.MR, 2022; The Business Research Company, 2023b).</td></tr>
<tr><td>Energy Demand
Short term: 3
Medium term: 3</td><td>Considering three main technologies including transformers, wind turbines, and vehicle motors for both conventional vehicles and EVs, energy demand share is 42% and 61% in the short term and medium term, respectively. Additionally, electrical steel accounted for 37% and 32% market shares of soft magnetic materials in 2018 and 2019, respectively. However, this material accounted for 67% and 60% market value of energy applications among other soft magnetic materials in 2018 and 2019, respectively. A score of 3 was given for both short and medium term.</td></tr>
<tr><td>Substitutability Limitations
Short term: 3
Medium term: 2</td><td>Alternatives to electrical steel exist at the material level but do not seem to play a major role. Amorphous steel is used in place of electrical steel in distribution transformers, commercial and industrial transformers, as well as current transformers (Metglas, n.d.). However, for large power transformers, there are no substitutes for electrical steel (Totemeier, 2004). For relays, inductors and high-frequency transformers, nickel iron alloys are being used (Totemeier, 2004). In the medium term, with nickel iron alloy increasing in use and with advances in technologies, viable substitutions for electrical steel may emerge.
In addition to material substitution, there are alternative motor designs for EVs to reduce manufacturing scrap, which is currently 30–45% or even up to 70% (Vittori et al., 2021). Also, axial flux motors, which are used in niche markets such as Ferrari LaFerrari and are planned for use in Mercedes AMG in 2024, utilize GOES rather than NOES.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 2, medium term: 2</i></td></tr>
<tr><td colspan="2">The growth of EVs requires a significant supply of high-grade NOES for traction motors called xEV steel while also requiring a greater supply of lower-grade NOES for low-power motor applications such as electric power steering, fuel pumps, seat motors, and sunroof motors. On average, each car has 35–45 low-power motors per car, with the low end being 20 and high end being 80 motors/car (Vittori et al., 2021). While existing capacity is able to meet demand for lower-grade NOES, and producers have announced plans to invest in EV-grade NOES in the next 3–5 years, it is still unclear whether supply will be able to meet demand (Vittori et al., 2021). Adding more complexity to the picture is that most producers can manufacture GOES and NOES in the same facility. Recent announcements have been made on increasing xEV steel (Hosokawa, 2022) with higher profit margins, which threaten the GOES supply for non-EV sectors due to lack of investment in GOES. EVs also have indirect exposure to the GOES supply due to GOES uses in charging infrastructure (Vittori et al., 2021).</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>Presently, availability is limited due to increasing demand and other events such as COVID-19, supply chain issues, etc. However, this year, major companies like Nippon Steel will catch up, and production capacity will be increased by almost 40%. Near-term capacity shortages between 2023 and 2025 — before new capacity comes online in 2025 — are expected to occur for both GOES and NOES. Most xEV-grade NOES can run at only 90% capacity. In 2020, xEV steel grade accounted for 320 kt, an amount that is expected to grow to 2.5 Mt in 2027 and to 4 Mt in 2033 (Vittori et al., 2021). Given projected capacity expansion, a shortage of 61 kt might occur in 2026. The shortages can increase to 357 kt in 2027 and 927 kt in 2030 without significant investments from existing producers or new players. It takes an existing manufacturer 3 years to expand its capacity and a new player from 2–8 years to produce xEV steel on top of the initial 3 years (Vittori et al., 2021).
There are also downstream bottlenecks for the EV sector with there being only 20 motor core lamination stampers globally that can meet the original equipment</td></tr>
</table>

	manufacturers' (OEMs') requirements (Vittori et al., 2021). There are onlyfive companies producing stamping presses and less than 10 tool shops to manufacture unique stamping dies to support advanced motor designs (Vittori et al., 2021; United States Steel Corporation, 2022; Vittori et al., 2021). There are also downstream bottlenecks for the EV sector with 20 motor core lamination stampers globally that can meet the OEMs' requirements (Vittori et al., 2021). Most investment announcements by major producers such as Posco, JFE, and ArcelorMittal (Magnetics Business & Technology, 2022) are to increase NOES production capacity over GOES capacity (Hosokawa, 2022; JFE Steel Corporation, 2023), causing a concern for the future supply of GOES. When comparing demand trajectories of three of the aforementioned energy technologies and current capacity as shown in Appendix D, short-term trajectories slightly exceed current capacity but medium term trajectories will cause some major concerns. Scores of 2 and 3 were given for short term and medium term, respectively.
Competing Technology Demand Short term: 2 Medium term: 2	In 2021, around 90% of electrical steel was used in transformer, generator, and motor applications (Fact.MR, 2022) in which 52% was used in transformers (The Business Research Company, 2023b). By end use, automobiles, energy, household appliances, and manufacturing accounted for 80% of market share (Fact.MR, 2022). There is less of a concern for competition with non-energy applications, but more of a concern regarding the competition between EVs and grid applications as stated above. With the rising demand of power generation and electric vehicle production, the need for electric motors, transformers, and generators will increase, driving the market for electrical steel. Although there are some other applications such as inductors, their CAGR ranges from 3.6% by 2026 (Modor Intelligence, 2022) to 4.3% by 2029 (Maximize Market Research, 2022), which yields a score of 2.
Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	As of 2022, China dominates the electrical steel market with ~19% of the electrical steel production, followed by Korea (13%), Japan (12%), Germany (11%), and Russia (8%). Other countries have a market share of <4%. The Russia–Ukraine war is also creating disruptions in the steel export industry, introducing price hikes as Russia produces 8% of the global steel (Fyfe, 2022; Tuck, 2023). In the medium term, the supply share of various countries might remain similar with the hope that no major wars will further disrupt supply. The score for PRS factors is 50th percentile, so a score of 2 was given for both short term and medium term.
Codependence on Other Markets Short term: 1 Medium term: 1	Electrical steel is an alloy of iron and silicon. The volatility and increasing trend of raw material prices (iron ore, industrial gases, and Si) in the next decade might pose a threat to the industry. However, both steel and Si are abundant and do not cause a major disruption.
Producer Diversity Short term: 1 Medium term: 1	The HHI index based on global electrical steel export is 1413, showing a diverse market.

Historical Price and Production

Data are not available.

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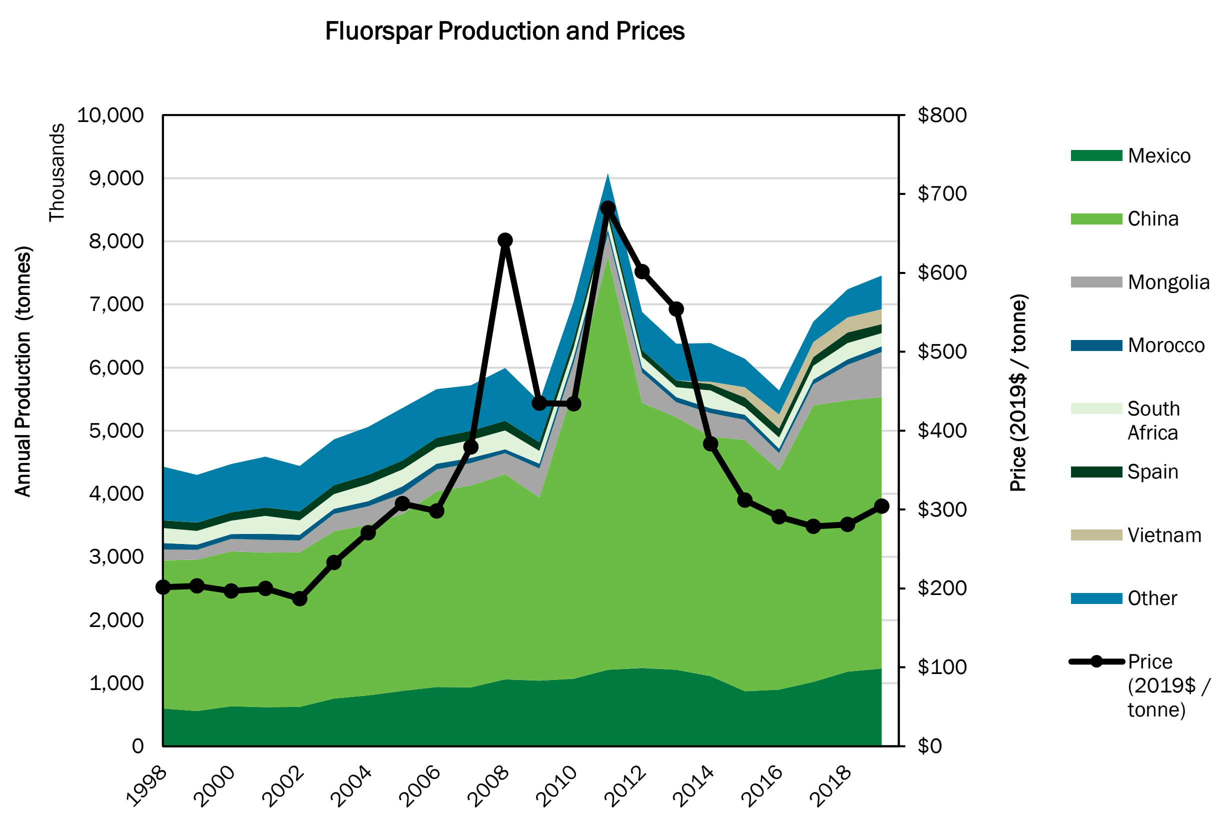
<table>
<tr><th>Element: Fluorine (F)</th><th>Atomic number: 9</th></tr>
<tr><td colspan="2">Fluorine is mainly used for hydrogen fluoride (HF) production, steel making, and aluminum smelting. Among the in-scope energy applications, fluorine is used in the cathode binder material and electrolyte salt of lithium-ion batteries (LIBs) for both EVs and stationary energy storage. The most common fluorine-containing mineral is fluorspar (also known as fluorite), which is also the name of the beneficiated material.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 2, medium term: 2</i></td></tr>
<tr><td colspan="2">The share of fluorine demand for energy applications will increase from 5% of the total demand in 2025 to 22% in 2035. This increase will be exclusively driven by fluorine’s use in LIBs. Fluorine-free cathode binder materials and electrolyte salts exist, but they have not been demonstrated commercially and/or have serious performance concerns.</td></tr>
<tr><td>Energy Demand
Short term: 1
Medium term: 2</td><td>• In 2025, fluorine demand for energy applications will account for 5% of the total demand.
• In 2035, fluorine demand for energy applications will account for 22% of the total demand. EV batteries represent the most dominant sub-technology and will account for 19% of the total demand.
• Across all scenarios, all LIBs use fluorine.</td></tr>
<tr><td>Substitutability Limitations
Short term: 3
Medium term: 3</td><td>• Lithium hexafluorophosphate ($LiPF_6$) is the electrolyte salt used in commercial LIBs. Electrolyte salts that do not contain fluorine exist, such as lithium perchlorate and lithium tris(oxalato) phosphate. The former has been phased out due to safety concerns. The latter has shown promising results in the lab but needs further research to demonstrate its viability for commercialization.
• Polyvinylidene fluoride (PVDF) is the cathode binder material used in commercial LIBs. Anode binder materials such as carboxymethyl cellulose and styrene-butadiene rubber have been proposed as substitutes for PVDF, together with water-based electrode manufacturing. However, the substitution could lead to corrosion and mechanical integrity issues of the cathode and severely affect battery performance.
• Synthetic fluorspar could be produced from various waste streams, but it is not suitable for battery applications because battery-grade materials require high purity.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 3, medium term: 3</i></td></tr>
<tr><td colspan="2">Supply risk for fluorine is high in both the short and the medium term. Current production capacity can meet nearly all short-term demand projections, but it will fall short of medium-term demand projections. China accounted for 68% of global production in 2022, and its market dominance is expected to continue. Limited new production capacity has been planned in Mongolia, the U.S., Canada, and the U.K.</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>• In 2025, all demand projections will exceed current production capacity by 1–4%.
• In 2035, all demand projections will exceed current production capacity by 40–70%.
• Except for the Lost Sheep Mine in the U.S., no new fluorspar mines are expected to start production by 2024, and it can take 8 years to fully develop a new fluorspar mining project.
• Moderate expansions have been planned for mines in Mongolia, Canada, and the U.K.</td></tr>
<tr><td>Competing Technology Demand
Short term: 4
Medium term: 4</td><td>• Other major uses of fluorspar include HF production, steel making, and aluminum smelting.
• HF is used in the production of semiconductors. The CAGR of the global semiconductor market, and thus its fluorine demand, could exceed 10%, driven by advancements in artificial intelligence (AI) and more connected devices.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 3
Medium term: 3</td><td>• Based on 2022 production data, fluorine receives a weighted average of 40.6, which roughly matches the score of China.
• Production shares of Mongolia, the U.S., Canada, and the U.K. are expected to increase moderately over the next few years as their new or expanded mining projects ramp up production. However, those changes are not expected to change the PRS score.</td></tr>
<tr><td>Codependence on Other Markets
Short term: 1
Medium term: 1</td><td>• Fluorspar is mined and beneficiated on its own and does not depend on other markets.
• Fluorine is also produced domestically in the U.S. as a by-product of phosphoric acid production, conversion of depleted uranium hexafluoride, and</td></tr>
</table>

	industrial waste streams. However, the volume is small (<10%) compared with imports for consumption.
Producer Diversity Short term: 3 Medium term: 3	• Based on 2022 production data, fluorine receives an HHI of 4842. China accounted for 68% of global production, Mexico 12%, South Africa 5%, and Mongolia 4%. • New or expanded mining projects that have been planned are not expected to change the producer diversity score.

Historical Price and Production



Note: Prices are for acid-grade fluorspar (>97% CaF_2).

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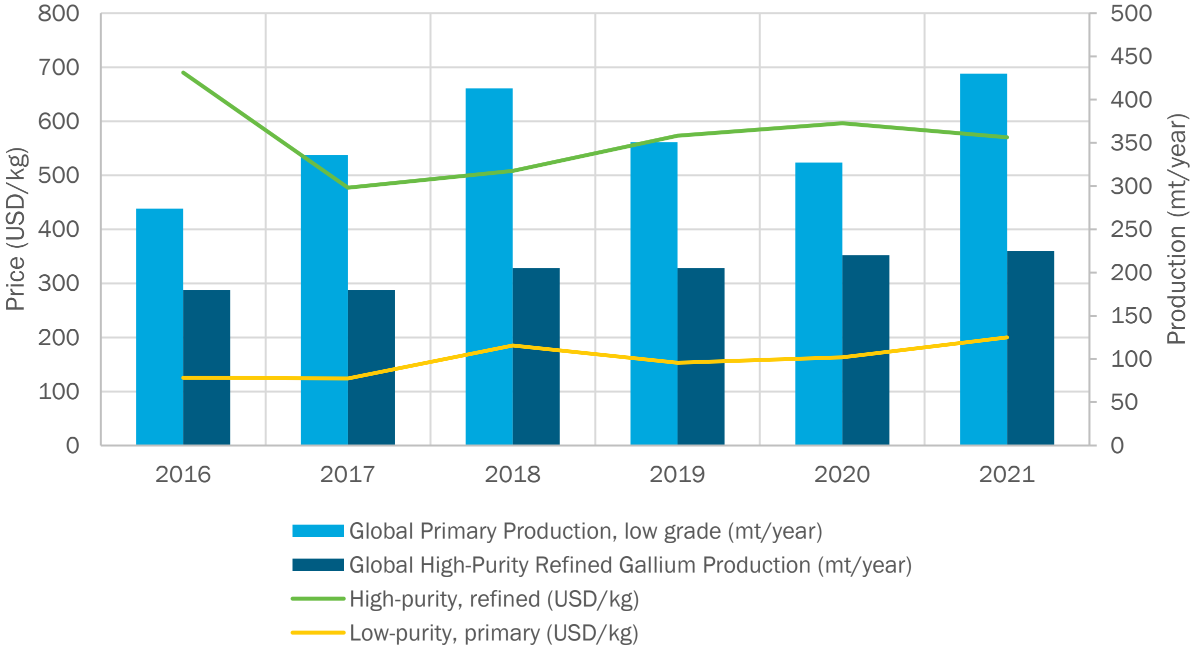
- Fortune Business Insights: Semiconductor market size, share & Covid -19 impact analysis. Available at: https://www.fortunebusinessinsights.com/semiconductor-market-102365

<table>
<tr><th>Gallium (Ga)</th><th>Atomic number: 31</th></tr>
<tr><td colspan="2">Gallium is a soft, silvery metal that is liquid at room temperature and used in applications such as integrated circuits, laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells.</td></tr>
<tr><td colspan="2">Importance to Energy: Short term: 3, medium term: 3</td></tr>
<tr><td colspan="2">Gallium is utilized in several different energy applications such as LEDs, solar panels, power electronics, and permanent magnets. Many of these applications will continue to experience increased growth in demand over the coming years and will remain important to future energy applications.</td></tr>
<tr><td>Energy Demand
Short term: 4
Medium term: 4</td><td>Gallium plays a critical role in energy applications such as LEDs, solar panels, power electronics, and permanent magnets. These energy applications represent anywhere from ~77–87% of the total market share of gallium in the short and medium terms. Additionally, of these energy applications, LEDs have a global market share of >50%.</td></tr>
<tr><td>Substitutability Limitations
Short term: 2
Medium term: 2</td><td>Varying levels of substitutability exist for gallium in different energy applications. There is no technology to replace gallium in LED compositions, only preliminary technology to reduce gallium content (Gaffuri et al., 2021). However, alternative lighting sources such as incandescent, fluorescent, etc., exist to the detriment of luminous efficacy and at the expense of more rare earths (IEA, 2022c).
For power electronics, Si and SiC semiconductors can substitute GaN although GaN has higher operating frequencies than Si and SiC (Rosina and Villamor, 2022). Other semiconductor applications such as power amplifiers can also be substituted by technology utilizing silicon. Developers of solar applications see silicon as the predominant technology and a viable substitute for gallium-based solar PV technology.

Based on the dominant application of LEDs, a score of 2 was given to this metric.</td></tr>
<tr><td colspan="2">Supply Risk: Short term: 3, medium term: 3</td></tr>
<tr><td colspan="2">Supply risk for gallium is elevated due to the lack of diversity with primary gallium production. Additionally, because primary production of gallium comes from China, the risk is increasingly elevated due to less stringent environmental compliance and potential supply disruptions to non-allied countries.</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>Primary and high-purity gallium production is currently operating below existing production capacities. Additionally, gallium is recovered during semiconductor manufacturing for secondary production. Under aggressive growth in demand for both the near term and medium term, gallium production could become problematic based on current production capacity estimates without further consideration for application grades. The 2021 recycling capacity was 273 mt/year while high-purity refining capacity was 325 mt (Jaskula, 2023).</td></tr>
<tr><td>Competing Technology Demand
Short term: 3
Medium term: 3</td><td>Gallium arsenide wafers in varying applications are projected to grow at a CAGR of 6.5% (MarketWatch, 2023). These wafers find a home in a multitude of applications such as in transistors, computers, integrated circuits, and other high-frequency electrical applications (Wafer World).</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 3
Medium term: 3</td><td>Primary production of gallium is dominated by China (97% market share), yielding a host of concerns with supply disruption (including environmental restrictions imposed on bauxite production) and market manipulation (Jaskula, 2023). The PRS score was calculated at 42%.</td></tr>
<tr><td>Codependence on Other Markets
Short term: 4
Medium term: 4</td><td>Gallium is predominantly produced — over ~90% (Jia et al., 2022; USGS, 2022b) — as a by-product of processing bauxite, and the remainder comes from zinc-processing residues (Jaskula, 2023).</td></tr>
<tr><td>Producer Diversity
Short term: 4
Medium term: 4</td><td>China dominates primary production of low-purity gallium at ~98% of global primary production. However, refined gallium is produced in a number of countries (including Canada, China, Japan, Slovakia, and the</td></tr>
</table>

United States), and secondary production of refined gallium provides more diversity (USGS, 2022b). The computed HHI index is 9606.

Historical Price and Production



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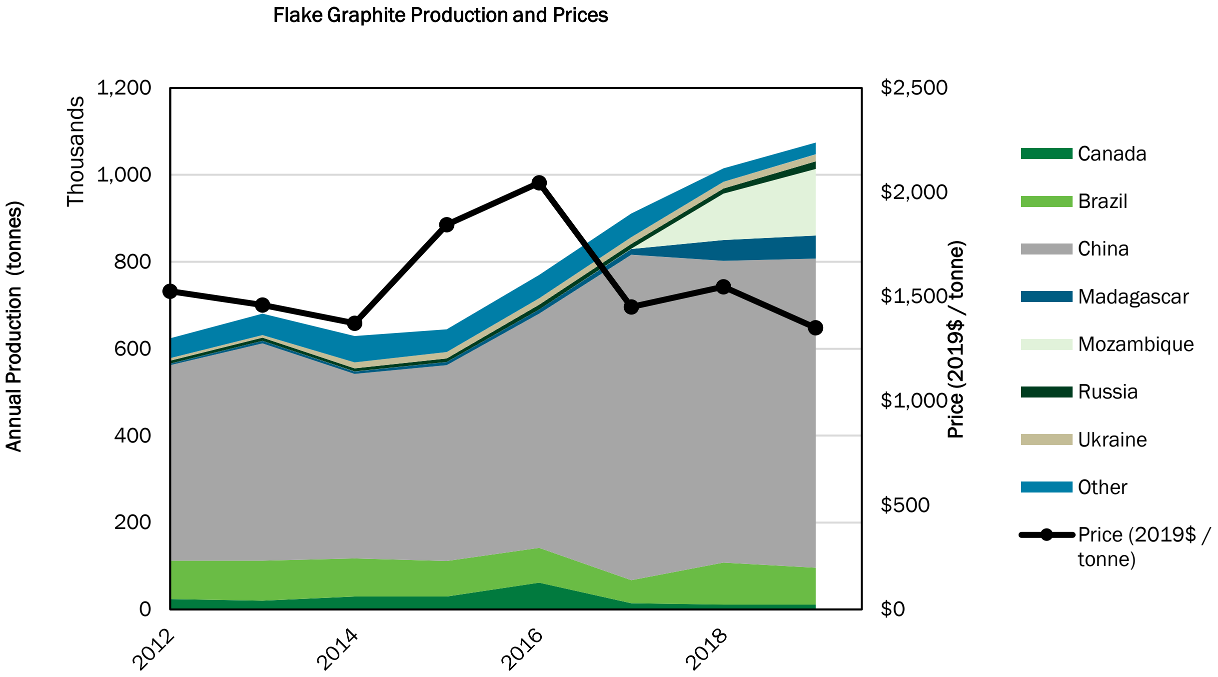
<table>
<tr><th>Element: Graphite (C)</th><th>Atomic number: 6</th></tr>
<tr><td colspan="2">Graphite is a form of carbon that has a layered structure. It is used in batteries, fuel cells, and nuclear reactors. Beyond energy applications, major uses of graphite include refractories, foundries, and lubricants. Among the three types of natural graphite, only flake graphite is suitable for battery and fuel cell applications.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 3, medium term: 3</i></td></tr>
<tr><td colspan="2">Increases in graphite demand will be predominantly driven by its use as the anode active material in batteries for EVs and stationary energy storage systems. Synthetic graphite can replace natural graphite but costs more. Other anode materials (e.g., Si and $Li_4Ti_5O_{12}$) can be used in lieu of graphite, but complete substitution is unlikely due to technological challenges and performance concerns.</td></tr>
<tr><td>Energy Demand
Short term: 3
Medium term: 4</td><td>• In 2025, flake graphite demand for energy applications will account for 64% of the total demand. EV batteries represent the most dominant sub-technology and will account for 55% of the total demand.
• In 2035, flake graphite demand for energy applications will account for 91% of the total demand, and EV batteries will account for 74% of the total demand.
• In high adoption scenarios, all batteries and fuel cells use graphite, and the share of natural graphite is 53%.</td></tr>
<tr><td>Substitutability Limitations
Short term: 2
Medium term: 2</td><td>• Natural graphite can be substituted out with synthetic graphite.
• Synthetic graphite can help prolong battery cycle life. However, it is more expensive on a per-kg basis and more energy-intensive to produce.
• Silicon can be a partial substitute for graphite as an anode active material for batteries. It has higher capacity but can cause degradation issues because it swells during charging, and therefore needs to be blended with graphite for use in batteries.
• Contradictory information exists as to whether synthetic or natural graphite is preferred for use in silicon/graphite blends.
• Lithium titanium oxide can also be a partial substitute for graphite as an anode active material for batteries. However, the low capacity confines its use to applications where low-temperature operation and/or fast charging are particularly important, such as stationary storage in cold climates and heavy-duty EVs.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 3, medium term: 3</i></td></tr>
<tr><td colspan="2">Supply risk for graphite is high in both the short and the medium term. Current production capacity falls far short of medium-term demand projections, and planned new capacity is not sufficient to completely close the gap. China accounted for 66–82% of global production in 2017–2021, and its market dominance is expected to continue. Tanzania and Mozambique are expected to become major producers over the next few years.</td></tr>
<tr><td>Basic Availability
Short term: 3
Medium term: 3</td><td>• In 2025, the high demand projection will exceed current production capacity by 79%.
• In 2035, all demand projections will exceed current production capacity by 34%–822%.
• A handful of new projects with a combined capacity of 700,000 metric tons per year (tpy) have been planned in China. In Africa, three projects with a combined capacity of 185,000 tpy have started construction, four projects totaling 685,000 tpy have planned construction, and three projects totaling 163,000 tpy have completed feasibility studies. However, even after expansion, global production capacity of graphite will still struggle to meet the high demand projections.</td></tr>
<tr><td>Competing Technology Demand
Short term: 2
Medium term: 2</td><td>• Other major applications of flake graphite include refractories (mostly for steel making), foundries, friction products (e.g., brake pads), and lubricants.
• The CAGR of global steel production, and thus its graphite demand, could exceed 3% but remain below 5% as it rebounds from the pandemic and the war in Ukraine.
• CAGRs of graphite demand for other applications would not exceed 3%.</td></tr>
</table>

Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• Based on 2021 production data, graphite receives a weighted average of 39.8, which roughly matches the score of China. • The production share of Africa (notably Tanzania and Mozambique) is expected to increase over the next few years as the planned mining projects start production. As a result, the weighted average for graphite would decrease but should still remain above 30.
Codependence on Other Markets Short term: 1 Medium term: 1	• Graphite is mined and produced on its own and does not depend on other markets.
Producer Diversity Short term: 3 Medium term: 3	• Based on 2021 production data, graphite receives an HHI of 4812. China accounted for 68% of the global production, Brazil 9%, Mozambique 8%, and Madagascar 8%. • Taking the new mining projects into account, future global graphite production will be concentrated in China, Tanzania, and Mozambique. This should improve the HHI but not enough to change the producer diversity score.

Historical Price and Production



Note: USGS data for graphite production by type date back to 2012.

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Element: Iridium (Ir) Atomic number: 77

Iridium is the least-abundant platinum group metal, accounting for <2**%** of mined content. The chemical, electrochemical, and electronics industries currently account for the majority of iridium demand.

Importance to Energy: *Short term: 2, medium term 3*

Supporting the clean energy economy, iridium is the anode catalyst in proton electrolyte membrane (PEM) electrolyzers in the production of hydrogen. Iridium is also used in chemical catalysts and electrocatalysts that improve process energy and material efficiencies.

Energy Demand Short term: 2 Medium term: 3	• PEM electrolyzer technology for the production of hydrogen is nascent but emergent. • PEM electrolyzers are the only in-scope energy application for iridium considered in this analysis. The highest market share of iridium for this application is projected to occur in the penetration and material intensity scenario (Trajectory D), specifically: 10% in 2025 and 56% in 2035: • Catalysts and electrocatalysts that account for 45–50% of iridium demand (Johnson Mathey PGM Market Report, 2022) contribute to process energy and material efficiencies.
Substitutability Limitations Short term: 2 Medium term: 2	• Ruthenium has been studied as a partial substitute for iridium catalysts in proton exchange membrane electrolysis cell (PEMECs). However, this substitution has been found to have reduced catalyst stability in laboratory testing. • For hydrogen production, substitutes for PEM electrolyzers include alkaline (commercialized) and solid oxide (under development). PEMECs, however, provide performance and operating advantages. • Substitutes for hydrogen production also include biofuel pathways, and steam methane reforming (SMR) coupled with carbon capture, utilization, and storage are a substitute technology for PEM electrolyzers. Significant research funds are focused on development of hydrogen production technologies from a variety of feedstocks.

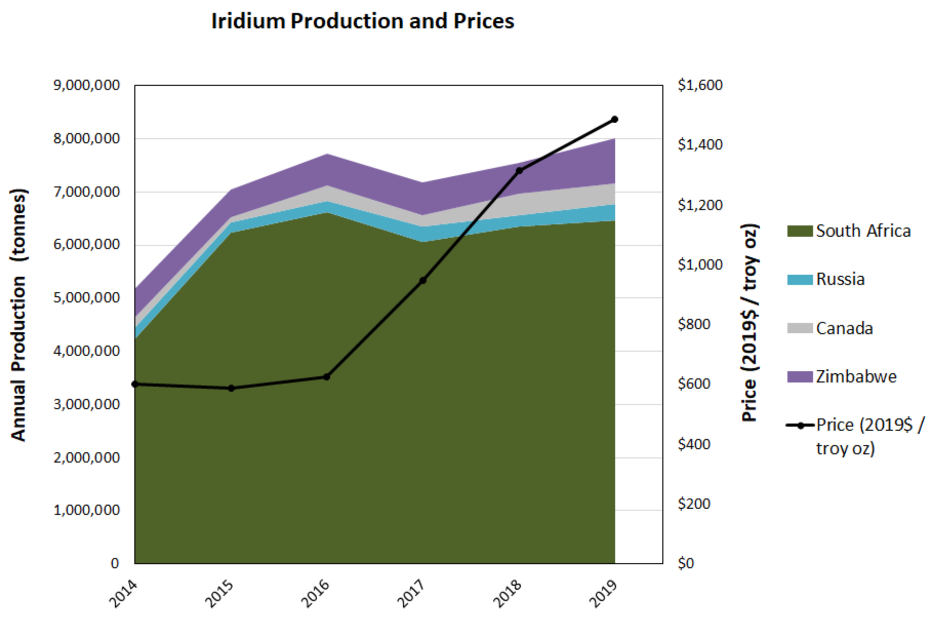
Supply Risk: *Short term: 3, medium term: 4*

Iridium is one of the rarest elements in the earth's crust. A particular challenge to the supply of iridium in coming years is the expected decline in demand for co-products palladium and rhodium used in internal combustion vehicles' catalytic converters and palladium used in diesel engine vehicles' catalytic converters. The majority of iridium is produced from mines and refiners in South Africa and Zimbabwe where mine operations have been affected by environmental, operational, safety, and labor issues.

Basic Availability Short term: 2 Medium term: 4	• PEM electrolyzer technology is nascent but emergent. • For all trajectories, the iridium demand exceeds 2020 capacity. By 2025, 3% to 12% more iridium capacity would be required to meet anticipated demands in the scenarios. In 2035, iridium capacity would need to triple to meet projected demands in the scenarios. A significant cause of this increase is growth in non-energy demands (assumed to be 3%), which may be responsive to price increases that would occur when demand exceeds supply capacity, thereby lowering the total demand. ○ Trajectory A: 2025; percent of 2020 Ir capacity = 102% ○ Trajectory B: 2025, percent of 2020 Ir capacity = 103% ○ Trajectory C: 2025, percent of 2020 Ir capacity = 104% ○ Trajectory D: 2025, percent of 2020 Ir capacity = 113% ○ Trajectory A: 2035, percent of 2020 Ir capacity = 138% ○ Trajectory B: 2035, percent of 2020 Ir capacity = 145% ○ Trajectory C: 2035, percent of 2020 Ir capacity = 161% ○ Trajectory D: 2035, percent of 2020 Ir capacity = 309% • CAGR for PEM electrolyzers >10% in the short and medium terms.
Competing Technology Demand Short term: 1 Medium term: 1	• Demand growth of iridium for non-energy applications is expected to follow GDP trends (<3% growth). However, this growth rate could be mitigated (reduced) by increased iridium prices, which may occur should PEMEC demands increase to the forecasted levels. • Iridium is used in the chemical, electrochemical, and electronics industries.

	• The production of tin oxide crucibles for high-temperature applications, with limited substitutability, is currently the most demanding application for iridium.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• The PRS factors' weighted average percentile for iridium is 37, based on 2020 production data. • Iridium production is concentrated in South Africa, where PGM mining and production have been interrupted by mechanical failures, safety issues, and labor unrest. • Political stability and social factors are also important in the second- and third-largest iridium-producing countries, specifically, Russia and Zimbabwe.
Codependence on Other Markets Short term: 4 Medium term: 4	• Iridium is the least-abundant element of the platinum group metals with a significant dependency on demands and market prices of platinum, palladium, and rhodium. • Iridium is not produced as a main product, and no excess by-product supply is known, although iridium may be recoverable from platinum mine overburden, discarded ores, and tailings. • The availability of iridium could be further challenged if other platinum group metals with which it is coproduced (particularly palladium and rhodium used in catalytic converters) decline.
Producer Diversity Short term: 4 Medium term: 4	• The HHI is 7986. • South Africa accounted for 89% of iridium production in 2020, followed by Zimbabwe (8%) and Russia (3%). • No significant changes are expected in the regional production of iridium.

Historical Price and Production



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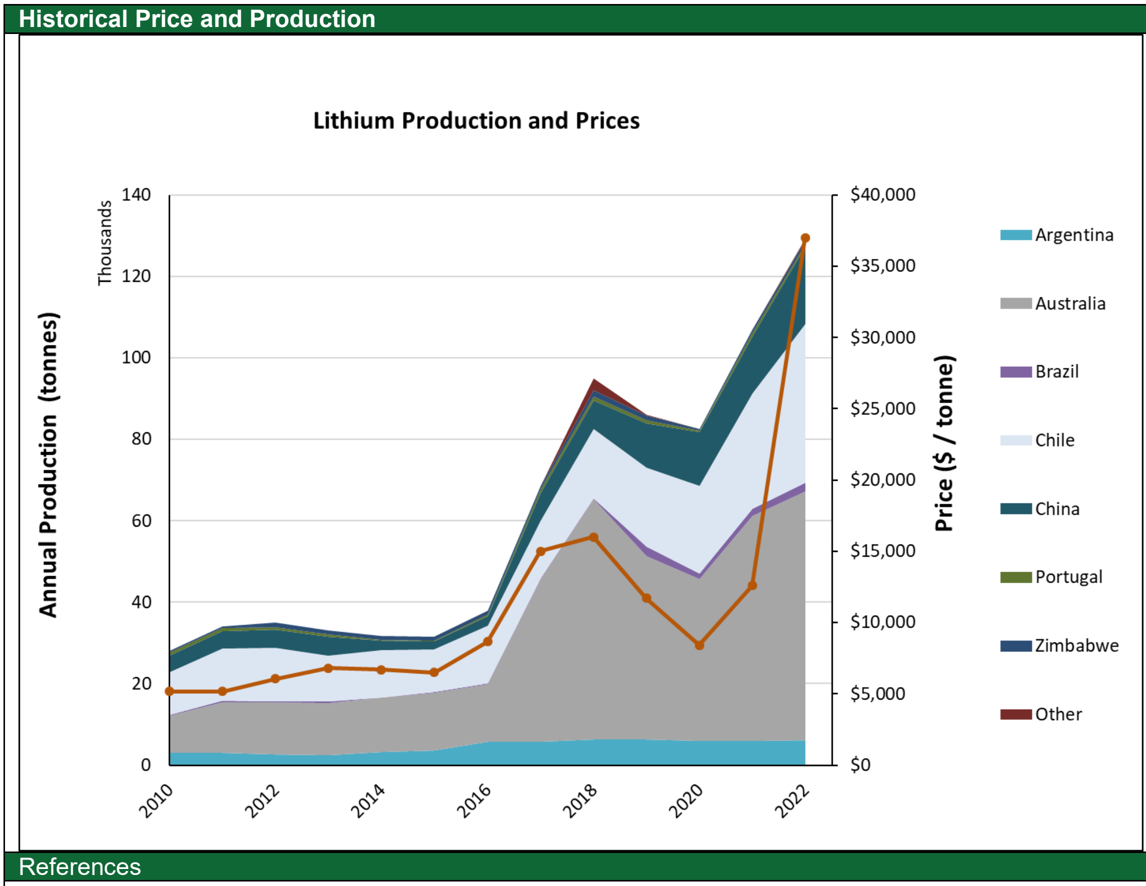
Element: Lithium (Li)	Atomic number: 3
Lithium is used in the Li-ion batteries in EVs, consumer electronics and stationary storage, metallurgy and coatings, ceramics and glass, lubricant grease, air treatment, pharmaceuticals, and polymers.	
Importance to Energy: *Short term: 4, medium term: 4*	
Lithium used in Li-ion batteries for electric vehicles is expected to be a key driver of future Li demand. Li for stationary storage is also expected to be an important and growing use. Lithium is found to be very important to clean energy both in the short and medium terms due to its key importance for electric vehicles and the difficulty in substituting away from lithium.	
Energy Demand Short term: 4 Medium term: 4	• In 2025, about 90% of Li demand is expected to be for EV batteries and stationary storage batteries in the highest demand scenario. • In 2035, about 97% of Li demand is expected to be for EV batteries and stationary storage batteries in the highest demand scenario. • All vehicle batteries are expected to use lithium in both the short and medium terms.
Substitutability Limitations Short term: 4 Medium term: 4	• In the short term, lithium use in Li-ion batteries cannot be easily replaced, as all models of Li-ion batteries use lithium, while the energy density of NiMH batteries is not high enough to support electric vehicles with large ranges. • Some reduction in Li may be possible by increasing the energy density of the battery, such as by replacing LFPs with NMC batteries. • Alternative battery chemistries that do not use lithium are possible, such as sodium-ion batteries, but more research is required before they will become viable.
Supply Risk: *Short term: 2, medium term: 3*	
Supply risk for lithium is moderate in the short term, and high in the long term. Lithium is relatively abundant, and there are sources of supply in relatively friendly countries; however, the challenges keeping up with expected rapid increases in demand and the concentration of lithium refining in a small number of countries contribute to supply concerns.	
Basic Availability Short term: 3 Medium term: 4	• In the short term, all four trajectories exceed current production capacity. • In the medium term, the amount of new production needed to meet the demand trajectories would be even higher, making it more challenging to meet that level of demand. • There are significant Li resources that can be brought online to help meet the new demand, many of which are being actively developed. • However, at the levels of new production needed for batteries, higher-cost deposits may need to be developed to meet this rapid growth in demand.
Competing Technology Demand Short term: 1 Medium term: 1	• Other uses for Li include: in batteries for consumer electronics, metallurgy and coatings, ceramics and glass, lubricant grease, air treatment, pharmaceuticals, and polymers. • None of these uses of Li is projected to grow faster than the expected economic growth rate of 3%.
Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	• A weighted average of 53.94 is found if the location of refining into carbonates and hydroxides is used. The largest refiner, China, receives an average rating of 41.5. The next-largest refiner, Chile, has a rating of 72. • The average rating is higher (71.3) if the location of extraction is used due to the high rating of the largest Li mining country, Australia.
Codependence on Other Markets Short term: 1 Medium term: 1	• Lithium is largely produced on its own or as the primary product with minor by-products.
Producer Diversity Short term: 3 Medium term: 3	• The HHI score of 4344 is for Li refining into Li carbonate and hydroxide, which is largely concentrated in China (60%) and Chile (26%). • Lithium extraction has a lower HHI score, 3137, with the largest producer being Australia, with 45% of the market.

Historical Price and Production



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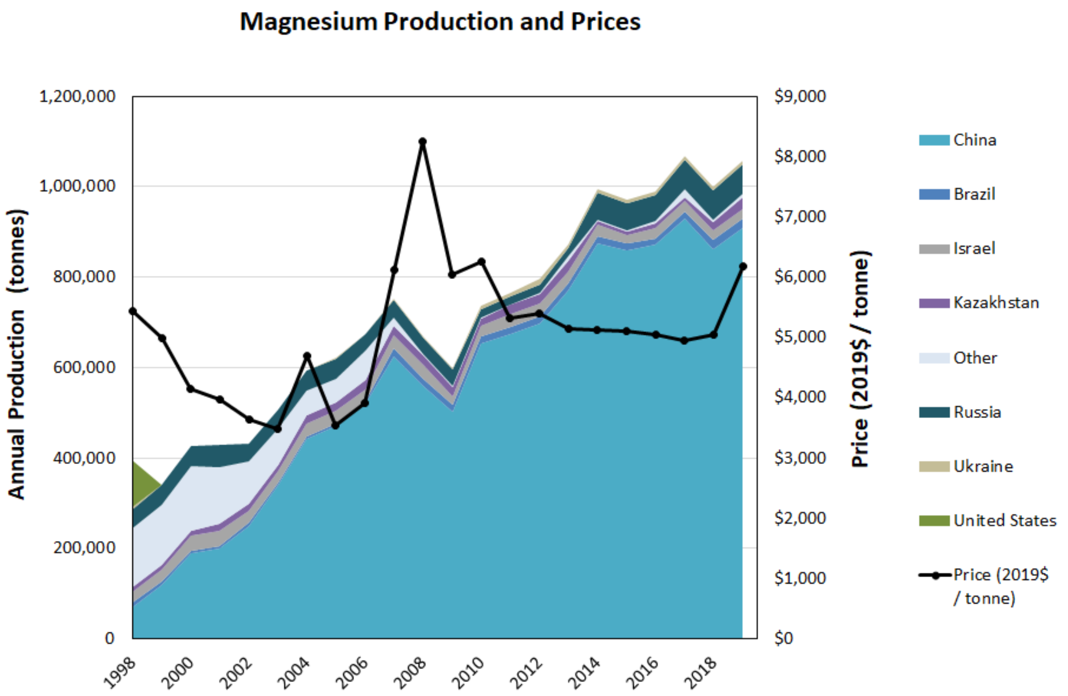
Element: Magnesium (Mg)	Atomic number: 12
Magnesium is an alkaline earth metal that is often used as a hardening and casting alloy for aluminum in the transportation sector in addition to making materials lighter. Magnesium is also used in iron and steel to remove sulfur.	
Importance to Energy: *Short term: 3, medium term: 3*	
Use of magnesium will increase and is being driven by the lightweighting of vehicles primarily through use of magnesium alloys and Mg's incorporation into advanced high-strength steel. While substitutes for magnesium are available, performance would decline, and widespread production capabilities are not thoroughly available.	
Energy Demand Short term: 3 Medium term: 3	• Energy demand by 2025 constitutes 74% of total magnesium demand in its highest demand trajectory (Trajectory D), creating major magnesium demand in energy applications. • By 2035, the energy demand percentage under the high penetration scenario, Trajectory D, increases to 81%. The highest level of sub-technology adoption within magnesium technologies is 38% in the short term and 39% in the medium term.
Substitutability Limitations Short term: 3 Medium term: 2	• The applicability of aluminum alloys in automotive production would decline if magnesium content were reduced, as magnesium increases strength and improves weldability. • The increased usage of AHSS steel in lightweighting reduces the content of magnesium in the material composition. However, all aluminum alloys must be replaced by AHSS steel or polymer composites to substitute out magnesium, as magnesium is an essential alloying element in aluminum alloys. • Magnesium alloy utilization in the lightweighting of automobiles is projected to remain low until 2040, as the application is limited to inner body parts and supply chains are not well established. Therefore, substitutability of magnesium alloys by other alloys altogether is a viable option. • Polymer composites that produce the same reduction in mass as magnesium alloys provide an option for substitutability; however, the recyclability, and application-specific production create high costs, keeping the composites from being viable in the near term.
Supply Risk: *Short term: 2, medium term: 3*	
The supply risk of magnesium is moderate in the short term due to production levels and the capacity of magnesium production meeting all demand trajectories. In the medium term, supply risk has the potential to worsen given that the geographic profile of magnesium extraction is highly concentrated in one area, which can disrupt supply if export or environmental regulations lower capacity.	
Basic Availability Short term: 1 Medium term: 2	• In the short term, production capacity of magnesium can meet demand for all trajectories, including the highest intensity demand trajectory. By 2035, trajectories C and D outstrip 2020 production capacity levels, creating moderate concern in the medium term about meeting projected magnesium demand. • Magnesium is abundant in the Earth's crust and can be found in natural minerals such as dolomite, sea-brines, and seawater, all of which are found globally. Resources, therefore, are theoretically unlimited as magnesium can be recovered from seawater along the world's coastlines. Although there are theoretically unlimited resources, magnesium is primarily produced through mined dolomite in the leading producer country, China, utilizing an energy-intensive but economical process known as the Pigeon process. Production through seawater, on the other hand, is economically costly and energy intensive. Technology would need to improve in order to produce a low-cost, low-energy form of magnesium through seawater and tap the vast resources available. • Production amounts do not account for U.S production as amounts are not published to avoid disclosing proprietary data. If U.S. production is similar to the production-to-capacity ratio levels published by other countries, then production amounts can sufficiently meet all short-term demand trajectories. • A total of 85% of the world's magnesium supply is produced using the Pigeon process in China. The process mixes calcined magnesium ore with ferrosilicon in an arc furnace to produce briquettes. These briquettes are then fed into a reduction furnace at very high temperatures under low pressure to release magnesium vapor,

	which is then cooled and collected before being remelted into ingots. This process is energy intensive and produces 37 kg of CO_2 in order to produce 1 kg of magnesium, creating environmental concerns regarding the production process. Additionally, sulfur hexafluoride, which is used to protect molten magnesium from oxidation, is a factor in global warming and can be subjected to strict emissions regulations. • The other method of magnesium production utilizes electrolytic processes that require access to a renewable energy source, such as hydropower, to reduce environmental impact. The transition to clean energy will require that magnesium production be sited close enough to renewable power energy to power the electrolytic processes, such as hydropower. This siting practice may cause mild bottleneck concerns, as production is centered around certain geographic areas that have enough hydropower to supply magnesium production. • There are three potential European magnesium projects with plan to start producing magnesium as early as 2025. Other European projects project several magnesium production capacity increases of approximately 30,000–45,000 mt each. Canada and Australia have projects in their start-up phase to boost supply. Western Magnesium in the U.S. has claimed that they have a 100,000-mt final capacity of magnesium supply. Magnesium output globally is projected to reach about 1.8 million mt by 2030. • Supply shortages might be experienced as the main producer of magnesium, China, is reducing magnesium output to curb its carbon emissions and reduce costs. In 2021, Shaanxi magnesium production facilities were asked to cut to 40% of capacity until the end of the fiscal year, creating concerns over magnesium shortages if cuts continue. The inability to store magnesium on a long-term basis provides a shortage problem if the producers decide to lessen output.
Competing Technology Demand Short term: 2 Medium term: 2	• Magnesium is used as an alloying agent to aluminum, where the aluminum-magnesium alloy is used predominantly in the packaging industry. The packaging industry in the short term is projected to grow at a CAGR of 3.5%. By 2030, this compound annual growth rate should hold at approximately 3.5% and may present mild supply concerns if it continues to 2035.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• With 88% of production concentrated in China, magnesium supply can be affected by low political stability, regulatory quality, ineffective rule of law, and environmental health concerns. • The second greatest percentage of production comes from Russia at 5% which presents low political stability issues that may impact traded supply.
Codependence on Other Markets Short term: 1 Medium term: 1	• Magnesium is mined as the main product and is unlikely to become dependent on other markets.
Producer Diversity Short term: 4 Medium term: 4	• China accounts for approximately 88% of market share in the production of magnesium, followed by Russia (5%), Israel (2%), Brazil (2%), and Kazakhstan (2%).

Historical Price and Production



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Element: Manganese (Mn) Atomic number: 25

Manganese is a transition metal that is primarily used for its alloying properties in steel. Manganese is also used in aluminum alloys and batteries.

Importance to Energy: *Short term: 2, medium term: 2*

Use of manganese in energy applications, including in the lightweighting of vehicles and in electric vehicle batteries, stationary storage batteries, and hydrogen electrolyzers is expected to consist of a small percentage of total manganese demand in both the short term and medium term. High sub-technology adoption of manganese in lithium-ion battery technology will create mild concerns regarding energy demand in both time frames.

Energy Demand
Short term: 2
Medium term: 2

- Manganese demand in energy applications consists of 4% of the total manganese in the short term, which increases to 8% in the medium term.
- The highest level of sub-technology adoption within manganese technologies is 53% in the short term for application of manganese to lithium-ion NMCs batteries. By the medium term, the market share adoption increases to 60%.

Substitutability Limitations
Short term: 3
Medium term: 3

- Manganese is an essential component in the creation of steel, and while it is present in small amounts, it cannot be fully substituted out from AHSS steels.
- Reducing or eliminating the prevalence of manganese in aluminum alloys or magnesium alloys is possible but will greatly reduce the corrosion resistance or the tensile strength of the alloys.
- Substitution between aluminum alloys, magnesium alloys, or AHSS between each other in lightweight material composition (except for polymer composites) can only reduce the amount of manganese present as all materials have a presence of manganese within them.
- Manganese has no substitute in converting iron to steel. Therefore, manganese is essential for lightweight steel production, which constitutes approximately 90 percent of manganese consumption.
- In the short term, manganese could be fully substituted out of Li-ion batteries by replacing NMC and LMO batteries with LFP or NCA batteries. If replaced with LFPs, there would be some trade-offs in performance such as lower energy density and poor performance in cold weather.
- Advanced NMC batteries with higher nickel content such as NMC 811 or 955 can also reduce the manganese content of Li-ion batteries without fully eliminating it.
- In the medium term, if the industry moves toward low/no cobalt and nickel chemistries, it could be harder to substitute out manganese since promising alternative chemistries (e.g., lithium manganese iron phosphate [LMFP], lithium-metal polymer (LMP), and LNMO) all contain manganese except for LFP.
- For hydrogen production by electrolysis, substitutes exist for solid oxide electrolyzers, which contain manganese and include alkaline and PEM electrolyzers which do not contain manganese. Additionally, substitutes of electrolysis for hydrogen production also include biofuels pathways; and steam methane reforming coupled with carbon capture, utilization, and storage are a substitute technology for solid oxide electrolyzers.
- Mn is present in NMC chemistries for ESS batteries; however, it can be fully substituted out with LFP chemistry.
- In the medium to long term, if the industry moves toward LIBs based on low/no cobalt and nickel chemistries, it could be harder to substitute out Mn since promising alternative chemistries (e.g., LMFP, LMP, LNMO) all contain Mn except for LFP. On the other hand, battery technologies other than LIBs (e.g., redox flow and sodium-ion batteries) that are being considered for stationary applications do not contain Mn.

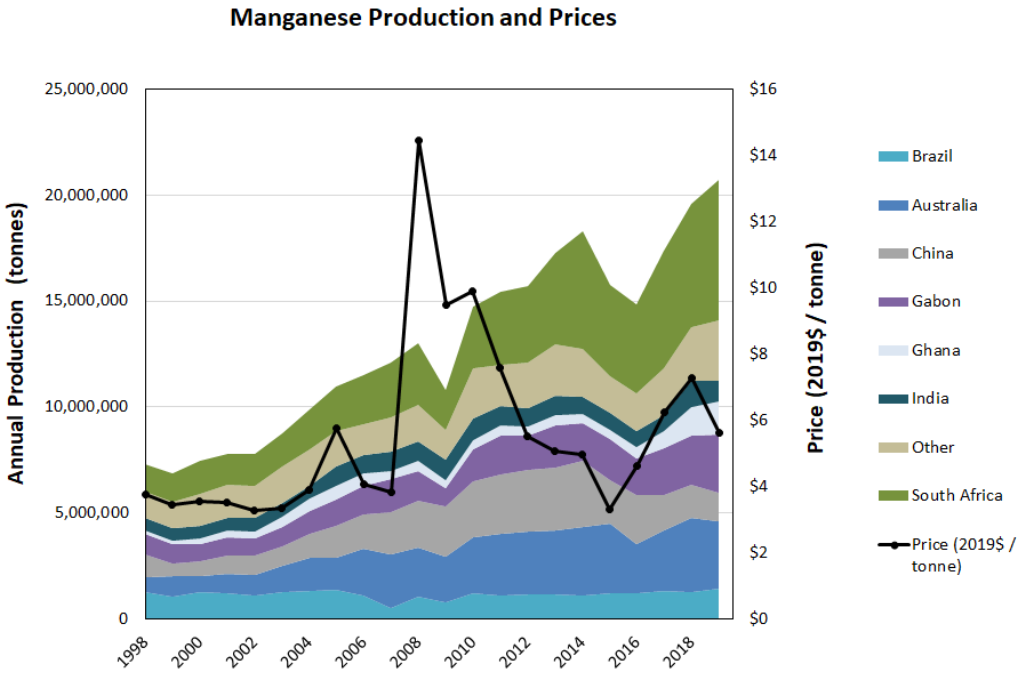
Supply Risk: *Short term: 1, medium term: 2*

The supply risk of manganese will be minimal in the short term as production capacity will easily meet expected demand and strong producer diversity exists. Supply risk should increase slightly in the medium term given potential supply chain bottlenecks and the viability of deposit ore grade.

Basic Availability Short term: 1 Medium term: 2	• In the short term, all demand trajectories for manganese can be met by both 2020 production and 2020 production capacity. By 2035, all demand trajectories slightly exceed 2020 production but are well below 2020 production capacity, representing no concern on basic availability for manganese. • Manganese resources can be produced through seabed resources in conjunction with typical land-based deposits and districts but are technologically and economically unproven. Manganese would most likely be a by-product of seabed mining and would not be economically recovered at all in some scenarios. Additionally, seabed mining would potentially redistribute millions of square kilometers of seabed, and thus researchers would need to assess the marine ecosystem effects of such mining. • There are 23 contracts related to exploration of nodules and crusts of manganese mineral deposits in the deep ocean; these have been signed with the International Seabed Authority. In addition, resource/reserve, baseline, and environmental impacts are currently being conducted. Full-scale mining of marine ferromanganese deposits is not yet viable, however. • Globally identified resources of manganese are greater than 17 billion mt, where the Kalahari manganese district in South Africa dominates, containing more than 70% of the global resources, or approximately 12.6 billion mt. Kalahari contains high-grade ore and has the potential to provide enough high-quality manganese to meet long-term demand. Other large resources of manganese include the Molango district in Mexico and Bolshe Tokmak in the Ukraine, both of which have much lower grades of manganese. Overall, identified global resources are enough to meet future manganese demand, but increases in efficiency of mining and processing will be needed to convert many low-grade ore deposits into workable production areas. • The chemical composition of manganese deposits of the world indicates that average manganese ore grade is about 24 percent, indicating that most manganese deposits are of low-grade ore. To expand production capacity to more areas, technology improvements and efficiency will need to accelerate to make these low-grade deposits viable. • New U.S.-based manganese production is currently being developed to meet projected high demand for manganese in EV battery production. The European Union and Canada are currently developing manganese refining capacity, but production will not be started in the near term. Manganese production in South Africa should expand in the near term as major manganese miners South32, Tshipi é Ntle, United Manganese of Kalahari, and Assmang are increasing production investments and capacity. In Gabon, Eramet has issued a notice that it intends to expand manganese mine production from 4.3 million tons to 7 million tons by 2023. • South Africa does face some export bottlenecks that may limit supply out of the region. The harbor at Coega has a dedicated manganese handling capacity of 12 million tons, which is less than the total Mn exports moved out of the country. The rest of the manganese is shifted to six different South African harbors through a railway system that is close to capacity. • Production bottlenecks may occur in the processing of manganese into high-purity manganese used in lithium-ion batteries. Only certain manganese ores, such as carbonate ores, can feasibly be used for the mining and production of high-purity manganese in the battery industry. While carbonate ores are common in places such as China, they are low-grade ores.
Competing Technology Demand Short term: 1 Medium term: 1	• Competing industry demand is primarily driven by the construction industry. Approximately 90 percent of manganese consumption is used by the steel industry, where the housing and construction sector uses more than 50% of steel production. This industry is projected to grow at a 2.7% CAGR from 2020 to 2025, and by 2030, steel demand in construction is projected to be the same, effectively decreasing the compound annual growth rate to 1.3%. There should be limited concern about competing technology demand interfering with manganese supply in both the short term and medium term.

Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	• Production of manganese is widely dispersed across the globe, but a large majority of production occurs in South Africa, Gabon, and China, where political stability as well as the rule of law are less reliably enforced.
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 with other markets.
Producer Diversity Short term: 1 Medium term: 1	• Production of manganese is diverse with South Africa accounting for 36% of the market share, followed by Gabon (23%), Australia (17%), China (5%), Ghana (5%), and India (2%).

Historical Price and Production



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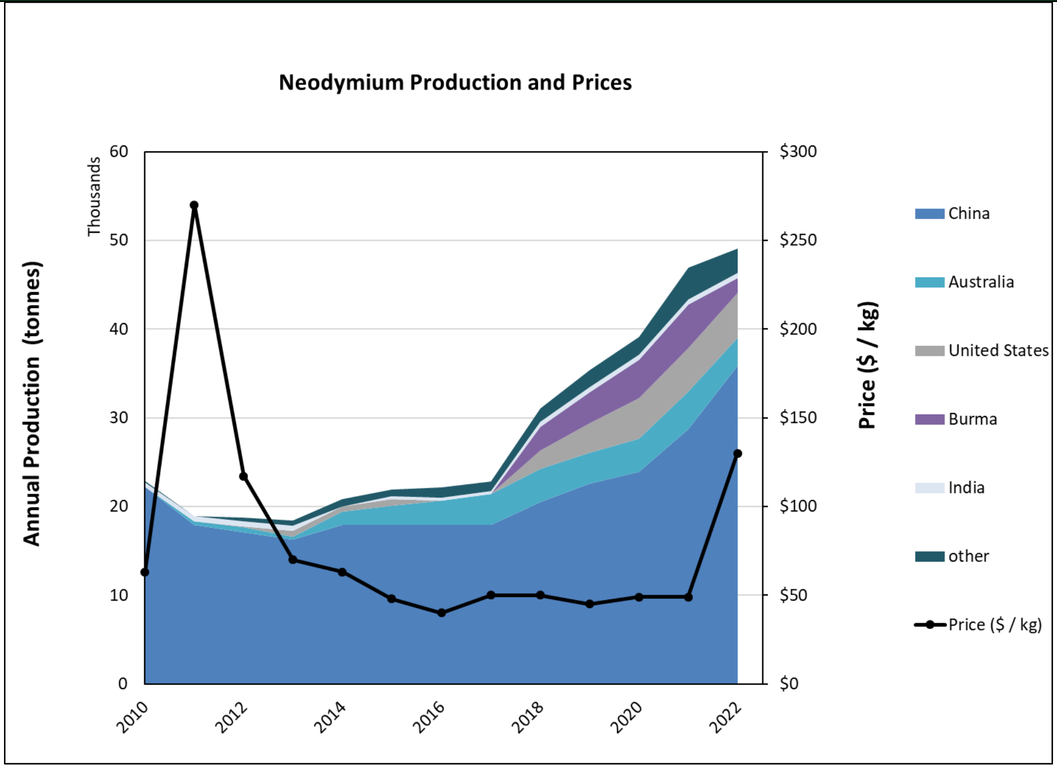
Element: Neodymium (Nd)	Atomic number: 60
Neodymium is a rare earth metal that is used in the production of powerful NdFeB magnets, which are used in applications such as electric vehicle motors, wind turbine generators, consumer electronics, industrial motors, and non-drivetrain uses in vehicles. In addition, Nd oxide is used in ceramics and glasses, in catalysts, and in some alloys.	
Importance to Energy: *Short term: 3, medium term: 3*	
Neodymium used in electric vehicles and wind turbines are both key drivers of demand, with vehicles being the more important source of growth in the medium term and beyond. Neodymium is found to be important to clean energy because of its use in supporting demand growth in electric vehicles and offshore wind turbines, as well as potential performance losses if alternatives motors and generators are used that do not require Nd.	
Energy Demand Short term: 3 Medium term: 3	• In 2025, about 42% of Nd demand is expected to be from magnets in EVs and wind turbines. • In 2035, 65% of Nd demand is expected to be from EVs and wind turbines. • Component share of permanent magnet motors in electric vehicles is estimated to be 98%, with percentages likely to stay above 50% through 2040.
Substitutability Limitations Short term: 3 Medium term: 3	• NdFeB magnets have alternatives in electric vehicles, including induction motors and electrically excited brushed motors, which have been used in vehicles such as early versions of the Tesla and some BMW EVs. However, alternatives have disadvantages, such as lower efficiency for induction motors, and as a result represent a small share of the total market. • NdFeB magnets are used in a relatively small portion of onshore wind turbines; however, their use offers significant advantages for offshore wind turbines and would be more difficult to replace. • Tesla has announced plans to switch away from NdFeB magnets, likely to use ferrite magnets instead, suggesting some increase in substitutability in the medium term. • Short-term substitution with Pr is possible up to a point, but Pr naturally occurs at about the 25%–75% ratio with Nd, with more than 25% of the Nd/Pr content of the magnet being Pr is unlikely. • Substitution of Ce for some Nd in magnets may also be possible.
Supply Risk: *Short term: 3, medium term: 4*	
Supply risk for neodymium is high in the short term and especially in the medium term. Nd is produced largely in China, and while there has been some progress toward diversifying supplies, significant challenges still remain.	
Basic Availability Short term: 3 Medium term: 4	• Demand for Nd is projected to exceed current capacity by 2025 in all four trajectories, although by a very small margin in the lowest scenario. • Demand for Nd is projected to significantly exceed current supply by 2035 in all four trajectories. • While many rare-earth deposits have been under development since the early 2010s, a limited number have been able to advance to the construction stage. • The projects that have advanced the farthest are based on a limited set of mineral types that have already been demonstrated at a commercial scale. • While there are sufficient quantities of rare earths in the ground to meet the projected increases in demand, new types of rare-earth minerals may need to be developed, which could lead to cost increases.
Competing Technology Demand Short term: 3 Medium term: 3	• Other uses for Nd include: as magnets in consumer electronics, industrial applications, and non-drivetrain vehicle motors, as well as in ceramics and glasses, catalysts, and alloys. • Adamas Intelligence (2020) projects that magnet use in industrial applications and in consumer electronics will grow between 5% and 10% per year.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• The weighted average score for rare earth metal refining, which is dominated by China, is 42.5. The largest producer, China, receives an average rating of 41.3. • Current rating for Nd oxide and NdPr oxide separation is 43.0, and for mining it is 47.4. • Additional separation capacity is being added outside of China, particularly in the U.S., which is likely to improve the rating of separation. However, it is unclear how much additional metal refining capacity will be added outside of China, so this has not been accounted for in the ratings for the metal refining stage.
Codependence on Other Markets Short term: 3 Medium term: 3	• Nd is the largest source of revenues for most rare-earth deposits, but significant amounts of revenues are expected to come from other rare-earth co-products. • Some deposits also have significant revenues from other products, including the largest source of light rare-earth (LRE) production, Bayan Obo, which is also an iron mine, in

	China. However, Bayan Obo contains rare earth minerals such as monazite and basnasite that are separate from the minerals used to produce iron, and rare earth production might continue even if iron markets collapsed. • Some light rare earths (LREs) are produced from deposits where heavy rare-earth elements (HREEs) are expected to be the primary revenue source.
Producer Diversity Short term: 4 Medium term: 4	• About 90% of metal refining currently occurs in China, leading to an HHI score of 8125 for metal refining by country, which is the most concentrated of the stages analyzed. • The current HHI score for Nd oxide separation is almost as high, estimated at 7643, while the HHI score for mining is somewhat lower at 5485, but still high enough to be rated as a 4. • Additional separation capacity is being added outside of China, particularly in the U.S., but it is not yet clear how much new metal refining capacity will be added.

Historical Price and Production



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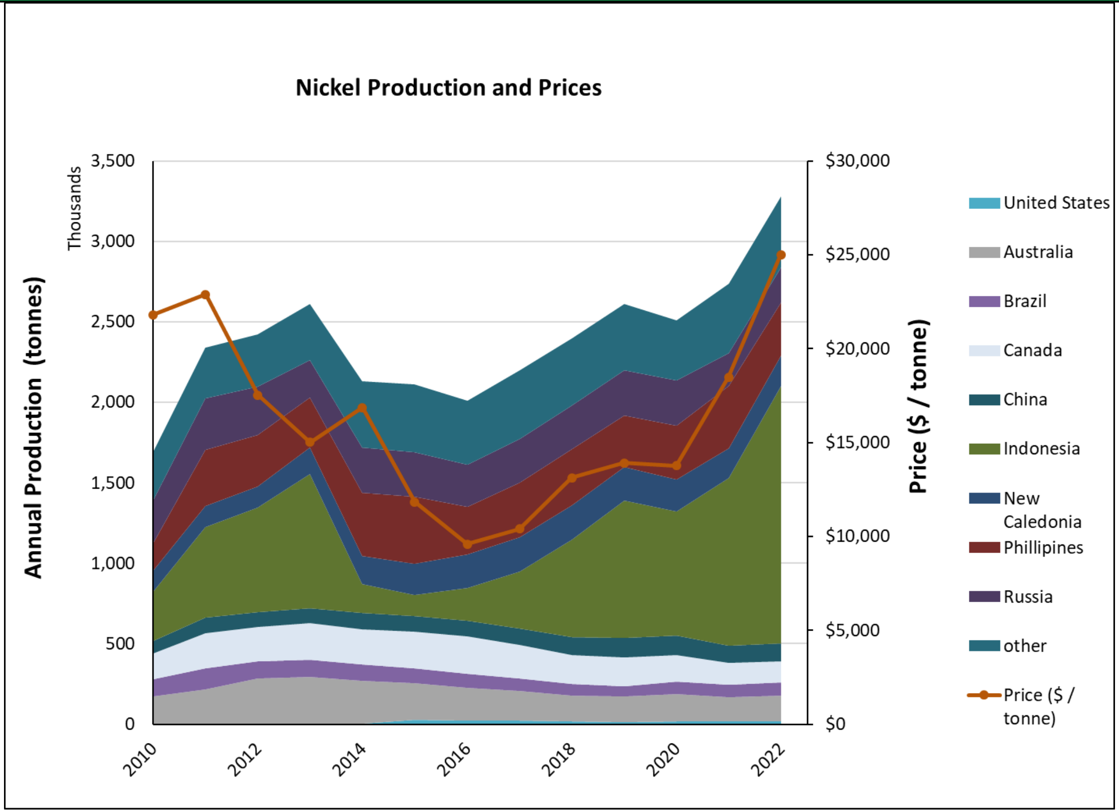
<table>
<tr><th>Element: Nickel (Ni)</th><th>Atomic number: 28</th></tr>
<tr><td colspan="2">Nickel is used in the cathodes of Li-ion batteries in electric vehicles, consumer electronics and stationary storage, stainless steel, metallurgy and coatings, electroplating, and other alloys.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 3, medium term: 4</i></td></tr>
<tr><td colspan="2">Nickel used in Li-ion batteries for electric vehicles is expected to be a key driver of future nickel demand. Rapid growth in demand is also expected for nickel used in batteries for stationary storage, as well as for solid oxide electrolyzers and fuel cells, is also expected to grow rapidly, but will contribute a smaller share to total demand. Nickel is found to be important to clean energy in the short term and especially in the medium term largely because of its importance in Li-ion batteries. It would be possible to substitute away from its use but at the cost of some loss in performance.</td></tr>
<tr><td>Energy Demand
Short term: 3
Medium term: 4</td><td>• In 2025, about 43% of Ni demand is expected to be from EV batteries, stationary storage batteries, and solid oxide electrolyzers in the highest demand scenario.
• In 2035, about 78% of Ni demand is expected to be from EV batteries, stationary storage batteries, and solid oxide electrolyzers in the highest demand scenario.
• In high adoption scenarios, about 98% of vehicle batteries could use Nickel.</td></tr>
<tr><td>Substitutability Limitations
Short term: 2
Medium term: 3</td><td>• In the short term, nickel use in Li-ion batteries could be fully substituted out through replacement of NMC and NCA batteries with LFP batteries. If replaced with LFPs, there would be some trade-off in reduced performance such as lower energy density and poor performance in cold weather.
• Advanced NMC batteries have high nickel content and may be more difficult to substitute away from as these technologies improve relative to alternatives.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 2, medium term: 3</i></td></tr>
<tr><td colspan="2">Supply risk for nickel is moderate in the short term, and high in the long term. Nickel is relatively abundant, and there are relatively diverse sources of supply; however, the challenge is keeping up with the expected rapid increases in demand and the presence of some sensitive countries among the list of suppliers contribute to supply concerns.</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>• All trajectories exceed current production capacity by 2025 — although just barely for the lowest trajectory.
• All trajectories exceed current production capacity by larger amounts by 2035.
• Sufficient reserves and resources exist to meet projected demand needs in the short and medium terms; however, there may be increasing challenges in meeting demand if it rises at the rates seen in the high demand trajectories.
• This analysis includes both sulphide ores, which can easily be processed into the class I nickel needed for batteries, and laterite ores, which are normally used to produce lower-grade class II nickel but can be processed into class I nickel at a higher cost.
• Sulphide ores are in shorter supply than laterite ores, so to meet the expected growth in demand for class I nickel, it may be necessary to increase the production of class I nickel from laterite ores, which would likely increase costs.</td></tr>
<tr><td>Competing Technology Demand
Short term: 1
Medium term: 1</td><td>• Other uses for Ni include: in stainless steel production, batteries for consumer electronics, metallurgy and coatings, electroplating, and other alloys.
• None of these markets are expected to grow faster than 3%.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 3
Medium term: 3</td><td>• Nickel mining countries receive a weighted average score of 41.3. Scores are higher for class I nickel mining, nickel refining, or class I nickel refining.
• The largest nickel mining country, Indonesia, receives an average rating of 40.6. The second- and third-largest producers, The Philippines and Russia, reduce the score, while Australia, Canada, and New Caledonia (France) help raise it.
• China and Russia are significant players in Class I nickel mining and refining, but they are balanced by a diverse set of producers including Canada, Japan, and Norway.</td></tr>
<tr><td>Codependence on Other Markets
Short term: 2
Medium term: 2</td><td>• While nickel is often produced in conjunction with copper and/or cobalt, it is usually the primary product of mines where it is produced.</td></tr>
<tr><td>Producer Diversity
Short term: 2
Medium term: 2</td><td>• Almost half — 49% — of mined nickel comes from Indonesia, which contributes to an HHI score of 2795 for all nickel mining.</td></tr>
</table>

- There is greater producer diversity in mining that is used for Class I nickel, with the largest producer being Russia with 21% of the market, as well as for Class I nickel refining, with the largest producer being China with 25% of the market.

Historical Price and Production



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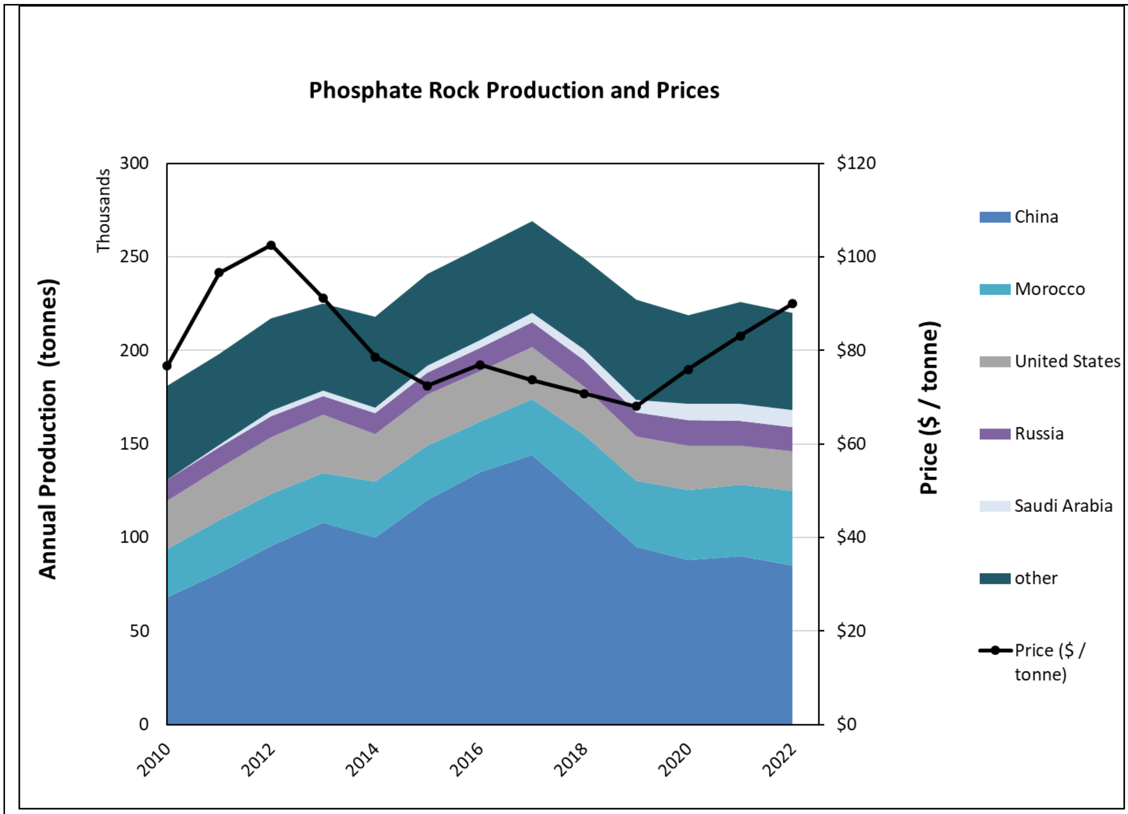
Element: Phosphorus (P)	Atomic number: 15
Phosphorus is most abundant within the agricultural sector; however, it does have some applications in energy storage technologies. These uses include in EV batteries and stationary storage batteries.	
Importance to Energy: *Short term: 1, medium term: 1*	
Using the IEA's four trajectories, it is projected that both stationary storage batteries and EV battery demand will increase and therefore so will the amount of P increase in demand.	
Energy Demand Short term: 1 Medium term: 1	• The market share of phosphorus for energy application is less than 10%. • The market share of the most dominant sub-technology (EV batteries) is less than 10% of P usage. • This is calculated using the four IEA trajectories as data inputs alongside production and demand figures from 2020 (assuming a 5% CAGR) with a production capacity of 90%.
Substitutability Limitations Short term: 2 Medium term: 2	• LIBs are alternatives to LFP chemistry with better energy density although they are more expensive.
Supply Risk: *Short term: 1, medium term: 2*	
Most of the supply risk of phosphorus comes from its extensive and almost exclusive use in agriculture. This usage leaves a small percentage of the P supply for battery storage, which is sufficient to support current energy-related P demand. However, if demand increases under certain trajectories, an increase in P imports may be necessary. Most P is mined domestically, which may lead to instability in the event of a supply chain issue. In that event or the event of increased reliance on imports of P, supply risk may increase.	
Basic Availability Short term: 1 Medium term: 2	• Currently, an overwhelming majority of phosphorus is mined domestically (90%), with an overwhelming majority of the mined phosphate rocks being used agriculturally (95%). • The small percentage left over can still meet current demand for energy use in stationary and EV battery storage because the concentrations are currently relatively low. • However, there are projections — under Trajectory D, specifically —where demand would exceed the estimated future phosphorus capacity, as projected with an annual growth rate matching that of the gross domestic product (GDP) growth rate (3%). • This is not a major concern, though, because of the ability of the U.S. to expand its phosphorus imports.
Competing Technology Demand Short term: 1 Medium term: 3	• Currently, an overwhelming majority of phosphorus is used in agriculture (over 90%). • The CAGR of the food sector is projected to be 9.1% until 2027.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• Currently, a majority of phosphorus is produced in China, the United States, Morocco, and Russia. • Currently, the United States uses mostly domestically produced phosphorus. • However, the other countries with high P production all score relatively low on the World Governance Indicators' (WGI's) scoring system. • This means that while P is robust in its supply, if demand for P increases greatly under Trajectories like C and D, there may be an increase in reliance on imports of phosphates, which lends in part to the scoring.
Codependence on Other Markets Short term: 1 Medium term: 1	• Phosphorus is exclusively mined on its own and is not a by-product of production of any major element.
Producer Diversity Short term: 1 Medium term: 1	• Phosphorus production is distributed fairly evenly across the world, with the HHI score of phosphorus registering at 2,036. • While Morocco holds most of the world's reserves of P, this will not impose a supply risk unless production is scaled up massively, which is unlikely to occur in the medium term.
Historical Price and Production	



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Element: Platinum (Pt) **Atomic number: 78**

Platinum is a transition metal used in energy applications, including vehicle catalytic converters and chemical and petroleum refining catalysts (where catalysts contribute to energy and material efficiencies). Other demands include in jewelry, electronics, and investment. Platinum demand for catalytic converters is expected to decline after 2025 as vehicle technologies transition to battery and fuel cell-powered vehicles (FCEVs). This decline may be mitigated as PEM fuel cells and electrolyzers are adopted as important technologies for the hydrogen economy. The FCEVs marketed today are equipped with PEM fuel cells.

Importance to Energy: *Short term: 2, medium term 2*

Use of platinum in energy applications constitutes a significant portion of total platinum demand. Clean energy technologies considered for this assessment are: catalytic converters, PEM FCEVs, and PEM electrolyzers.

Energy Demand
Short term: 2
Medium term: 2

- Platinum demand for catalytic converters and FCEVs are interrelated, as FCEVs do not contain catalytic converters. Consequently, when FCEV demand increases, demand for catalytic converters decreases.
- The market share of all in-scope energy technologies is above 45% for all trajectories.
- Short term: In 2025, the catalytic converter market accounts for the dominant demand, accounting for 54% of demand in the High Penetration, High Material Intensity case (Trajectory B).
    - Trajectory A – 2025: catalytic converters 47%
    - Trajectory B – 2025: catalytic converters 54%
    - Trajectory C – 2025: catalytic converters 45%
    - Trajectory D – 2025: catalytic converters 53%
- Medium term: By 2035, FCEV demand is dominant in the High Penetration scenarios, accounting for 57% of demand (Trajectory D), while catalytic converters remain dominant in the Low Penetration scenarios, accounting for 43% of demand (Trajectory B).
    - Trajectory A – 2035: catalytic converters 38%
    - Trajectory B – 2035: catalytic converters 44%
    - Trajectory C – 2035: FCEVs 44%
    - Trajectory D – 2035: FCEVs 57%
- Platinum is also used as a catalyst in the refinery (3%) and chemical (10%) industries, where it is important for energy and material efficiency. These energy applications are not in scope for this analysis.
- CAGRs for both PEM fuel cells and PEM electrolyzers are >10% in the short and medium terms.

Substitutability Limitations
Short term: 2
Medium term: 2

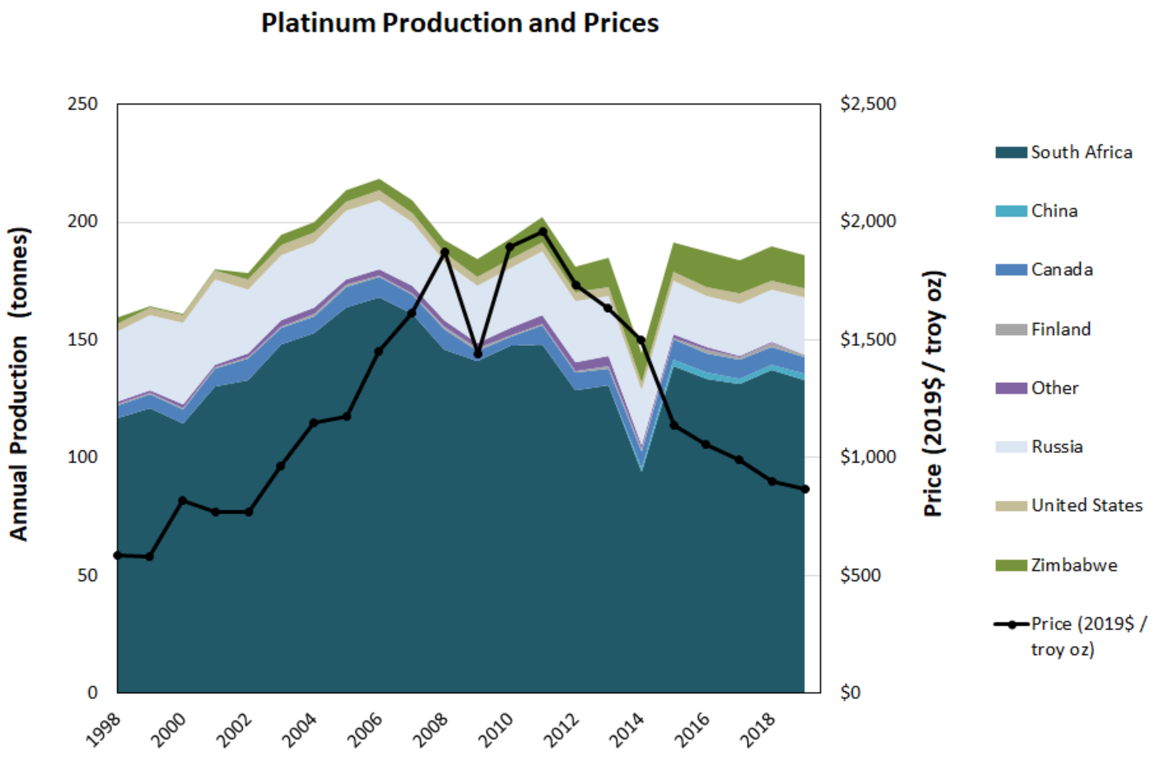
- To an extent, platinum in catalytic converters may be substituted by palladium. Palladium, however, is currently more expensive than platinum, and the substitution could affect performance.
- Internal combustion engine (ICE) and diesel vehicles can be substituted by electric vehicles, reducing demand for platinum in catalytic converters. Factors affecting this substitution include consumer choice, technology evolution, manufacturer decision making, and government actions.
- Substitutes exist for FCEVs, particularly battery electric, hybrids, diesel, and ICE vehicles.
- For hydrogen production by electrolysis, substitutes for PEM electrolyzers include alkaline (commercialized) and solid oxide (under development) technologies.
- Substitutes for electrolysis for hydrogen production also include biofuels pathways and steam methane reforming coupled with carbon capture, utilization, and storage technologies. Significant research funds are focused on development of hydrogen production technologies from a variety of feedstocks.
- For heavy-vehicle applications in particular, FCEVs have advantages over battery-powered vehicles (faster fueling, longer distances).
- Likewise, PEM electrolyzers have advantages over other electrolyzer types (higher turndown-ratio and dynamic response).

Supply Risk: *Short term: 3, medium term: 3*

The supply risk for platinum is significant in the short and long term. Platinum demands for vehicles (catalytic converters in internal combustion and diesel engine vehicles) and for FCEVs will exceed current production in a few years. Platinum production is increasingly concentrated in South Africa and Zimbabwe, where mine operations

have been affected by environmental, operational, safety, and labor issues. Russia is also a major producer of platinum.	
Basic Availability Short term: 3 Medium term: 3	• Platinum is the major product of platinum group mines in South Africa, Zimbabwe, and the United States. Platinum is also recovered from nickel and copper mines in Russia and Canada, as well as from mines located in other countries including China and Finland. • For most scenarios in 2025 and 2035, platinum demands exceed the estimated 2020 capacity (224 tonnes). The highest demand deficit occurs in the High Penetration, High Material Intensity scenarios (Trajectory D) in 2035, reaching 191% of current capacity. Forecasted demands as a percentage of 2020 platinum capacity are: o Trajectory A, 99% by 2025 and 113% by 2035. o Trajectory B, 115% by 2025 and 130% by 2035. o Trajectory C, 95% by 2025 and 135% by 2035. o Trajectory D, 115% by 2025 and 192% by 2035. • Platinum group metal mines have experienced environmental issues, mechanical failures, and strikes that have limited production in the past. However, major mines are owned and operated by publicly owned companies that are increasingly focusing on environmental, social, and governance objectives. • In 2022, platinum recovered from recycled catalytic converters accounted for >24% of global platinum demand. Given the value of platinum, expectations are that platinum will likely be recovered and recycled from end-of-life FCEVs and PEM electrolyzers.
Competing Technology Demand Short term: 1 Medium term: 1	• Demand growth of platinum for non-energy applications is expected to follow GDP trends (<3% growth). However, this growth rate could be mitigated (reduced) by increased Pt prices that would occur should FCEV and PEMEC demands increase to the forecasted levels. • Platinum investing may have some mitigating effect on platinum supply deficits if investors sell when prices increase in response to undersupply. However, the platinum investment market is volatile and not a dependable long-term resource.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• The political, regulatory, and social factors weighted average percentile for platinum is 40, based on 2020 production data. • Platinum production is concentrated in South Africa, where platinum group metals (PGM) mining and production have been interrupted by mechanical failures, safety issues, and labor unrest. • Political stability is a factor for the second- and third-largest platinum-producing countries: Russia and Zimbabwe.
Codependence on Other Markets Short term: 1 Medium term: 1	• Platinum is mined as a major product from mines in South Africa, Zimbabwe, and the United States. Some platinum is recovered from minerals that may contain nickel and copper, specifically mines in Russia and Canada. • Production of platinum is subject to the concentration and prices of the other platinum group metals with which it is coproduced. As sales of combustion and diesel engine vehicles decline, palladium and rhodium demand for catalytic converters will decline, which could reduce the profits of platinum group metal mining and refining.
Producer Diversity Short term: 4 Medium term: 4	• The HHI is 5656. • In 2022, South Africa accounted for 74% of platinum mining, followed by Russia (11%), Zimbabwe (8%), Canada (3%), the United States (2%), and other countries (2%). PGMs mined in the United States, however, are currently refined in South Africa. • PGM companies are developing new mines; however, most of the expected growth is in South Africa and Zimbabwe.

Historical Price and Production



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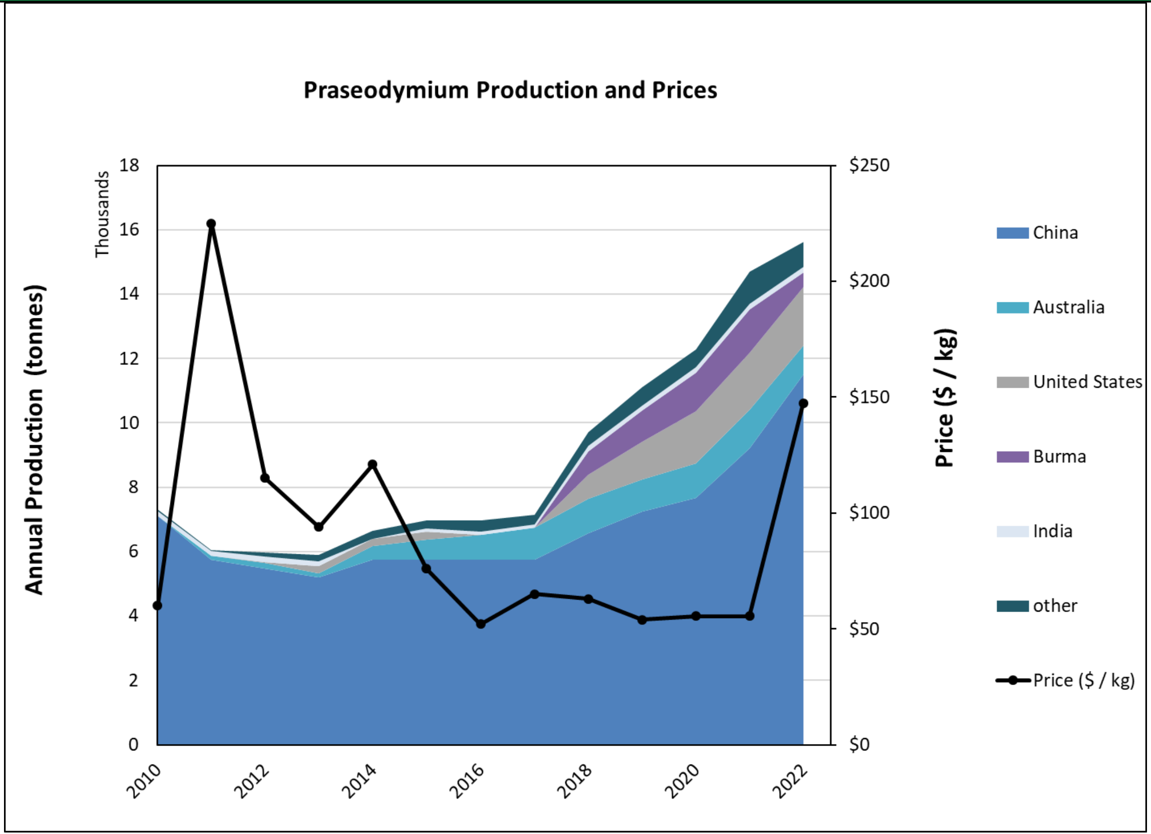
<table>
<tr><th>Element: Praseodymium (Pr)</th><th>Atomic number: 59</th></tr>
<tr><td colspan="2">Praseodymium is a rare-earth metal that is used in the production of powerful NdFeB magnets, which are used in applications such as electric vehicle motors, wind turbine generators, consumer electronics, industrial motors, and non-drivetrain uses in vehicles. In addition, Nd oxide is used in ceramics and glasses, in catalysts, and in some alloys.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 2, medium term: 3</i></td></tr>
<tr><td colspan="2">Praseodymium used in electric vehicles and wind turbines are both key drivers of demand, with vehicles being the more important source of growth in the medium term and beyond. Praseodymium is found to be moderately important to clean energy in the short term and more so in the medium term because of its use in supporting demand growth in electric vehicles and offshore wind turbines. It is commonly combined with neodymium in magnets and has similar properties, but it is found to be slightly less important because NdFeB magnets can more easily eliminate the use of Pr by substituting Nd than the other way around.</td></tr>
<tr><td>Energy Demand
Short term: 2
Medium term: 3</td><td>• In 2025, about 26% of Pr demand is expected to be from magnets in EVs and wind turbines.
• In 2035, about 46% of Pr demand is expected to be from EVs and wind turbines.
• Component share of permanent magnet motors in electric vehicles is estimated to be 98%, with percentages likely to stay above 50% through 2040.</td></tr>
<tr><td>Substitutability Limitations
Short term: 2
Medium term: 2</td><td>• NdFeB magnets have alternatives in electric vehicles, including induction motors and electrically excited brushed motors, which have been used in vehicles such as early versions of Tesla and some BMW EVs. However, alternatives have disadvantages, such as lower efficiency for induction motors, and as a result represent a small share of the total market.
• NdFeB magnets are used in a relatively small portion of onshore wind turbines; however, they offer significant advantages for offshore wind turbines and would be more difficult to replace.
• Tesla has announced plans to switch away from NdFeB magnets, likely intending to use ferrite magnets instead, suggesting some increase in substitutability in the medium term.
• Short-term substitution with Nd is possible, as some magnets use just Nd and no Pr, but Nd is subject to the same supply limitations as Pr, so replacing Pr with Nd is unlikely to help resolve criticality concerns.
• Substitution of Ce for some Pr in magnets may also be possible.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 3, medium term: 4</i></td></tr>
<tr><td colspan="2">Supply risk for praseodymium is high in the short term and especially high in the medium term. Pr is produced largely in China, and while there has been some progress toward diversifying supplies, significant challenges still remain.</td></tr>
<tr><td>Basic Availability
Short term: 3
Medium term: 4</td><td>• Demand for Pr is projected to exceed current capacity by 2025 in all four trajectories, although by a very small margin in the lowest scenario.
• Demand for Pr is projected to significantly exceed current supply by 2035 in all four trajectories.
• While many rare-earth deposits have been under development since the early 2010s, a limited number have been able to advance to the construction stage.
• The projects that have advanced the farthest are based on a limited set of mineral types that have already been demonstrated at a commercial scale.
• While there are sufficient quantities of rare earths in the ground to meet the projected increases in demand, new types of rare-earth minerals may need to be developed, which could lead to cost increases.</td></tr>
<tr><td>Competing Technology Demand
Short term: 3
Medium term: 3</td><td>• Other uses for Pr include: in magnets in consumer electronics, industrial motors and automotive motors in conventional vehicles, ceramics and glasses, catalysts, and alloys.
• Adamas Intelligence (2022) projects that magnet use in industrial applications and in consumer electronics will grow between 5% and 10% per year.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 3
Medium term: 3</td><td>• The weighted average score for rare-earth metal refining, which is dominated by China, is 42.5. The largest producer, China, receives an average rating of 41.3.
• Current rating for Pr oxide and NdPr oxide separation is 42.9, and for mining is 47.7.
• Additional separation capacity is being added outside of China, particularly in the U.S., which is likely to improve the rating of separation. However, it is unclear how much additional metal refining capacity will be added outside of China, so this has not been accounted for in the ratings for the metal refining stage.</td></tr>
<tr><td>Codependence on Other Markets</td><td>• Pr is an important source of revenues, along with Nd, for most rare-earth deposits, but a significant amount of revenues are expected to come from other rare-earth co-products.</td></tr>
</table>

Short term: 3 Medium term: 3	• Some deposits also have significant revenues from other products, including the largest source of light rare earth production, Bayan Obo in China, which is also an iron mine. However, Bayan Obo contains rare-earth minerals such as monazite and basnasite that are separate from the minerals used to produce iron, and rare-earth production might continue even if iron markets collapsed. • Some LREs are produced from deposits where HREEs are expected to be the primary revenue source.
Producer Diversity Short term: 4 Medium term: 4	• About 90% of metal refining currently occurs in China, leading to an HHI score of 8125 for metal refining by country, which is the most concentrated of the stages analyzed. • The current HHI score for Nd oxide separation is almost as high, estimated at 7872, while the HHI score for mining is somewhat lower at 5596 but still high enough for the short term to be rated as a 4. • Additional separation capacity is being added outside of China, particularly in the U.S., but it is not yet clear how much new metal refining capacity will be added.

Historical Price and Production



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<table>
<tr><th colspan="2">Silicon (Si) Atomic number: 14</th></tr>
<tr><td colspan="2">Silicon is the second most abundant material on earth and is a popular semiconductor used to manufacture a variety of chemicals (e.g., silanes, silicones, oils, elastomers, surfactants), metal alloys (e.g., aluminum and steel), solar cells, and computer chips.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 2, medium term: 3</i></td></tr>
<tr><td colspan="2">Silicon is the most popular photovoltaic material for solar cells due to its great abundance, mature processing industry, low toxicity, and ability to absorb visible light (Andreani et al., 2019). In 2021, crystalline silicon based solar cell technology alone accounted for 87.7% of the total PV market share (BCC Research, 2022). Silicon is also a key ingredient in lightweighting metals like aluminum and a variety of steels (including grain oriented electric steel and non-grain oriented electrical steel).</td></tr>
<tr><td>Energy Demand
Short term: 2
Medium term: 3</td><td>The combined silicon market share of lightweighting, solar cells, and electrical steel will be 34% in 2025 and 43% by 2035. These percentages suggested scores of 2 and 3 for the short and medium terms, respectively.

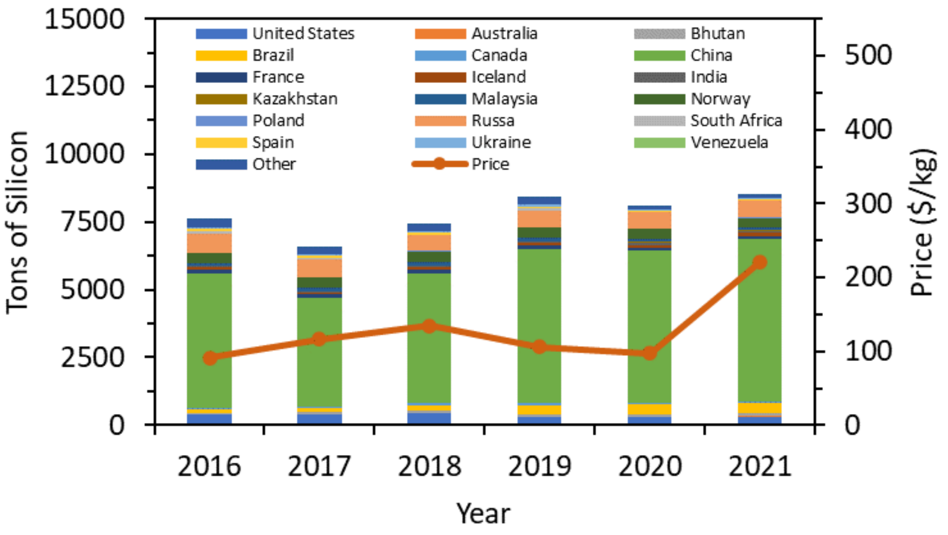
Silicon solar cells accounted for about 87.7% of total solar market dollar value in 2021 and are expected to drop by about 1% over the next 5 years (short-term score) (BCC Research, 2022). Despite this drop, silicon will still hold a market share greater than 50%. Market values over the next 15 years (medium-term score) are more speculative and have historically overestimated the decline of silicon in favor of other thin-film technologies. In writing this report, the authors were unable to find market mix predictions of various solar technologies beyond 2030. Thus, as a baseline scenario, we assumed that the silicon solar market share would decline to 70% by 2030 based on Weckend et al. (2016) and that this value would remain static out to 2037.
Regarding power electronics, Si is still the dominant technology with current market share at > 95% and projected to remain at 80% in 2027 (Rosina and Villamor, 2022).</td></tr>
<tr><td>Substitutability Limitations
Short term: 3
Medium term: 3</td><td>Thin-film solar cells are the main replacement option for silicon solar cells. In 2021, thin-film devices had a market share of 9.0%, which was expected to grow to 10% by 2027 (Basore and Feldman, 2022). This indicates major limitations given the slow adoption and relatively small throughput manufacturing capabilities of thin-film devices. Thus, a score of 3 was provided in the short term.

The main thin-film solar technologies are CdTe, cadmium-indium-gallium-selenide (CIGS), and amorphous silicon devices. CdTe is dependent on a minor metal tellurium, which would limit its ability to replace silicon (Basore and Feldman, 2022). Additionally, it is not always economical to extract tellurium from its co-dependent mining operation (such as copper mines) (Goldfarb et al., 2017). CIGS solar cells fabrication complexity and reliance on the rare material indium, which is already in high demand in the flat-panel display industry (U.S. Geological Survey, 2022a), make them unlikely candidates to replace bulk silicon devices. Additionally, the largest CIGS manufacturer in the world (and last manufacturer in Japan) switched to manufacturing silicon solar cells in 2021 (Bellini, 2021). Thin-film silicon solar cells suffer from low efficiency (about half the typical efficiencies from bulk silicon solar devices) due to poor light absorption from the limited amount of silicon used (Efaz et al., 2021). Due to the challenges faced by thin-film technologies, a score of 3 was provided for the medium term, which indicates the major limitations on the substitutability of crystalline silicon solar cells.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 2, medium term: 2</i></td></tr>
<tr><td colspan="2">The supply risk for silicon is mild for both the short term and medium term. Material demand for silicon in lightweighting and solar technologies can be easily met with production capacity in the short term. By the medium term, only the highest demand trajectories barely outpace 2020 production capacity. Production is highly constrained to China and the potential exists for competing demand to raise concerns on supply risk; but availability is high enough at the moment to meet energy demand.</td></tr>
<tr><td>Basic Availability
Short term: 1
Medium term: 2</td><td>Silicon is the second most abundant element on earth. Silicon (i.e., quartz) mines are typically found while searching for more lucrative materials such as gold (Basore and Feldman, 2022). Even with no efforts to scout new silicon (i.e., usually quartz that is processed into silicon) mines, current raw material supply can meet demand (U.S. Geological Survey, 2022b). As of 2020, current reserves are expected to meet demand for</td></tr>
</table>

	decades to come (Commission, 2020). Silicon reserves are difficult to estimate as new resources are constantly being discovered and estimates are in flux. By the end of the medium term, the two highest material intensity trajectories (C and D) barely pass 2020 production capacity, indicating mild concern in the medium term about the basic availability of silicon. Silicon for alloying and lightweighting applications (e.g., aluminum-silicon alloys) consumes about 35% of available raw materials by weight (EU Science Hub, 2019). Globally, aluminum has a 32% recycling rate (as of 2018), which can be more cost effective compared to mining aluminum (The International Aluminium Institue, 2020). Conversely, solar cells and electronics, which consume about 15% of raw silicon materials, are not commonly recycled except for in a few countries and States within the United States (California and Washington) (Komoto et al., 2018). As more solar farms are retired, however, recycling is expected to become a more common practice (Komoto et al., 2018). While no immediate supply chain risks exist, China has 70% of global production capacity for metal grade silicon (Basore and Feldman, 2022). Should China's manufacturing capabilities rapidly decline, it would have a significant effect on global supply chains. Two provinces in China, Xinjiang and Yunnan, make up more than 60% of silicon production, resulting in approximately 42% of the world's silicon production. Output regulations and COVID-19 policies within these provinces have caused bottleneck concerns for the output of silicon. Late rainy seasons and low rainfalls in these regions as well can result in decreased output as hydropower for silicon runs at curbed capacity. Demand for silicon and silicon wafers skyrocketed during the COVID-19 pandemic due to the increased usage of hardware and gadgets as people sheltered in place. As demand rose, supply was concurrently lowered due to trade tensions between the U.S. and China, as well as China reducing the amount of coal it uses in production in order to reduce carbon emissions. Additionally, manufacturers of silicon wafers had not expanded their capacity prior to the pandemic due to a supply glut in the early 2000s creating weariness in overexpanding. When demand rose sharply, manufacturers hit full capacity and could not increase their output fast enough to meet demand. These factors have led to rising silicon prices and a global shortage since 2020, which has begun to slightly subside in 2023. From an environmental perspective, the process to refine quartz raw materials into silicon is very energy intensive. Silicon requires 1000–1500 megajoules of primary energy per kilogram to process through a reaction with carbon in the form of coal, charcoal, and heat. The electricity needed to produce silicon can come from additional fossil fuel sources, which are vulnerable to possible environmental regulations being imposed on production. Efforts to improve efficient material handling, reduce energy consumption, and incorporate renewable energy use in the electric arc furnaces are underway. Wacker Chemie AG signed a deal with Norwegian electricity producer Statkraft to supply green electricity from hydropower to produce new silicon. Current work at the University of Wisconsin seeks to reduce the energy required and improves the environmental sustainability of silicon production. Additionally, the largest Brazil producer of silicon metal, RIMA, uses renewable resources such as charcoal or wood chips and renewable sources of electric energy to produce its silicon. A score of 1 was given to the short-term timeline because production capacity greatly exceeds the highest 2025 projected demand scenario (13.5 million mt of capacity in 2020 vs. the highest projected demand of 11.2 million mt in 2025). The medium-term timeline was given a score of 2 because the highest demand scenario for 2035 exceeded 2020 capacity by 3.5 million mt.
Competing Technology Demand Short term: 3 Medium term: 3	The chemical industry (e.g., fumed silica and silanes) is the main competing demand for metal grade silicon. As of 2019, about 50% of the demand came from the chemical industry (EU Science Hub, 2019). Various sources projected the silicon chemical industry CAGR to range from 4.3%–10.7% in the short term and 4.7%–6.1% in the medium term. The average of all of the CAGR projects for the short and medium terms was 6.8% and 5.3%, respectively. The average of all CAGR projects was used to assign a score of 3 in the short and medium terms.

Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	Because of the global reliance on China, which produces more than 70% of the global silicon raw material supply (U.S. Geological Survey, 2022b), this section will focus on its political, regulatory, and social factors. Russia and Brazil constitute the next-highest production shares at 6.8% and 4.6%, respectively (U.S. Geological Survey, 2022b), which is significantly lower than China's output. Regarding power electronics, ~38% came from China and 19.8% came from other Asia-Pacific countries in 2021 (Rosina and Villamor, 2022). A weighted average score of all countries that produce silicon based on market share and World Governance Indicators data for Political Stability, Regulatory Quality, Rule of Law, and Environmental Health was 47. Thus, a score of 2 was given for both the short and medium terms.
Codependence on Other Markets Short term: 1 Medium term: 1	Quartz mines with sufficient purity (to enable cost-effective refinement into silicon) are typically found while scouting for more lucrative materials (Basore and Feldman, 2022). Once found, however, silicon has no codependency on other markets.
Producer Diversity Short term: 3 Medium term: 3	China produces 70% of the world's silicon supply (U.S. Geological Survey, 2022b). Additionally, the United States has no crystalline silicon manufacturing capabilities, and 75% of imported silicon solar panels come from southeast Asian countries that are reliant on Chinese supply chains (Basore and Feldman, 2022). For aluminum and steel products, China produces more than half of the world's supply (Basore and Feldman, 2022). Of the top 10 companies that produce 96% of the world's polysilicon, seven are Chinese-based (Basore and Feldman, 2022). The HHI calculated for mining and refining was 4870, which corresponds to a score of 3. This is because there were 17 major mining countries in 2022 but only five major refining countries globally. Considering all of the silicon products and raw materials dependence on China, a score of 3 was given.

Historical Price and Production



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Silicon carbide (SiC) Atomic number: N/A

Silicon carbide is an important and recentrecently emerging semiconductor material, which is used to produce wide-bandgap power electronics devices, e.g., the metal–oxide–semiconductor field-effect transistor (MOSFET) and modules for converters and inverters.

Importance to Energy: *Short term: 3, medium term: 3*

The EV market is the primary driver for SiC, especially for inverters along with charging infrastructure for 800 V battery systems, to increase range and lower charging time (ACM Resarch, 2022). SiC has been used in both residential and commercial EV charging and energy storage. Other applications of SiC include in photovoltaic converters; power supply; rail; uninterrupted power supply (UPS) applications; motor drives for robotic arms; servo motors; high voltage alternating current (HVAC); and wind (Chiu and Dogmus, 2022).

Energy Demand Short term: 3 Medium term: 4	The fast-growing EV market accounted for 63% of the total SiC market in 2021 and is forecasted to be 76% in 2027 (Chiu and Dogmus, 2022; Rosina and Villamor, 2022). PV and energy storage had 14% market share in 2021 but will decline to 8% in 2027. Rail applications had a 7% market share in 2021, which will decline to 4% in 2027. EV charging infrastructure occupies 2–3% market share from now until 2027, while motor drive's market share ranges between 2% and 4% within the same period. The combined market share of listed applications varied from 89% in 2021 to 94% in 2027. For the most dominant application of EV chargers and EVs, SiC market share values are 28% and 53% in 2021 and 2027 (Chiu and Dogmus, 2022; Rosina and Villamor, 2022)., respectively. Therefore, its importance scores for the short and medium terms are 3 and 4, respectively.
Substitutability Limitations Short term: 2 Medium term: 2	For the EV market, the Si-based converter is still usable, although the SiC converter is preferred. A major advantage of SiC converters compared to Si converters is the higher operation frequency and lower switching losses. The higher-efficiency SiC devices enable smaller battery sizes and thus shorter charging times. So, although substitution is available at both the material or systems level, it has minor limitations in performance.

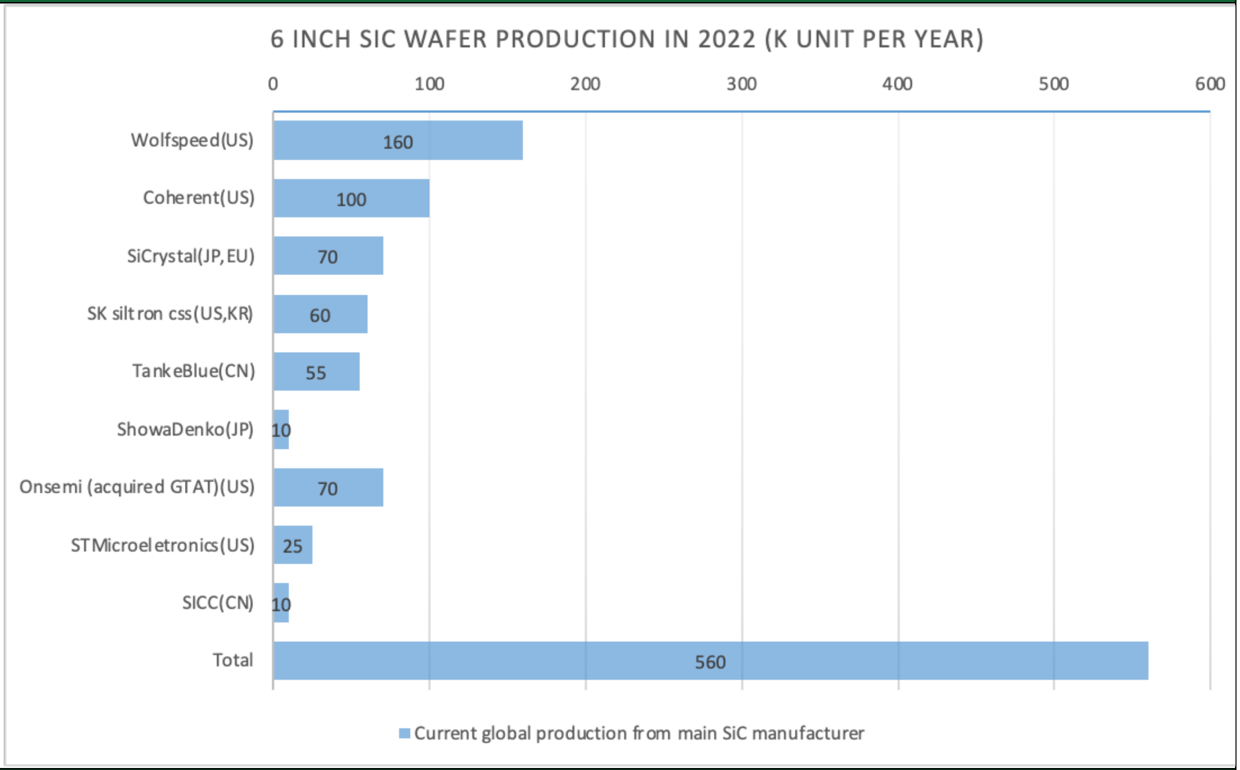
Supply Risk: *Short term: 2, medium term: 3*

SiC requires Si and various forms of synthetic graphite for manufacturing. Both materials are abundant. The main concern is in the manufacturing process of the wafer. SiC crystals require a long time (months) and a lot of energy (a high-temperature process) to grow. Because SiC is brittle and transparent, fabrication suffers from yield loss despite special handling treatment from wafer to device. Energy-intensive fabrication, special wafer handling, and yield all contribute to high wafer cost. The announced SiC wafer capacity of 2022 exceeds demand from the end systems (Chiu and Dogmus, 2022). However, improving costs by improving yield and quality is the main challenge.

Basic Availability Short term: 2 Medium term: 4	According to our conversation with a prominent U.S.-based SiC manufacturer, and the information from *Power SiC 2022 Market and Technology Report*, the manufacturing capacity cannot meet the fast-growing demand for SiC. Therefore, all SiC manufacturers are aggressively expanding their capacity, and it is expected that the "announced" wafer manufacturing capacity could exceed the demand (Chiu and Dogmus, 2022). However, considering the challenge of the low yield and high manufacturing cost, the quantity expansion does not result in high quality and yield. Also of note is that the announced capacity is not only for SiC but also for GaN. Multiple manufacturers have tried to integrate vertically at the wafer level to the device level to reduce supply risk and improve profits. Eight inch wafers are key to lower device costs but have only been demonstrated by only four suppliers. The reason why demand is high is partly because device manufacturers are stocking up on SiC due to its low yield (Frankly Media, 2023). Based on our demand projections, the high scenario will exceed current capacity in 2025. A score of 2 was given for the short term. By 2035, the high demand trajectory will be 16 times more than current capacity. A score of 4 was given for the medium term.
Competing Technology Demand Short term: 4 Medium term: 4	There are multiple sectors growing at high CAGRs such as UPS at 17% and power supply at 21%, resulting in a score of 4.

Political, Regulatory, and Social Factors Short term: 1 Medium term: 1	SiC is currently manufactured mainly in five countries, including Germany (30% market share), United States and Japan (29% market share each), The Netherlands (11% market share), and China (2% market share). Four of these five countries have stable political conditions, which results in a PRS weighted average percentile of 85% and a score of 1.
Codependence on Other Markets Short term: 1 Medium term: 1	The raw material supplies of silicon and synthetic graphite are not a concern. Silicon is produced as a main product.
Producer Diversity Short term: 2 Medium term: 2	As mentioned above, the market share based on discrete modules in 2020, Germany held ~30% market share, the U.S. and Japan each held ~29% market share, , The Netherlands accounted for ~11% market share, and the rest was held by China. The calculated HHI is 2639, which meets the criteria for a score of 2.

Historical Price and Production



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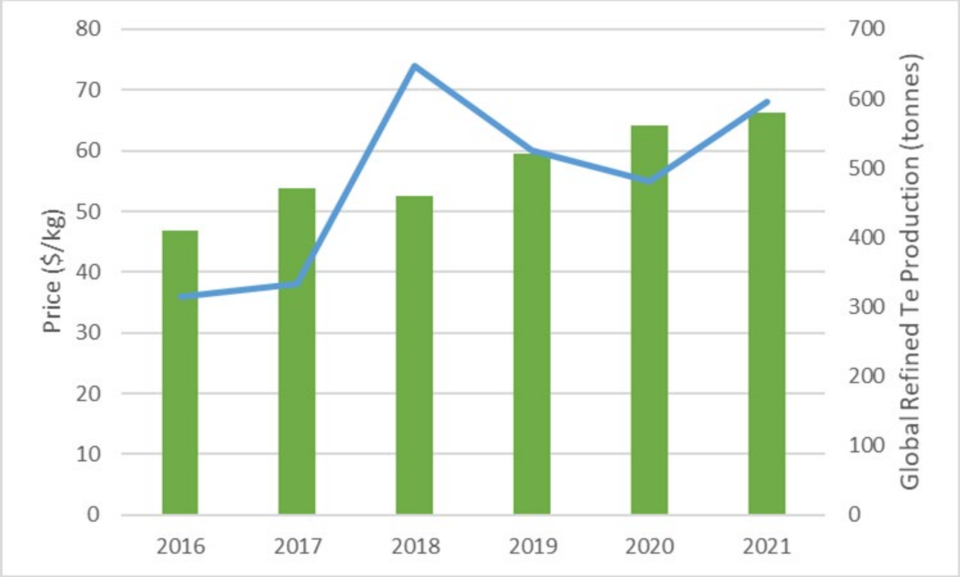
<table>
<tr><th>Tellurium (Te)</th><th>Atomic number: 52</th></tr>
<tr><td colspan="2">Tellurium is semi-grey metal most commonly used in cadmium telluride (CdTe) thin-film solar technologies but is also used in thermoelectric devices, as an alloying additive, as a vulcanizing agent in the rubber industry, and in photoreceptors and blasting caps (USGS, 2022c). Tellurium is primarily produced from copper anode slimes but can also be produced as a by-product from bismuth, copper, gold, nickel, lead-zinc ores, and other precious metals (USGS, 2022c).</td></tr>
<tr><th colspan="2">Importance to Energy: <i>Short term: 1, medium term: 1</i></th></tr>
<tr><td colspan="2">The primary application (40% of Te demand) of tellurium in the energy sector is for thin-film CdTe solar panels (USGS, 2022c). The market for CdTe thin-film solar panels makes up about 5% of global solar PV installations with a much larger share in the U.S. at 55% of newly installed capacity in 2021. Tellurium demand for solar applications is expected to rise as the demand for solar PV capacity continues to increase as projected by the U.S. Energy Information Administration (EIA). The other major energy application of Te is for thermoelectric devices (30% of Te demand) that can recover waste heat and convert it to electricity. This technology is projected to continue to grow quickly as an energy efficiency technology in industry, electronics, and transportation (Allied Market Research, 2021).</td></tr>
<tr><td>Energy Demand
Short term: 1
Medium term: 1</td><td>Based on 40% of Te used in thin-film solar and a CdTe global market share of 5%, a score of 1 was given for this metric.</td></tr>
<tr><td>Substitutability Limitations
Short term: 1
Medium term: 1</td><td>There are numerous other solar PV technologies available, including Si-based solar PV, that could easily substitute for CdTe solar PV installations.</td></tr>
<tr><th colspan="2">Supply Risk: <i>Short term: 3, medium term: 3</i></th></tr>
<tr><td colspan="2">Tellurium supply risk is expected in the short and medium terms largely due to its strong codependence with copper production markets, low producer diversity with the majority of the refined Te coming from China, and potential for demand to exceed supply unless tellurium production increases.</td></tr>
<tr><td>Basic Availability
Short term: 3
Medium term:4</td><td>With growing demand for tellurium in CdTe solar PV installations, significant increases in tellurium production are likely to be required to meet demand in the short term and even more so in the medium term. Current Te production is around 600 tonnes per year with projections for CdTe exceeding current supply in several of the short-term and all of the medium-term cases. Recycling of tellurium is low at less than 10% (USGS, 2022c). Tellurium is currently obtained inexpensively as a by-product of copper mining, but production from that source is nearing saturation in every country other than China. Increasing Te supply would require sourcing Te from China or using more-expensive methods (U.S. Department of Energy, 2022).

Based on demand trajectories as shown in Appendix D, by 2025, 3 out of 4 trajectories would exceed current capacity. Hence, a score of 3 was given for the short term. The highest trajectory will exceed current capacity by 63%. By 2035, all 4 trajectories will exceed current capacity, with the highest trajectory more than double current capacity. Thus, a score of 4 was given for the medium term.</td></tr>
<tr><td>Competing Technology Demand
Short term: 3
Medium term: 3</td><td>Approximately 40% of current tellurium production goes toward thin-film solar technologies, 30% for thermoelectric devices (CAGR of 8%), 15% as an alloying additive (3% CAGR) (Technavio, 2023), 5% as a rubber volcanizing agent (5% CAGR) (Fortune Business Insights, 2021), and 10% for other applications (USGS, 2022c). With 8% CAGR of thermoelectric devices, a score of 3 was given for both the short and medium terms. The grow rates of the non-energy applications are no greater than 5% (USGS, 2022c).</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 2
Medium term: 2</td><td>Due to the current moratoriums that have occurred on exporting Chinese minerals and with China owning most of the production of tellurium (62%), the short- and long-term supply risks are high from the primary import supplier for the U.S. In addition, Ten percent of tellurium production occurs in Russia, and political friction exists that could impact trade in the short and medium terms (USGS, 2022c). The weighted score for this metric is in the 54th percentile, yielding a score of 2. (USGS, 2022c).</td></tr>
<tr><td>Codependence on Other Markets
Short term: 4
Medium term:4</td><td>The production of Te and its global supply are very closely tied to copper as a result of copper slimes being the primary supply of Te production where the Te recovery is estimated to be about 40% (McNulty and Jowitt, 2022); however, it can also be produced as a by-product from mining of bismuth, gold, nickel, lead-zinc ores, and other precious</td></tr>
</table>

	metals to a much lesser extent. More than 90% of tellurium has been produced from anode slimes collected from electrolytic copper refining (USGS, 2022c).
Producer Diversity Short term: 3 Medium term:3	China is the world's leader in Te production, producing an estimated 300 tons (62%) of the global supply in 2020. Japan and Russia are interchangeably the second-largest producers of Te, producing 50 tons (10%) each. Canada and Sweden are the next-largest producers at 40 tons (8%) (USGS, 2022c) and 35 tons (7%), respectively. Bulgaria, South Africa, and The Philippines are also Te producers combining for less than 2% of global production (USGS, 2022c). The HHI is 4161.

Historical Price and Production



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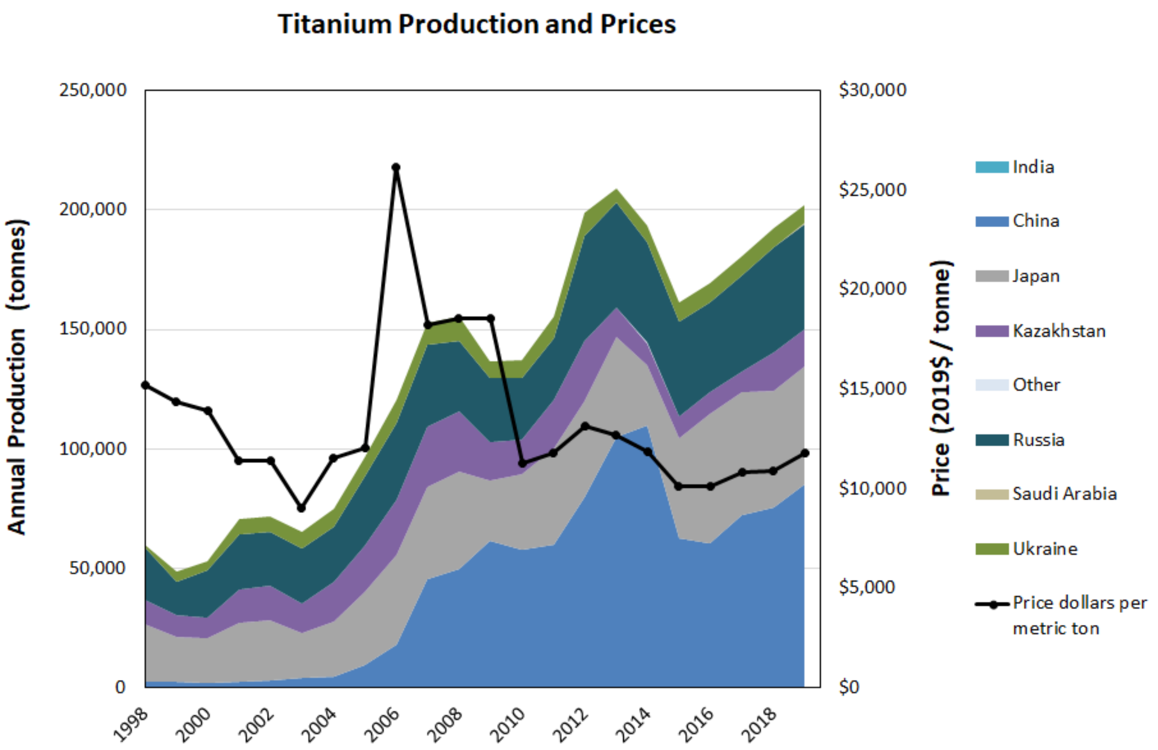
Element: Titanium (Ti)	Atomic number: 22
Titanium metal has high corrosion resistance and the highest of all metal’s strength-to-density ratio – properties important for corrosive applications in the chemical and petrochemical industries. The majority of titanium mined (~95%) is converted to titanium oxide (TiO_2) and marketed for a variety of applications. The remaining 5% of ores is refined into titanium sponge.	
Importance to Energy: *Short term: 2, medium term 2*	
Titanium, in the form of thin and porous metal foam, is used in the gas diffusion layers and bipolar plates of PEM electrolyzer anodes. Titanium and its alloys also have energy- and lightweighting-relevant applications in aircraft, spacecraft, ships, and power generation (including gas turbine blades). As mature technologies, these applications are not specifically evaluated in this analysis. Demand for titanium for lightweighting road vehicles is more emergent and included in this analysis. In this application, titanium is used as a minor alloying agent (approximately 0.2%) in aluminum casts.	
Energy Demand Short term: 2 Medium term: 2	• Emerging PEM water electrolyzer technologies rely on titanium sponge to support anode performance and longevity. • Titanium used for lightweighting road vehicles is also considered in this analysis as an emerging clean energy application. • The market shares for titanium in PEMECs and vehicle lightweighting are highest in the high material intensity and high demand scenarios (Trajectory D). In these trajectories, market shares are forecasted to reach 20% of 2020 capacity in 2025 and 26% of capacity in 2035. • Lightweighting road vehicles accounts for the largest clean energy titanium market share of 2020 capacity, reaching 20% in 2025 and 24% in 2035 in the high material intensity and demand scenarios (Trajectory D).
Substitutability Limitations Short term: 2 Medium term: 2	• Substitutes for titanium in lightweighting vehicle applications include aluminum, magnesium, manganese, and high-strength steels. • While material substitutions for titanium in PEM electrolyzers are minimal, system-level substitutions include different types of electrolyzers and hydrogen production from bio feedstocks and steam methane reforming with carbon capture utilization and storage. • Unlike other metals, titanium is uniquely resistant to corrosion in the highly acidic environment at PEM electrolyzer anodes. • Significant research is underway to reduce the titanium content in PEM electrolyzers. • Titanium alloys have high strength-to-weight ratios, the ability to withstand extreme temperatures, and corrosion-resistant properties that are desirable for several energy applications: ○ Gas turbine engines (fan blades and disks) ○ Lightweighting of aerospace, military, and other transportation applications ○ Heat exchangers and reaction vessels in chemical-processing, desalination, and power generation plants
Supply Risk: *Short Term: 2, Medium Term: 2*	
Basic Availability Short term: 1 Medium term: 2	• Titanium in-scope material demand forecasts do not exceed current titanium sponge production capacity in 2025. By 2035, three trajectories exceed current capacity. In the high material and demand scenario (Trajectory D), titanium demand accounts for 83% in 2025 and 121% in 2035 of 2020 capacity. • The PEM electrolysis demands for titanium sponge as a percentage of 2020 capacity are forecast to be near zero in 2025 and 3% in 2035 in the high penetration and material intensity case (Trajectory D). • The road vehicle lightweighting demand for titanium sponge as a percentage of 2025 production is forecast to be 17% in 2025 and 29% in 2035 in the high penetration and material intensity cases (Trajectory D). • The United States has a net import reliance of >95% for titanium sponge. • High capital, long lead times, and environmental impact hinder rapid expansion of titanium sponge capacity.

Competing Technology Demand Short term: 1 Medium term: 1	• No evidence exists that any non-energy applications of titanium sponge will increase at a higher rate than GDP in the near or medium term. • Competing energy technologies for titanium sponge include gas turbine blades and lightweighting in aerospace, spacecraft, and marine applications. • The majority (~95%) of titanium ores mined are processed and marketed as titanium oxide (TiO_2). While TiO_2 could be considered a competing demand, its demand is not expected to grow at a higher rate than GDP. • Ti sponge prices are volatile and highly dependent on fluctuating demand from the commercial aircraft industry and defense applications.
Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	• For this analysis, titanium supply risk metrics are defined for the production of titanium sponge, which is considered to have a higher supply risk than minerals for two reasons: (1) <5% of titanium minerals are refined to produce titanium sponge; and (2) titanium sponge refining is a more costly and environmentally challenging operation than the production of titanium oxide, which accounts for 95% of titanium ore demand. For comparison, metrics for titanium ores are reported in this summary. The USGS reports production data for both titanium minerals and titanium sponge. • Based on USGS 2020 global production data, the political, regulatory, and social factors weighted average percentile for titanium minerals is 44 (Score 3) and for titanium sponge is 51 (Score 2) • China accounts for 58%, Japan for 20%, Russia for 11%, and Kazakhstan for 6% of titanium sponge production. China accounts for 38%, Mozambique for 13%, and South Africa for 11% of titanium minerals production. U.S. mining accounts for about 1% of titanium minerals production.
Codependence on Other Markets Short term: 1 Medium term: 1	• Titanium sponge production is more dependent on titanium refining capacity, where it is the sole product, than on mining capacity. • Titanium ilmenite and rutile minerals are the main products from titanium mines. Mining co-products are zircon, monazite, and abrasive sands.
Producer Diversity Short term: 3 Medium term: 3	• Titanium minerals: HHI = 1955 (Score 1); titanium sponge: HHI = 3895 (Score 3). • Titanium sponge is refined from synthetic rutile (upgraded ilmenite) and natural rutile concentrates and marketed in the form of ingots, billets, sheets, coils, and tubes. • Titanium minerals are mined in more than 14 countries. Mines in China account for 38%, Mozambique 13%, South Africa 11%, and Australia 10%. Titanium mined in the United States accounts for about 1% of supply. • Geographic concentration of Ti sponge production is greater, with China accounting for 58%, Japan 20%, Russia 11%, and Ukraine 3%. • One titanium production plant in Utah is operational, with an estimated capacity of 500 tonnes/year titanium sponge. Titanium sponge plants in the United States that are not operating have capacity of 12,600 tonnes/year (recently closed) and 10,900 tonnes/year (idled).

Historical Price and Production



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<table>
<tr><th>Uranium (U)</th><th>Atomic number: 92</th></tr>
<tr><td colspan="2">Uranium is a silvery, white metal found in seawater and rocks and is used as a nuclear fuel source for nuclear energy generation. Isotope U-235 is the fissile component of natural uranium and typically makes up a small percentage (~0.7%) of typical, natural uranium.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 4, medium term: 4</i></td></tr>
<tr><td colspan="2">Uranium in nuclear fuels will continue to be the dominant application of uranium. Under optimistic nuclear capacity growth scenarios, uranium demand will increase as nuclear fuel demand increases.</td></tr>
<tr><td>Energy Demand
Short term: 4
Medium term: 4</td><td>Nuclear energy is believed to continue to play an important role in the future for carbon-free energy generation although with higher uncertainties compared to other power sources. From our estimates based on supply and demand data of uranium from the World Nuclear Association (2022a, 2022d), 80–90% of the quantity of the uranium supply is used for nuclear energy. Of the nuclear fuel application, uranium is used in 100% of the reactors. Therefore, a score of 4 was given for both short term and medium term.</td></tr>
<tr><td>Substitutability Limitations
Short term: 4
Medium term: 4</td><td>Uranium is required for all current reactor fuel types in varying mixtures and U-235 concentrations. Thorium has the potential to be used as a fuel source; however, it is not currently commercially used (World Nuclear Association, 2020b).</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 2, medium term: 2</i></td></tr>
<tr><td colspan="2">Supply risk is slightly elevated due to concerns surrounding projected production capacity of uranium in comparison to aggressive uranium demand projections. Additionally, Russia’s domination of the enrichment capacity is dominated by Russia poses a threat to the nuclear fuel supply for non-allies of Russia.</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>Despite available resources, projected demand under the most aggressive nuclear growth may exceed current production capacity. Two out of four trajectories will exceed current capacity by 2025, yielding a score of 2. By 2035, three out of four trajectories will exceed current capacity, yielding a score of 3.
Reprocessing/recycling of spent uranium fuel yields reprocessed uranium and plutonium, but neither have the same value as enriched uranium. Recycling is estimated to have the ability to replace 4–11% of natural uranium per year (NEA, 2023; World Nuclear Association, 2020a). Last, there are numerous planned and prospective uranium mines for the coming years and numerous currently idled uranium mines (World Nuclear Association, 2022c, 2022e).</td></tr>
<tr><td>Competing Technology Demand
Short term: 2
Medium term: 2</td><td>Almost all uranium is used in nuclear fuel applications. Other applications include radio-isotopes in the medical field, food-processing industry, nuclear weapons, and industrial sectors (Zeus Resources LTD, n.d.). Growth for medical applications is 5%/year (World Nuclear Association, 2023). Therefore, a score of 2 was given to this metric.</td></tr>
<tr><td>Political, Regulatory, and Social Factors
Short term: 2
Medium term: 2</td><td>A weighted PRS score of 51% was computed based on uranium production, while a score of 58 resulted from enrichment activity. The enriched uranium supply presents some concern due to the Ukraine–Russia war as the largest enrichment capacity in the world is located in Russia (Tenex) (World Nuclear Association, 2022b). Both calculations result in a score of 2.</td></tr>
<tr><td>Codependence on Other Markets
Short term: 1
Medium term: 1</td><td>Uranium is typically mined as a primary product. However, it can as be recovered as a by-product of copper, gold-bearing ores, and phosphate deposits (World Nuclear Association, 2022c).</td></tr>
<tr><td>Producer Diversity
Short term: 2
Medium term: 2</td><td>An HHI index score of 2969 was computed for uranium enrichment capacity. Neither uranium mining nor uranium enrichment capacity has a singular country providing more than 50% of supply. Kazakhstan was the leading primary supplying country in 2021 and held a market share of 45% (World Nuclear Association, 2022c). Russia was the leading enrichment capacity country in 2020 and held a market share of 46% (World Nuclear Association, 2022b).</td></tr>
</table>

Historical Price and Production

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Appendix B: Material Intensity

Table B.1 in this appendix details the material intensities used in demand projections for the screening and criticality assessment of all considered materials.

Table B.1 Material Intensity assumption summary for all candidate materials

Material	Application	Material Intensity	Production Yield(s)
Aluminum	Lightweighting	156.9 kg/vehicle - 373.0 kg/vehicle	
	EV batteries	BEV LDVs: 39.5-69.5 kg/vehicle PHEV LDVs: 6.3-11.0 kg/vehicle BEV HDVs: 82.9-146 kg/vehicle PHEV HDVs: 13.1-23.0 kg/vehicle	
	Stationary storage batteries	Li-ion: 552.5-647.2 kg/MWh NiMH: 37.5-2500 kg/MWh NaS: 36.9-2458 kg/MWh	
Cobalt	EV magnets	BEV/PHEV/FCEV cars: 11-22 g/vehicle BEV/PHEV/FCEV vans: 16-32 g/vehicle BEV/PHEV/FCEV buses: 22-43 g/vehicle BEV/PHEV/FCEV trucks: 32-65 g/vehicle	
	Wind turbine magnets	Direct Drive: 3.3-6.5 kg/MW Hybrid: 1.0-2.0 kg/MW Kumari et al, 2018 Habib et al, 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
	EV batteries	BEV LDVs: 3.5-14.8 kg/vehicle PHEV LDVs: 0.6-2.3 kg/vehicle BEV HDVs: 7.3-30.9 kg/vehicle PHEV HDVs: 1.2-4.9 kg/vehicle	
	Stationary storage batteries	Li-ion: 49.0-137.5 kg/MWh NiMH: 212.5-762.5 kg/MWh	
Copper	Vehicle (EV + ICE)	ICE: 8.16E-03 to 2.18E-02 mton EV: Hybrid Electric Vehicle (HEV) = 3.99E-02 mton Plug-in Hybrid Electric Vehicles (PHEV) = 5.99E-02 mton Battery Electric Vehicle (BEV) = 8.30E-02 mton Hybrid electric bus = 8.89E-02 mton Battery electric bus = 3.69E-01 mton (CDA, 2017)	
	Wind	Onshore: 2.9 – 3.52 mton per MW Offshore: 8 – 9.55 mton per MW (IEA, 2021; CDA, 2022)	
	All grid	~10 – 12 mton per GW (IEA, 2022)	
Dysprosium	EV magnets	BEV/PHEV/FCEV cars: 68-136 g/vehicle BEV/PHEV/FCEV vans: 102-204 g/vehicle BEV/PHEV/FCEV buses: 136-272 g/vehicle BEV/PHEV/FCEV trucks: 204-408 g/vehicle	

Material	Application	Material Intensity	Production Yield(s)
	Wind turbine magnets	Direct Drive: 2.4-7.9 kg/MW Hybrid: 0.7-2.4 kg/MW Kumari et al, 2018 Imholte et al, 2018 Habib et al, 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
Electrical steel	Vehicle motor	40-100kg per vehicle (Voestalpine, 2019)	
	Transformers	72.57 – 108.86 mt/unit of large power transformer (Deetman, Boer, Engelenberg, Voet, & Vuuren, 2021; International Energy Agency, 2022b)	
	Wind	1.36-4.81 mt/MW for onshore application and 2.45-3.47 mt/MW for offshore application (OpenEI, n.d.)	
Fluorine	EV batteries	BEV LDVs: 4.1-7.8 kg/vehicle PHEV LDVs: 0.6-1.2 kg/vehicle BEV HDVs: 8.5-16.4 kg/vehicle PHEV HDVs: 1.4-2.6 kg/vehicle	
	Stationary storage batteries	Li-ion: 56.9-72.8 kg/MWh	
Gallium	Solar (CIGS)	11 mt/GW; average of 2.3 & 19.7 mt/GW (Zimmermann & Gößling-Reisemann, 2014)	Deposition yield = 45% Fabrication yield = 92% Production yield = 100% (Song, Wang, Sen, & Liu, 2022)
	LEDs	0.02 – 0.03 grams Ga/LED (HSSMI, 2021)	25 – 50%; Estimated from (Song et al., 2022)
	Power electronics	5.12 g Ga/cm^3 in deposition layer (Song et al., 2022)	
	EV magnets	BEV/PHEV/FCEV cars: 1-3 g/vehicle BEV/PHEV/FCEV vans: 2-4 g/vehicle BEV/PHEV/FCEV buses: 3-6 g/vehicle BEV/PHEV/FCEV trucks: 4-8 g/vehicle	
	Wind turbine magnets	Direct Drive: 0.4-0.8 kg/MW Hybrid: 0.1-0.3 kg/MW Kumari et al, 2018 Habib et al, 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
Germanium	HVDC converter	20.4 g - 56.0 g per 6-inch wafer unit	
	Microchips	Percent of Ge production used in microchips (1%-2%) (IBM, 2022). Ge use is low in	

Material	Application	Material Intensity	Production Yield(s)
		microchip application and there was no data available on specific material intensity or the amount of microchips that contain Ge that are being produced in a given year, therefor using the current global Ge production that goes towards microchips and projecting demand based on expected sectoral growth rates provides the most accurate projection	
Indium	Solar	15.5 Ton/GW (0.0155 kg/kw) (Fraunhofer Institute for Solar Energy Systems ISE, 2022)	45.0% yield from deposition 92.0% device yield rate 41.4% overall yield data taken from the supporting info in (Song et al., 2022)
Lithium	EV batteries	BEV LDVs: 6.6-10.8 kg/vehicle PHEV LDVs: 1.1-1.7 kg/vehicle BEV HDVs: 13.9-22.7 kg/vehicle PHEV HDVs: 2.2-3.6 kg/vehicle	
	Stationary storage batteries	Li-ion: 56.9-72.8 kg/MWh	
Magnesium	Lightweighting	6.4 kg/vehicle - 24.0 kg/vehicle	
	Lightweighting	4.0 kg/vehicle - 11.1 kg/vehicle	
	EV batteries	BEV LDVs: 2.2-8.7 kg/vehicle PHEV LDVs: 0.4-1.4 kg/vehicle BEV HDVs: 4.7-18.1 kg/vehicle PHEV HDVs: 0.7-2.9 kg/vehicle	
	Stationary storage batteries	Li-ion: 31.4-84.7 kg/MWh NiMH: 100.0-500.0 kg/MWh	
Natural Graphite	Nuclear	Pebble bed reactors: • 2400-3600 mt/GW for startup • 800-1200 mt/GW for annual consumption (NextSource Materials; Subramanian 2017)	----
	EV batteries	BEV LDVs: 9.1-52.3 kg/vehicle PHEV LDVs: 1.4-8.3 kg/vehicle BEV HDVs: 19.1-109.7 kg/vehicle PHEV HDVs: 3.0-17.4 kg/vehicle	
	FCEV fuel cells	FCEV LDVs: 16.6-45.6 kg/vehicle FCEV HDVs: 40.0-91.3 kg/vehicle	
	Stationary storage batteries	Li-ion: 127.4-487.6 kg/MWh	
Neodymium	EV magnets	BEV/PHEV/FCEV cars: 232-464 g/vehicle BEV/PHEV/FCEV vans: 348-696 g/vehicle BEV/PHEV/FCEV buses: 464-928 g/vehicle BEV/PHEV/FCEV trucks: 696-1392 g/vehicle	

Material	Application	Material Intensity	Production Yield(s)
	Wind turbine magnets	Direct Drive: 88.3-176.6 kg/MW Hybrid: 27.2-54.4 kg/MW Kumari et al, 2018 Imholte et al, 2018 Habib et al, 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
Nickel	HVDC	2.8 - 48 kg/kW for switchgear and stainless-steel electrode	
	EV batteries	BEV LDVs: 17.0-62.9 kg/vehicle PHEV LDVs: 2.7-10.0 kg/vehicle BEV HDVs: 35.7-132 kg/vehicle PHEV HDVs: 5.6-20.9 kg/vehicle	
	Stationary storage batteries	Li-ion: 238.1-586.3 kg/MWh NiMH: 3125-9188 kg/MWh	
Phosphorous	EV batteries	BEV LDVs: 1.3-26.0 kg/vehicle PHEV LDVs: 0.2-4.1 kg/vehicle BEV HDVs: 2.7-54.4 kg/vehicle PHEV HDVs: 0.4-8.6 kg/vehicle	
Platinum	FCEV fuel cells	FCEV cars: 0.010 – 0.018 kg/vehicle FCEV vans: 0.015 – 0.027 kg/vehicle FCEV buses: 0.019 – 0.034 kg/vehicle FCEV trucks: 0.030 – 0.055 kg/vehicle	
Praseodymium	EV magnets	BEV/PHEV/FCEV cars: 34-68 g/vehicle BEV/PHEV/FCEV vans: 51-102 g/vehicle BEV/PHEV/FCEV buses: 68-136 g/vehicle BEV/PHEV/FCEV trucks: 102-204 g/vehicle	
	Wind turbine magnets	Direct Drive: 16.0-31.9 kg/MW Hybrid: 4.9-9.8 kg/MW Kumari et al, 2018 Imholte et al, 2018 Habib et al, 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
SiC	Power electronics	19.9 g-28.4 g per 6 inch wafer unit (Chiu & Dogmus, 2022)	From wafer to SiC device only 30-50% yield
Silicon	Solar	2.9 - 3.4 kg/kW (Frischknecht, Stolz, Krebs, de Wild-Scholten, & Sinha, 2020)	60% - yield, most waist is kerf from cutting the ingots (Li, Lin, Wang, Shi, Sun, Ban, Liu, & Chen, 2021) 67% yield according to (Frischknecht et al., 2020)
	Lightweighting	9.4 kg/vehicle - 26.5 kg/vehicle	

Material	Application	Material Intensity	Production Yield(s)
Tellurium	Solar (CdTe)	36 (mt/GW) in the high case (First Solar Correspondence) 20 (mt/GW) in the low case (European Commission Joint Research Centre, Alves Dias, Pavel, Plazzotta, & Carrara, 2020)	Te Production Yield (High) = 99% (Marwede & Reller, 2012)
Uranium	Nuclear	159 – 187 (mt U/GW) (World Nuclear Association, 2022)	----
Zirconium	Nuclear	11.9 t Zr/GW (Motta, Couet, & Comstock, 2015)	----

Appendix B References

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Appendix C: Screening Results

This appendix details the scoring of all materials and technologies considered in this report. Chapter 3 provided the methodology used for screening, accompanied by a list of key materials and lower risk materials sorted by their highest scores. Figure C.1 gives an overview of material scores by alphabetical order.

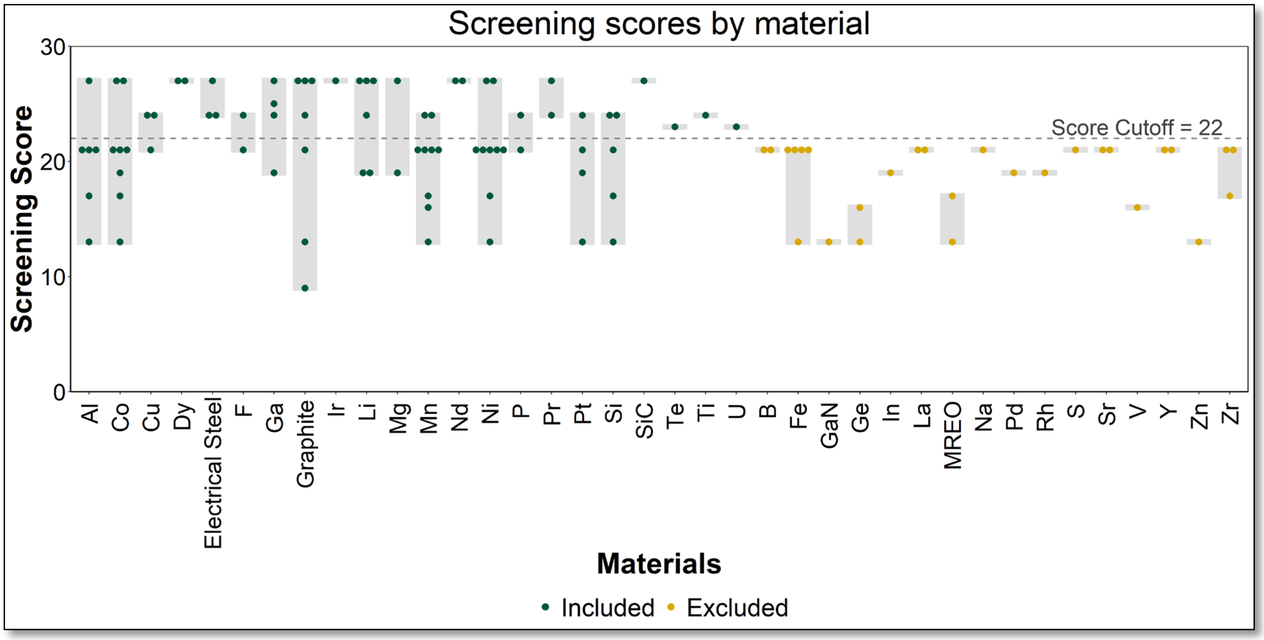

Figure C.1: Screening scores of candidate materials by alphabetical order

Table C.2 organizes materials by technology group.

Table C.2 Screening scores by sub-metric for technologies and materials

Technology/ Component	Material	Technology importance in 2030 (x2)	Material/ component specific technology adoption in 2030 (x4)	Additional material demand share (x3)	Total score
HVDC transformers & converters	Cu	3	3	1	21
	Ge	3	1	1	13
	Ni	3	3	1	21
Transformers	Electrical steel	3	3	3	27
Motors & generators	Electrical steel	3	2	3	24
Nuclear	U	1	3	3	23
	Zr	1	3	1	17

Technology/ Component	Material	Technology importance in 2030 (x2)	Material/ component specific technology adoption in 2030 (x4)	Additional material demand share (x3)	Total score
	Natural graphite	1	1	1	9
Solar	Si	3	3	2	24
	In	3	1	3	19
	Ga	3	1	3	19
	Te	3	2	3	23
Power electronics	GaN	3	1	1	13
	SiC	3	3	3	27
LED lighting	Ga	2	3	3	25
Microchips	Ge	3	1	2	16
Wind – wiring	Cu	3	3	2	24
Wind - magnets	Fe	3	3	1	21
	Nd	3	3	3	27
	Pr	3	3	3	27
	Dy	3	3	3	27
	B	3	3	1	21
	Ga	3	3	2	24
Energy storage	Li	3	3	2	24
	Co	3	3	2	21
	Ni	3	3	1	17
	Graphite	3	3	2	24
	V	3	1	2	16
	Zn	3	1	1	13
	Fe	3	1	1	13
	Al	3	3	1	21
	Na	3	3	1	21
	S	3	3	1	21
	F	3	3	1	21
	P	3	3	1	21

Technology/ Component	Material	Technology importance in 2030 (x2)	Material/ component specific technology adoption in 2030 (x4)	Additional material demand share (x3)	Total score
Vehicles-wiring	Cu	3	3	2	24
Vehicles-magnets	Nd	3	3	3	27
	Pr	3	3	3	27
	Dy	3	3	3	27
	B	3	3	1	21
	Ga	3	3	3	27
	Fe	3	3	1	21
Vehicle lightweighting	Mn	3	3	2	24
	Mg	3	2	3	23
	Al	3	1	3	19
	Si	3	3	2	24
	Ni	3	2	1	17
Electric Vehicles - batteries	Al	3	3	2	24
	Li	3	3	3	27
	Mn	3	3	2	24
	Co	3	3	3	27
	Fe	3	3	1	21
	Graphite	3	3	3	27
	F	3	3	1	24
	P	3	3	2	24
	Ni	3	3	3	27
	MREO	3	1	1	13
Conventional vehicles-catalysts	Pt	2	3	1	19
	Pd	2	3	1	19
	Rh	2	3	1	19
Fuel cell electric vehicles	Pt	3	1	1	13
	Graphite	3	1	2	16
	Pt	3	3	2	24

Technology/ Component	Material	Technolog y importance in 2030 (x2)	Material/ component specific technology adoption in 2030 (x4)	Additional material demand share (x3)	Total score
H_2 Electrolyzers - PEM	Ir	3	3	3	27
	Ti	3	3	2	24
H_2 Electrolyzers – Alkaline water	Ni	3	3	1	21
H_2 Electrolyzers – Solid oxide	La	3	3	1	21
	Sr	3	3	1	21
	Co	3	3	1	21
	Ni	3	3	1	21
	Y	3	3	1	21
	Zr	3	3	1	21
	Mn	3	3	1	21

Appendix D: Material Demand Trajectories

This appendix details the calculations of four demand trajectories and production capacity used for the "Basic availability" metric scoring as explained in Chapter 3.

Trajectory A is derived from low energy technology deployment such as Stated Policies Scenarios (STEPS) from the International Energy Agency (IEA) and similar agencies or low market growth rate from market reports, combined with low material intensity as shown in Appendix B. Trajectory B uses the same deployment scenario as Trajectory A but with a high material intensity. Trajectories C and D account for high deployment scenarios of energy technologies such as net-zero scenarios (NZEs) of the IEA or with high market growth rates. While Trajectory C considers low material intensity, Trajectory D evaluates high material intensity. When a material is considered for multiple energy technologies, the aggregated Trajectory A will be the sum of all Trajectory A values for each technology. A similar approach is used for the other three trajectories. Each of these trajectory scenarios was calculated for each material's respective clean energy technology.

Non-energy demand is assumed to have a growth rate of 3%, reflecting the global average economic growth. This non-energy demand is combined with other energy demand not considered in this report to form other demand. The plots in all figures in Appendix D show demand from considered energy technologies combined with other demand.

Regarding supply, only current production or capacity is shown here for estimating the gap between current supply and future demand. It is not within the scope of this report to estimate future supply. Where current capacity is missing, a capacity utilization of 86% was assumed based on statistics from the Federal Reserve System for the mining sector (Board of Governors of the Federal Reserve System, 2023).

D.1 Aluminum

Figure D.1 displays the demand of aluminum (Al) from 2020 to 2035 against current production and production capacity. Aluminum demand trajectories were based on three different clean energy technologies: lightweighting alloys, electric vehicle (EV) batteries, and stationary storage batteries. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios. For each trajectory, the demand for aluminum was calculated across the three clean energy technologies. In lightweighting, aluminum was calculated as the range of aluminum present across different lightweighting packages for three lightweighting materials: advanced high-strength steel, aluminum alloys, and magnesium alloys. This range was then applied to the weighted average mass of light-duty and heavy-duty vehicle types sold by year in the STEPS and NZE scenarios. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B. Total material demand for aluminum in 2020 was estimated to be 86.2 million metric tons (mt) sourced from CRU Consulting (CRU International, 2022). Aluminum 2020 production and production capacity are sourced from the U.S. Geological Society's (USGS's) *Mineral Commodity Summaries 2022* (USGS, 2022b) and incorporates a low-end 50% recycling rate (Nassar, Graedel, and Harper, 2015).

The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

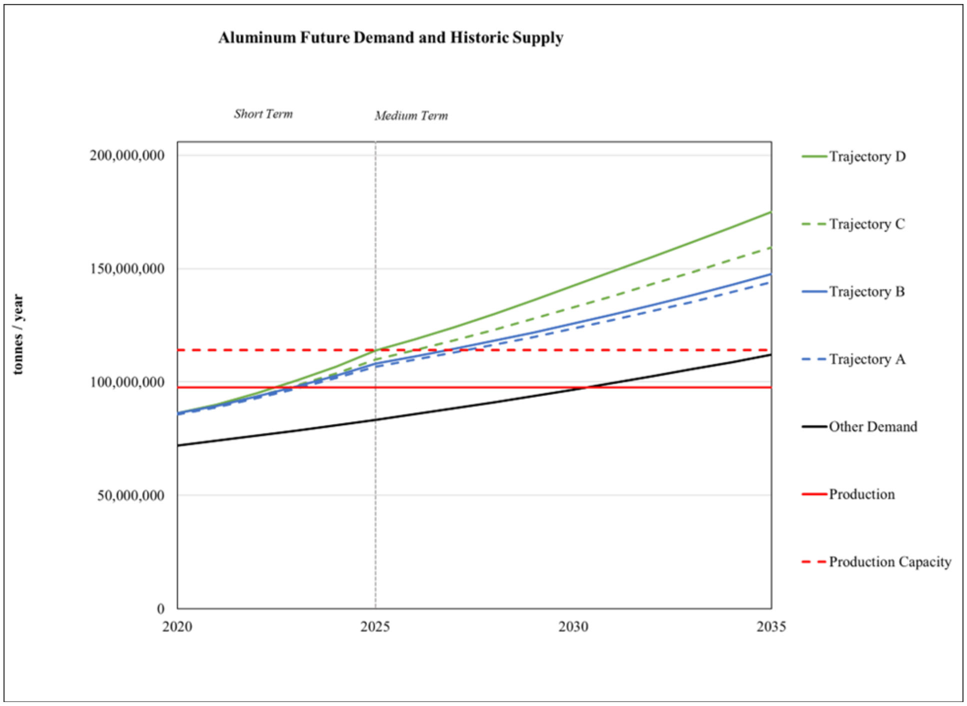

Figure D.1: Aluminum demand trajectories, current production, and production capacity

The demand trajectories for electric vehicles and stationary storage batteries were obtained by combining total demand projections for electric vehicles and stationary storage batteries in GW from the IEA (2022) *World Energy Outlook* and battery market reports with material intensity data for lithium ion, nickel metal hydride, and sodium sulfur batteries from the literature (Xu et al., 2020; Iloeje et al., 2022; Argonne, 2023).

Trajectory lines for aluminum were calculated as the total demand across the respective clean energy demand trajectories and total non-energy for each year. Non-energy demand for aluminum was estimated as the amount of total material demand not attributed to the highest trajectory demand for aluminum.

D.2 Cobalt

Figure D.2 displays the demand of cobalt (Co) from 2020 to 2035 against current production and production capacity. Cobalt demand trajectories utilized the combined trajectories of four clean energy technologies: electric vehicle batteries, stationary storage batteries, solid oxide electrolyzers, and solid oxide fuel cells. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios. The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

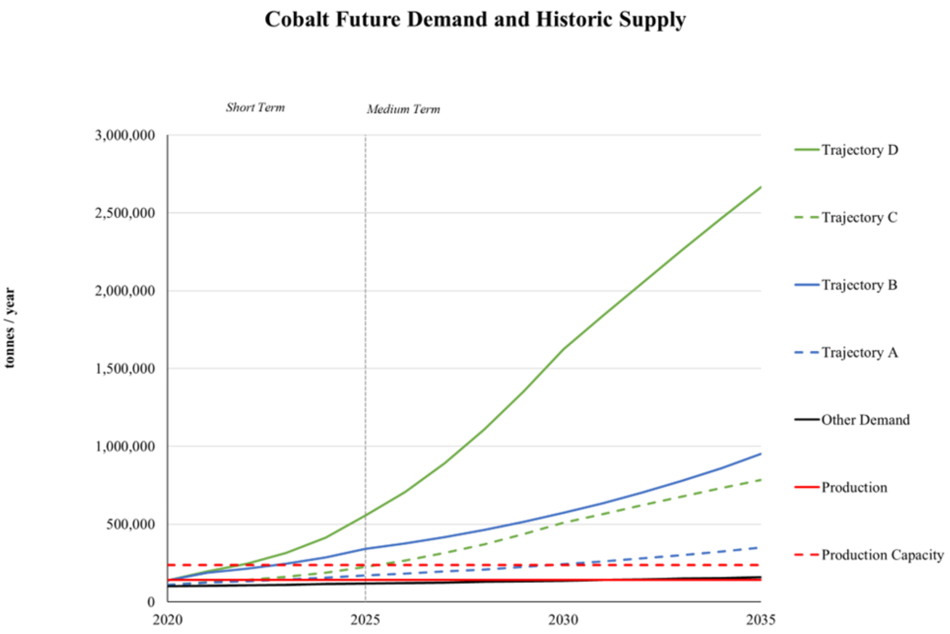

Figure D.2: Cobalt demand trajectories, current production, and production capacity

The production lines are based on 2020 data from the 2022 USGS estimates of global cobalt production. The demand trajectories were obtained by combining total demand projections for electric and fuel cell vehicles, stationary storage batteries in GW, and hydrogen use from the IEA (2022) *World Energy Outlook* and battery market reports with material intensity data for lithium-ion and nickel metal hydride batteries, fuel cells, and electrolyzers from the literature (Xu et al., 2020; Iloeje et al., 2022; Argonne, 2023). Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

Trajectory lines for cobalt were calculated as the total demand across the respective clean energy demand trajectories and total non-energy for each year. Non-energy demand for cobalt was estimated as the amount of total material demand not attributed to the highest trajectory demand for cobalt. Total material demand in 2020 was sourced from the *2022 USGS Mineral Yearbook*. From 2020, the non-energy demand of cobalt was projected to grow at a CAGR of 3.0%, which is based on gross domestic product (GDP) growth. Cobalt recycling rates are not incorporated in production amounts. Production capacity of cobalt was obtained by dividing production by an average capacity utilization rate.

D.3 Copper

Figure D.3 displays the demand of copper (Cu) from 2020 to 2035 against current production and production capacity. The technologies considered for Cu are wind turbines, EVs, internal combustion engine (ICE) vehicles, and the electric grid. We use STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we consider the high and low material intensity of Cu in selected technologies as listed in Appendix B. For instance, between 18 and 49 lbs. of Cu can be found in an ICE (Copper Developemnt Association, 2022). The non-energy demand curve represents Cu demand for other applications such as construction, chemicals, industrial processes, consumer electronics, etc. The production curve represents production of global refined Cu in 2020.

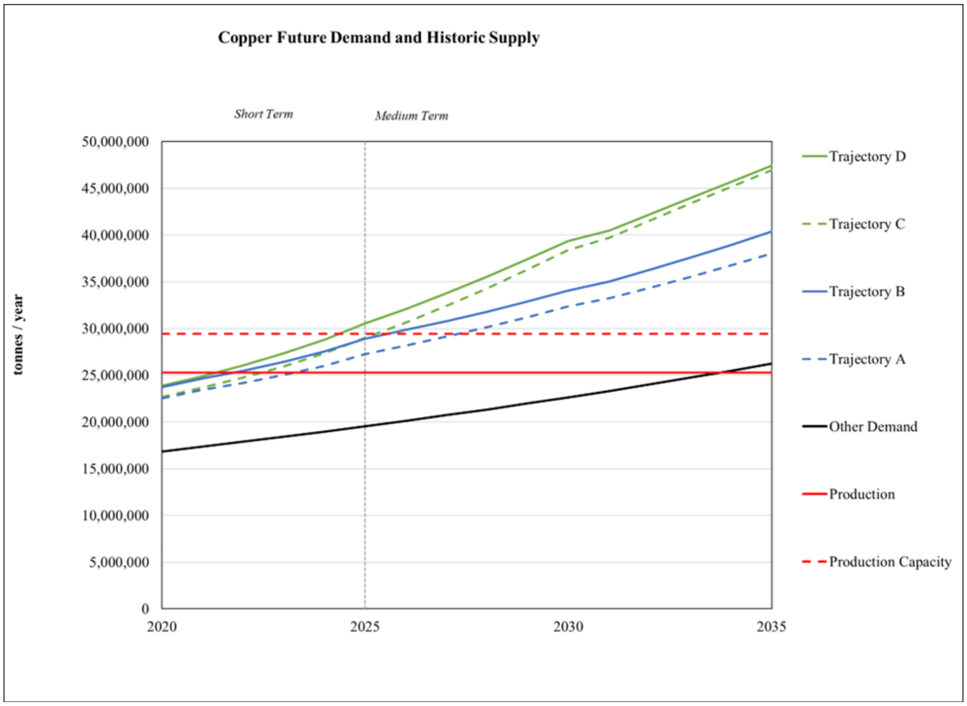

Figure D.3: Copper demand trajectories, current production, and production capacity

D.4 Dysprosium

Figure D.4 displays the demand of dysprosium (Dy) from 2020 to 2035 against current production and production capacity. The technologies considered for Dy are wind turbines and EVs. We use STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we consider the high and low material intensity of Dy in selected technologies as listed in Appendix B. The non-energy demand curve represents Dy demand for other applications such as consumer electronics, air conditioning, industrial machines, etc. Production was based on 2022 USGS estimates of total rare-earth production by country combined with estimates of shares of different rare earths in each country's mines. Total demand for 2022 is estimated to match total supply in 2022, and 2020 demand is estimated by assuming a 3% growth rate from 2020 to 2022. Recycling of end-of-life products does not contribute significantly to production levels. Production capacity for most countries was estimated based on maximum production levels over the last five years. Countries such as Burma and Madagascar, which recently reduced production based on USGS estimates while Chinese production quotas increased, are assumed to have the capacity to ramp production back up to previous levels. In addition, some known monazite processing capacity in the U.S. in excess of current production was accounted for.

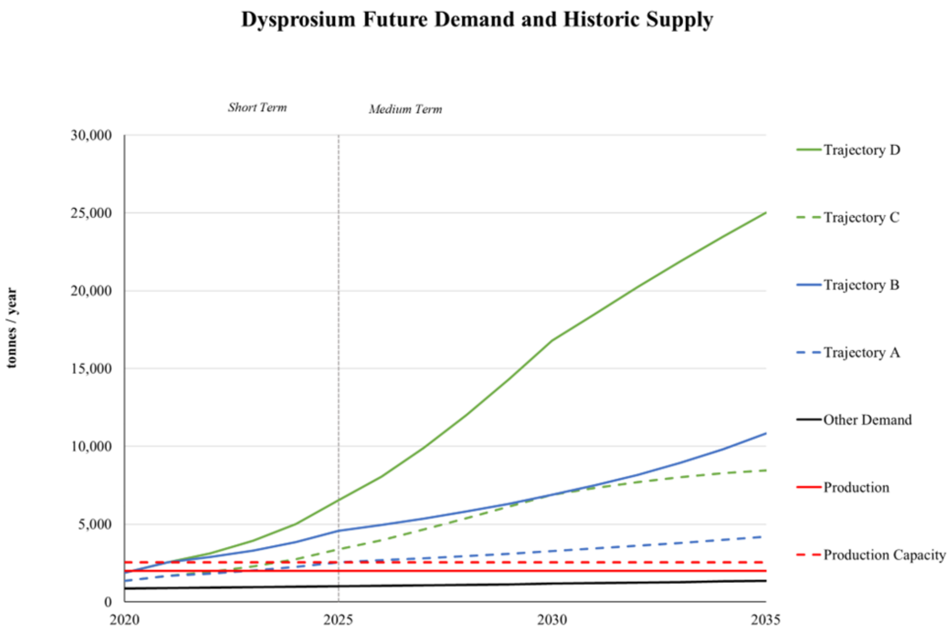

Figure D.4: Dysprosium demand trajectories, current production, and production capacity

D.5 Electrical steel

Figure D.5 displays the demand of electrical steel from 2020 to 2035 against current production and production capacity. Three different technologies were considered to generate the demand curve including transformers, wind turbines, and electrical vehicles. The STEPS scenario from the IEA was used to develop trajectory A and B for all technologies. The Announced Pledges Scenarios (APS), Sustainable Development Scenario (SDS), and NZE scenarios from the IEA were used for transformers, wind turbines, and EVs, respectively, to develop trajectories C and D. The low and high material intensity of electrical steel in each technology can be seen in Appendix B.

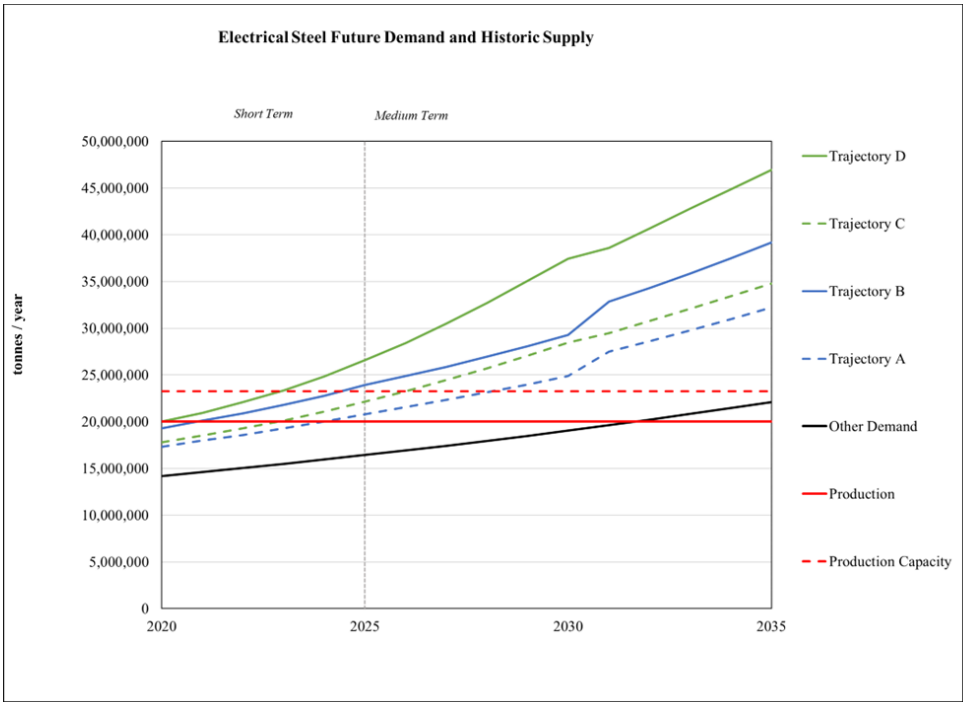

Figure D.5: Electrical steel demand trajectories, current production, and production capacity

D.6 Fluorine

Figure D.6 displays the demand of fluorine (F) from 2020 to 2035 against current production and production capacity. Fluorine future demand trajectories were based on electric vehicle batteries and stationary storage batteries. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios. The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

For each trajectory, the demand for fluorine was calculated for its use in lithium-ion batteries (LIBs) in electric vehicles and stationary storage. In LIBs, the amount of fluorine was calculated based on its content in two LIB components: lithium hexafluorophosphate and polyvinylidene fluoride, the contents of which (in kg/kWh LIB) were estimated with Argonne National Laboratory's BatPaC model for LIBs based on different cathode chemistry (Argonne 2023). A range of the fluorine content in LIBs was further developed based on projected LIB chemistry mixes reported in literature (Xu et al., 2020). This range was then applied to the projected battery sizes of light-duty and heavy-duty vehicle types sold by year in the STEPS and NZE scenarios to calculate the fluorine demand for electric vehicle batteries, and also applied to projections of stationary storage deployment in GW from the EIA (2022) *World Energy Outlook*. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

Trajectory lines for fluorine were calculated as the total demand for fluorine across LIB technologies and total non-energy for each year. Non-energy demand for fluorine was estimated as the amount of 2020 total fluorine demand minus its demand for clean energy technologies in the same year. From 2020 onward, the non-energy demand of fluorine was projected to grow at a CAGR of 3% per year, which was based on GDP growth. The

2020 total world fluorine demand is assumed to equal 2020 production, which was sourced from USGS. Fluorine production amounts were solely on primary production, and fluorine production capacity was calculated by dividing 2020 global production by a capacity utilization factor of 86%.

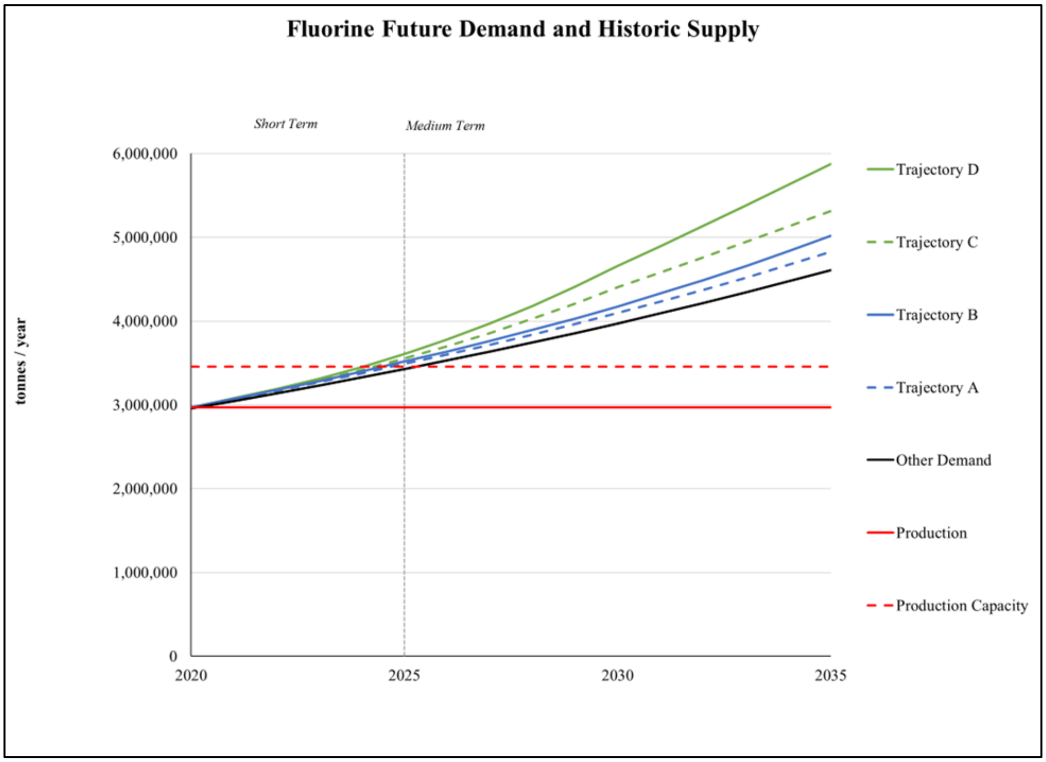

Figure D.6: Fluorine demand trajectories, current production, and production capacity

D.7 Gallium

Figure D.7 shows four different demand scenarios for gallium (Ga) from 2020 to 2035 against current production and production capacity. Energy applications considered in this analysis for gallium were light-emitting diode (LED) lighting, magnets in EVs and wind turbines, solar cells, and power electronics. Due to the varying data availability for each of the energy applications, a variety of different sets of data were utilized to create the demand scenarios. For example, LED lighting relied on the U.S. Department of Energy's (DOE's) "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications" report (Elliott, Yamada, Penning, Schober, and Lee, 2019), magnets in EVs and wind turbines relied on IEA projection data, solar cells relied on IEA STEPs and NZE projection data, and power electronics relied on data from Yole Reports (Ayari and Chiu, 2022). Once these scenarios were developed that established what the projected technology prevalence would be, material intensities and production yields, when applicable, were applied. This approach resulted in the final trajectory results. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B. Production data were obtained from the USGS (2022a). Of this data, production of high-purity refined gallium was identified as the material form of interest due to the requirement that most semiconductor-based applications use 6N purity or higher (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2006). To compute the production capacity of total high-purity gallium, the primary high-purity gallium production capacity was summed with the secondary high-purity gallium production capacity. Regarding current production, because recycling output is not available, an assumed 85% capacity utilization was used to derive production from capacity. This number was then added to primary high-purity gallium production to compute the total supply of high-purity gallium.

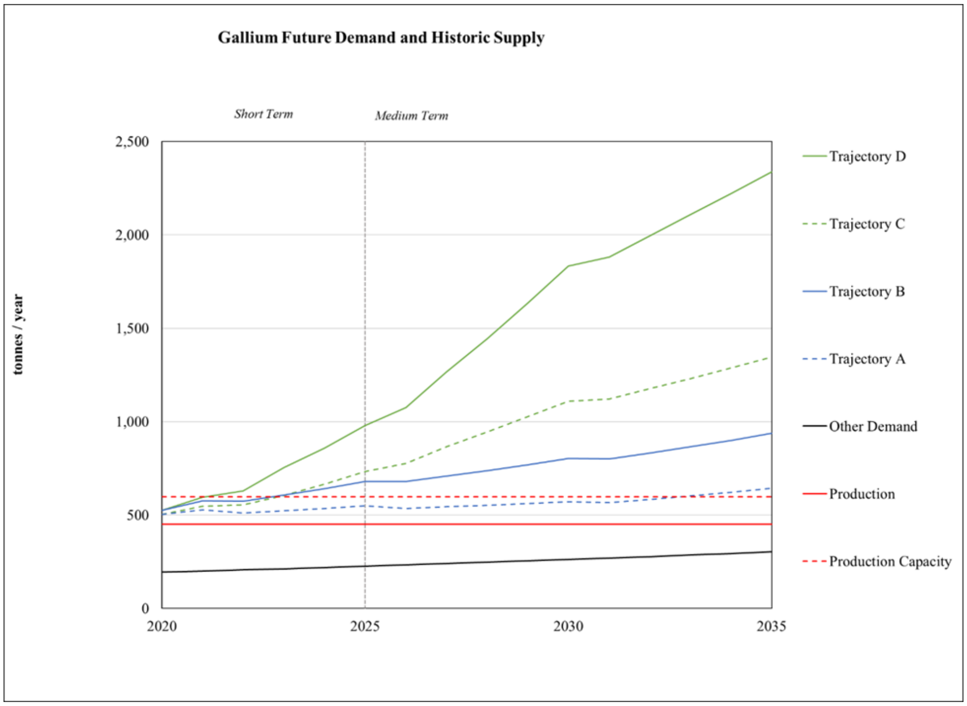

Figure D.7: Gallium demand trajectories, current production, and production capacity

D.8 Graphite

Figure D.8 shows four different demand scenarios for graphite (C) from 2020 to 2035 against current production and production capacity. Trajectories of future graphite demand were based on four clean energy technologies: electric vehicle batteries, stationary storage batteries, fuel cell electric vehicles (FCEVs), and nuclear. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of the IEA's STEPS and Net Zero Emission scenarios. The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

For each trajectory, the demand for graphite was calculated for its use in lithium-ion batteries (LIBs in electric vehicles and stationary storage. In LIBs, the amount of graphite was calculated based on its content (in kg/kWh LIB) in the anode, which was estimated with Argonne National Laboratory's BatPaC model for LIBs based on different cathode chemistry (Argonne, 2023). A range of the graphite content in LIBs specific to each technology was further developed based on projected LIB chemistry mixes, silicon content in the anode, and shares of natural vs. synthetic graphite reported in the literature (Xu et al., 2020; Eshetu et al., 2021; Pillot, 2021). The graphite range for vehicle LIBs was then applied to the projected battery sizes of light-duty and heavy-duty vehicle types sold by year in the STEPS and NZE scenarios to calculate the graphite demand for electric vehicle batteries, and the stationary LIB graphite range to projections of stationary storage deployment in GW from the EIA (2022) *World Energy Outlook* to calculate the graphite demand for stationary storage batteries. Graphite demand for fuel cell electric vehicles was calculated based on estimated graphite content (in kg/MW) in fuel cell stack (Badgett et al., 2022), fuel cell sizes for light-duty and heavy-duty vehicles, and their projected sales, while graphite demand for nuclear was calculated based on estimated graphite content (in metric ton per MWe) in pebble bed reactor and projected nuclear power deployment scenarios. The shares of natural vs. synthetic graphite in fuel cells are assumed to be the same as those in LIBs, while graphite demand for nuclear is assumed to be 100% natural graphite. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

Trajectory lines for graphite were calculated as the total demand for graphite across all four clean energy technologies and total non-energy for each year. Non-energy demand for graphite was estimated as the amount of 2020 total graphite demand minus its demand for clean energy technologies in the same year. From 2020 onward, the non-energy demand of graphite was projected to grow at a CAGR of 3% per year, which was based on GDP growth. The 2020 total world graphite demand is assumed to equal 2020 production, which was sourced from USGS (USGS, 2022c). Graphite production amounts were based solely on primary flake production, and graphite production capacity was assumed to equal the maximum global production from 2017–2021 as reported by USGS (USGS, 2022c).

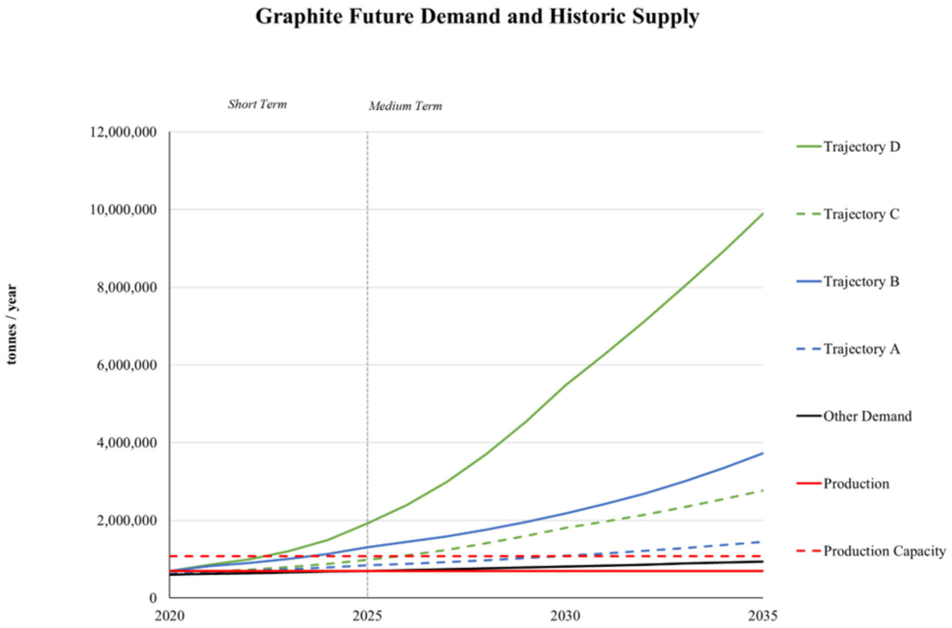

Figure D.8: Graphite demand trajectories, current production, and production capacity

D.9 Iridium

Figure D.9 displays the demand of iridium (Ir) from 2020 to 2035 against current production and production capacity. The only technology considered for Ir is proton electrolyte membrane (PEM) electrolyzers. We use STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we consider the high and low material intensity of Ir in selected technologies as listed in Appendix B. The non-energy demand curve represents Ir demand for other uses such as in the chemical, electrochemical, and electronics industries. Production was based on 2021 USGS estimates of platinum group metal (PGM) production combined with other sources on iridium shares in PGM mining.

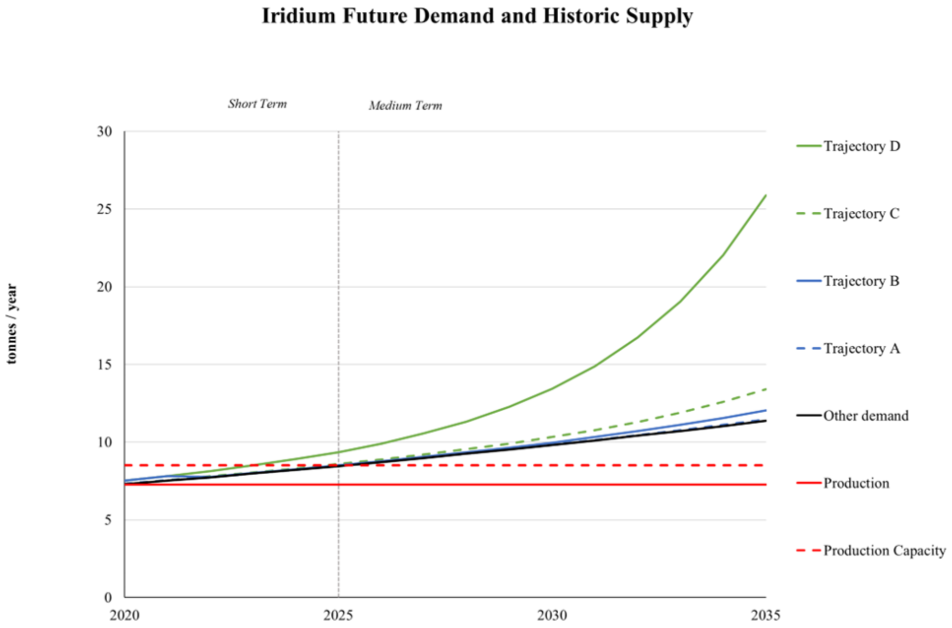

Figure D.9: Iridium demand trajectories, current production, and production capacity

D.10 Lithium

Figure D.10 shows four different demand scenarios for lithium (Li) from 2020 to 2035 against current production and production capacity. Demand trajectories are modeled for the following clean energy demand areas: lithium-ion batteries for electric vehicles and for stationary storage. All other areas of demand are counted as non-energy demand and are assumed to grow at 3%. Trajectories A and B are based on the IEA *World Energy Outlook's* STEPS scenarios for growth in electric vehicle sales and stationary storage needs in MW, while Trajectories C and D are based on IEA's NZE (net zero emissions) scenarios. Trajectories A and C are based on low material intensities, while trajectories B and D are based on high material intensities for lithium-ion batteries from the literature (Xu et al., 2020; Argonne 2023), as described in Appendix B. Total primary lithium demand is estimated from USGS's *2018* mineral yearbook and applying a 9% growth rate since then, based on historical CAGR also from USGS's *2018* mineral yearbook.

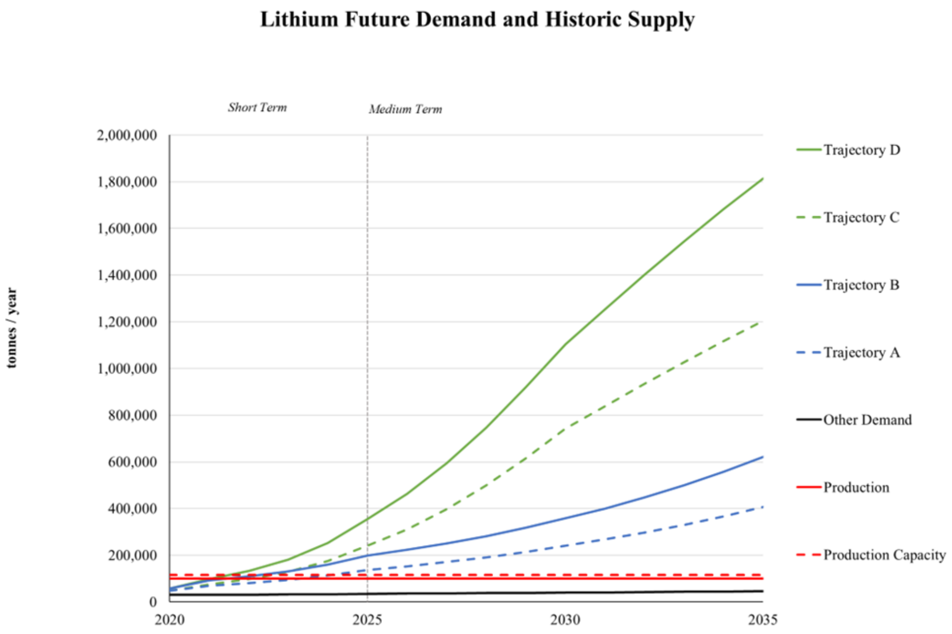

Figure D.10: Lithium demand trajectories, current production, and production capacity

D.11 Magnesium

Figure D.11 shows four different demand scenarios for magnesium (Mg) from 2020 to 2035 against current production and production capacity. Lightweighting in light-duty and heavy-duty vehicles was used as the technology group for magnesium future demand trajectories. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios. The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

For each trajectory, the demand for magnesium was calculated for one clean energy technology application: lightweighting. In lightweighting, the amount of magnesium was calculated as the range of magnesium present across different lightweighting packages for two lightweighting materials: aluminum alloys and magnesium alloys. This range was then applied to the weighted average mass of light-duty and heavy-duty vehicle types sold by year in the STEPS and NZE scenarios. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

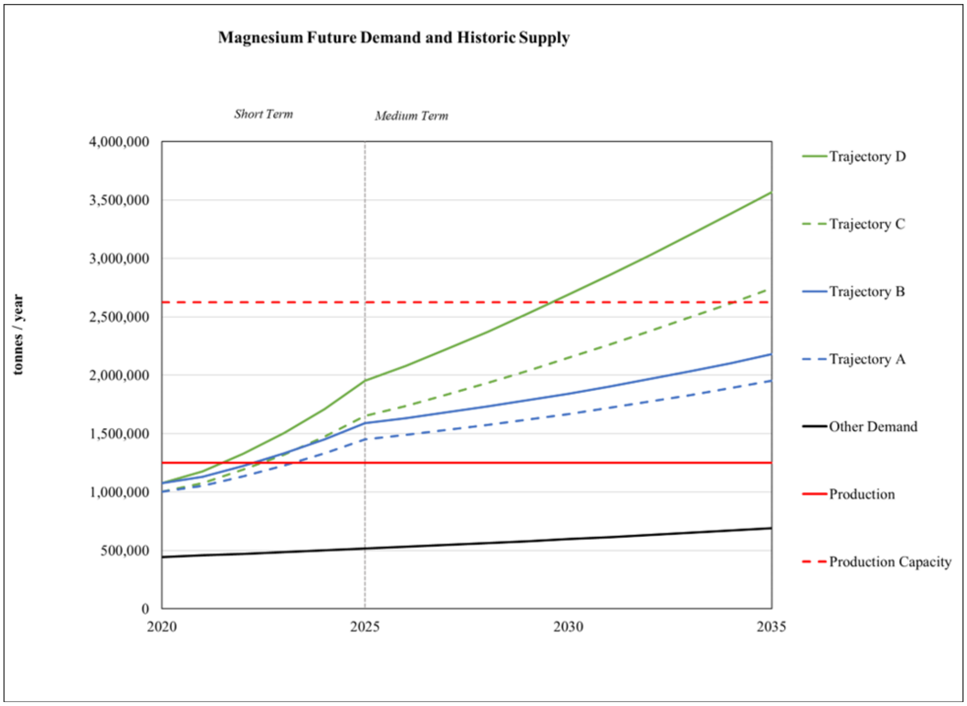

Figure D.11: Magnesium demand trajectories, current production, and production capacity

Trajectory lines for magnesium were calculated as the total demand for magnesium across lightweighting technologies and total non-energy for each year. Non-energy demand for magnesium was estimated as the amount of total material demand not attributed to the highest trajectory demand for magnesium. Magnesium's 2020 total world material demand is sourced from the USGS *2018 Minerals Yearbook* and projected out with a 5% CAGR sourced through the USGS *2018 Minerals Yearbook*. Magnesium material demand encapsulates only primary magnesium demand. Magnesium 2020 production is sourced from the USGS *Mineral Commodities Summaries 2022* and incorporates a low-end recycling rate of 25%. Magnesium's 2020 production capacity is sourced from the USGS *2020 Minerals Yearbook's* tables-only release and incorporates a low-end recycling rate of 25% used for the production estimation.

D.12 Manganese

Figure D.12 shows four different demand scenarios for manganese (Mn) from 2020 to 2035 against current production and production capacity. Manganese demand trajectories were calculated based on the five clean energy technologies of lightweighting alloys, electric vehicle batteries, hydrogen electrolyzers, stationary storage batteries, and solid oxide fuel cells. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios. The demand for manganese in lightweighting alloys was calculated as the range of manganese present across different lightweighting packages for four lightweighting materials: high-strength steel, advanced high-strength steel, aluminum alloys, and magnesium alloys. This range was then applied to the weighted average mass of light-duty and heavy-duty vehicle types sold by year in the STEPS and NZE scenarios. Total world demand for manganese was estimated to be 17.9 million metric tons in 2018 and was projected to 2020 with a 2.8% CAGR (USGS, 2018). Manganese production was sourced through the 2022 minerals commodity summary (USGS, 2022b), and production capacity was estimated to have a 70% capacity utilization rate (The International Manganese Institute, 2013).

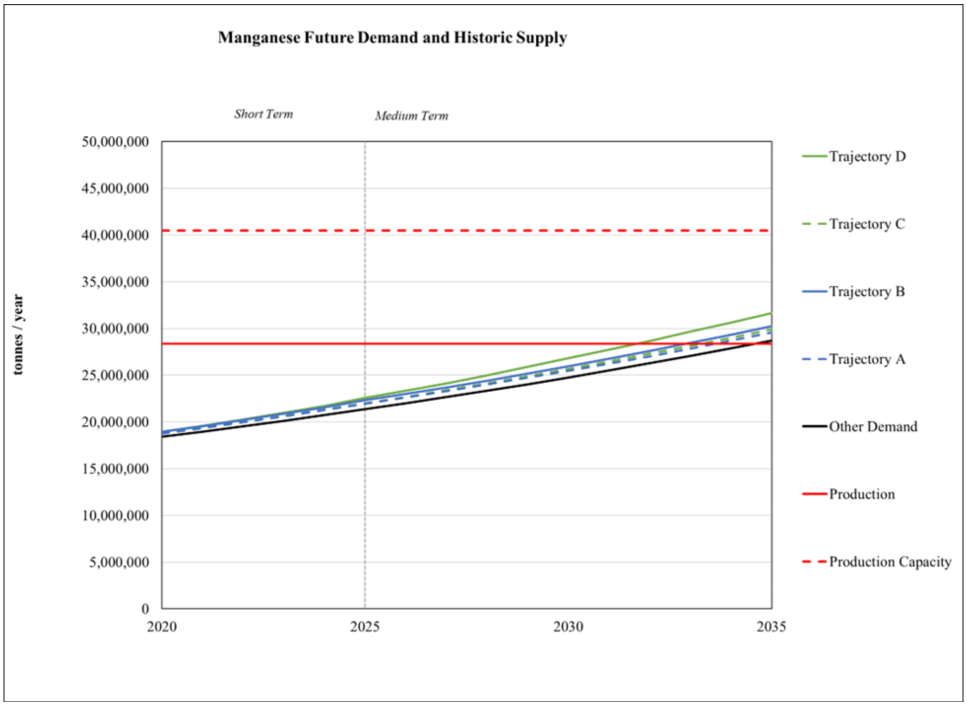

Figure D.12: Manganese demand trajectories, current production, and production capacity

Manganese is utilized in a myriad of different technologies across the clean energy landscape. Therefore, demand trajectories were calculated based on the five clean energy technologies of lightweighting alloys, electric vehicle batteries, hydrogen electrolyzers, stationary storage batteries, and solid oxide fuel cells. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios. The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

The demand trajectories for electric vehicle batteries, stationary storage, fuel cells, and electrolyzers were obtained by combining total demand projections for electric and fuel cell vehicles, stationary storage batteries in GW, and hydrogen use from the IEA (2022) *World Energy Outlook* and battery market reports with material intensity data for lithium-ion and nickel metal hydride batteries, fuel cells, and electrolyzers from the literature (Xu et al., 2020; Iloeje et al., 2022; Argonne 2023). Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

Trajectory lines for manganese were calculated as the total demand for manganese across the five clean energy technologies and total non-energy for each year. Non-energy demand for manganese was estimated as the amount of total world material demand not attributed to the highest trajectory demand for manganese.

D.13 Neodymium

Figure D.13 displays the demand of neodymium (Nd) from 2020 to 2035 against current production and production capacity. Four trajectories are modeled for the following clean energy demand areas: NdFeB magnets for EV motors and NdFeB magnets for wind turbine generators. The non-energy demand curve represents Nd demand for other applications, such as consumer electronics, air conditioning, industrial machines, etc., and is assumed to grow at 3%. Trajectories A and B are based on IEA's STEPS scenarios for growth in electric vehicle and wind turbine sales, while Trajectories C and D are based on the IEA's NZE (net zero emissions) scenarios. Trajectories A and C are based on low material intensities, while trajectories B and D are based on high material intensities, as described in Appendix B. Total demand for 2022 is estimated to match total supply in 2022, and 2020 demand is estimated by assuming a 3% growth rate from 2020 to 2022.

Production was based on 2022 USGS estimates of total rare-earth production by country combined with estimates of shares of different rare-earths in each country's mines. Recycling of end-of-life products does not contribute significantly to production levels. Production capacity for most countries was estimated based on maximum production levels over the last five years. Countries such as Burma and Madagascar, which recently reduced production based on USGS estimates while Chinese production quotas increased, are assumed to have the capacity to ramp production back up to previous levels. In addition, some known monazite processing capacity in the U.S. in excess of current production was accounted for.

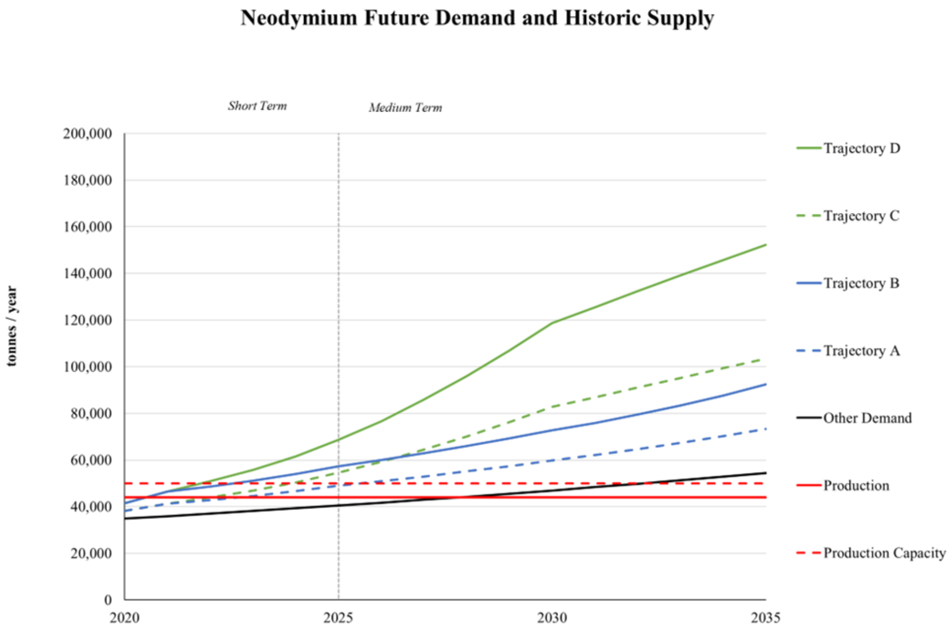

Figure D.13: Neodymium demand trajectories, current production, and production capacity

D.14 Nickel

Figure D.14 displays the demand of nickel (Ni) from 2020 to 2035 against current production and production capacity. Demand trajectories are modeled for the following clean energy demand areas: lithium-ion batteries for electric vehicles and for stationary storage, eletrolyzers for generating hydrogen, and fuel cells for vehicles. All other areas of demand are counted as non-energy demand and are assumed to grow at 3%. Trajectories A and B are based on the IEA's *World Energy Outlook's* STEPS scenarios for growth in electric and fuel cell vehicle sales, stationary storage needs in MW, and hydrogen use, while Trajectories C and D are based on the IEA's NZE (net zero emissions) scenarios. Trajectories A and C are based on low material intensities, while Trajectories B and D are based on high material intensities for lithium-ion and nickel metal hydride batteries, fuel cells, and electrolyzers from the literature (Xu et al., 2020; Iloeje et al., 2022; Argonne 2023), as described in Appendix B. Total primary nickel demand is estimated from the USGS's *2017 Minerals Yearbook* and by applying a 5% growth rate since then, based on historical CAGRs from the USGS's *2018 Minerals Yearbook*.

Production is based on 2020 USGS estimates from the USGS's *Mineral Commodity Summaries 2022* of total nickel production. Stainless steel is recycled at a high rate, but because this process does not produce separated nickel that can be used to meet energy demand, it is not included in this analysis. Non-energy demand for nickel, likewise, includes only primary demand. While some nickel from lithium-ion batteries is recycled, and recycled quantities are likely to grow in the future, the amount produced from end-of-life batteries in 2020 is estimated to be small enough not to substantially affect worldwide nickel supply.

Production capacity is estimated using the capacity utilization rate of 82% that was calculated for 2014 in the 2019 CMS.

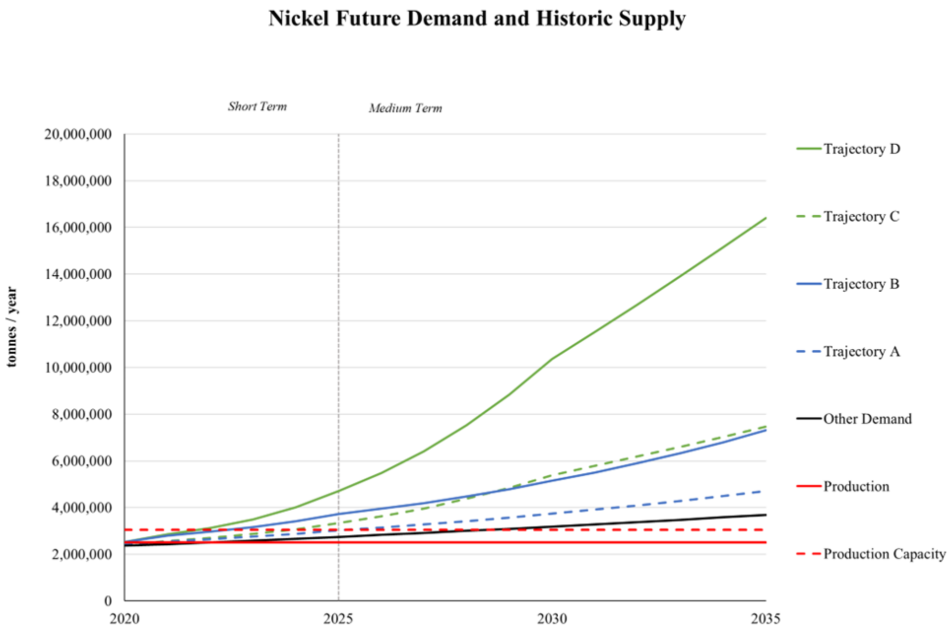

Figure D.14: Nickel demand trajectories, current production, and production capacity

D.15 Phosphorous

Figure D.15 displays the demand of phosphorous (P) from 2020 to 2035 against current production and production capacity. Phosphorus demand trajectories utilized the combined trajectories of two clean energy technologies: electric vehicle batteries and stationary storage batteries. Phosphorus is used in lithium-iron-phosphate (LFP) batteries and in the electrolyte of nearly all lithium-ion batteries. Four different scenarios for each technology type were created and, respectively, added together to produce the four different trajectories. The four different trajectories consist of the IEA's STEPS and Net Zero Emission scenarios. The four different trajectories can be broken down by the following assumptions: Trajectory A – STEPS scenario and low material intensity, Trajectory B – STEPS scenario and high material intensity, Trajectory C – NZE scenario and low material intensity, and Trajectory D – NZE scenario and high material intensity.

The production lines are based on 2020 data from 2022 USGS estimates of global phosphorus production. The demand trajectories for stationary storage batteries were obtained by combining total demand projections for batteries in GW from the IEA (2022) *World Energy Outlook* and battery market reports with material intensity data for lithium ion and nickel metal hydride batteries from the literature. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

Trajectory lines for phosphorus were calculated as the total demand across the respective clean energy demand trajectories and total non-energy for each year. Non-energy demand for phosphorus was estimated as the amount of total material demand not attributed to the highest trajectory demand for phosphorus. Total material demand in 2020 was sourced from the USGS's *2022 Minerals Yearbook*. From 2020, the non-energy demand of phosphorus was projected to grow at a CAGR of 3.0%, which is based on global GDP growth.

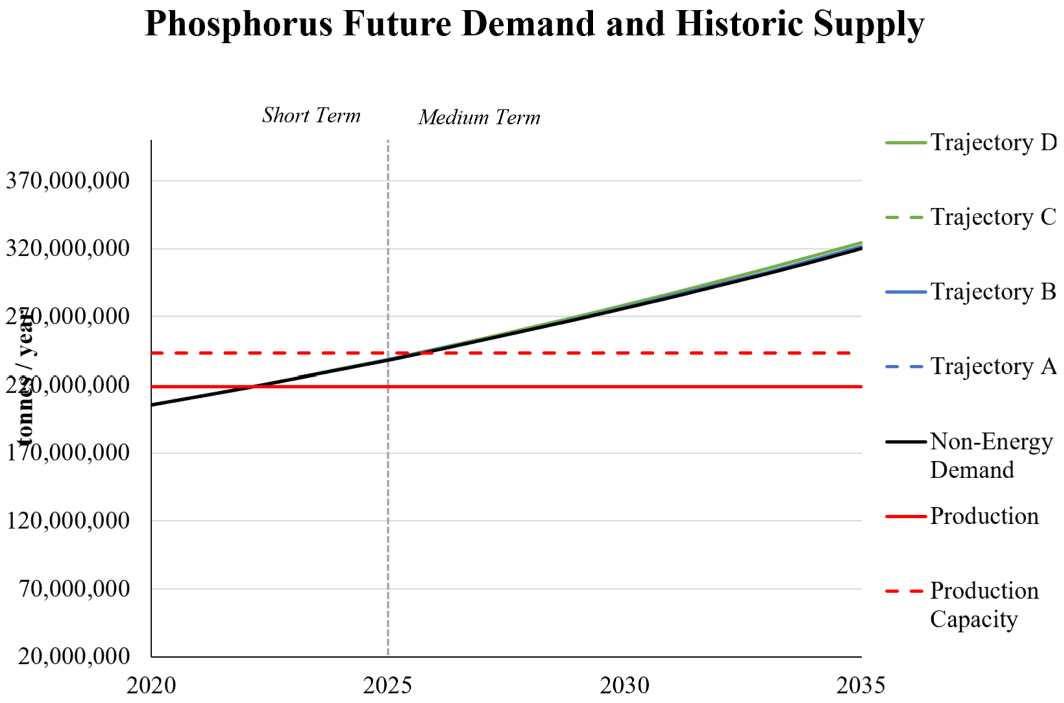

Figure D.15: Phosphorous demand trajectories, current production, and production capacity

D.16 Platinum

Figure D.16 displays the demand of platinum (Pt) from 2020 to 2035 against current production and production capacity. The energy technologies considered for Pt were PEM electrolyzers, fuel cell vehicles, and catalytic converters. We use STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we consider the high and low material intensity of Pt in selected technologies as listed in Appendix B. The non-energy demand curve represents Pt demand for other applications such as jewelry, electronics, and investment. Production estimated were based on 2021 USGS estimates of platinum production, and production capacity was estimated using an assumed 86% capacity utilization.

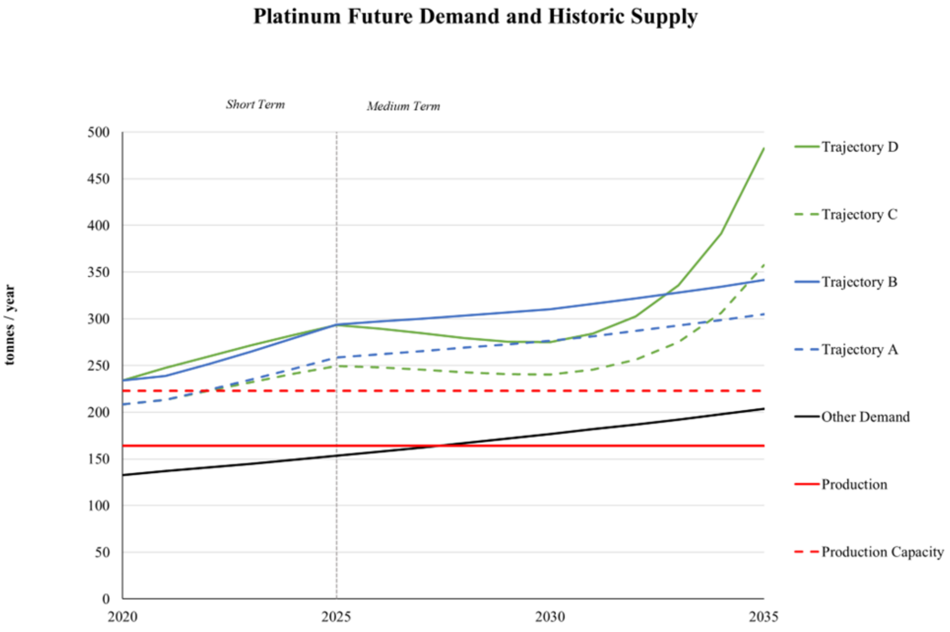

Figure D.16: Platinum demand trajectories, current production, and production capacity

D.17 Praseodymium

Figure D.17 displays the demand of praseodymium (Pr) from 2020 to 2035 against current production and production capacity. The technologies considered for Pr are wind turbines and EVs. We use STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we consider the high and low material intensity of Pr in selected technologies as listed in Appendix B. The non-energy demand curve represents Pr demand for other applications such as consumer electronics, air conditioning, industrial machines, etc. Production was based on 2022 USGS estimates of total rare-earth production by country combined with estimates of shares of different rare earths in each country's mines. Total demand for 2022 is estimated to match total supply in 2022, and 2020 demand is estimated by assuming a 3% growth rate from 2020 to 2022. Recycling of end-of-life products does not contribute significantly to production levels. Production capacity for most countries was estimated based on maximum production levels over the last five years. Countries such as Burma and Madagascar, which recently reduced production based on USGS estimates while Chinese production quotas increased, are assumed to have the capacity to ramp production back up to previous levels. In addition, some known monazite processing capacity in the U.S. in excess of current production was accounted for.

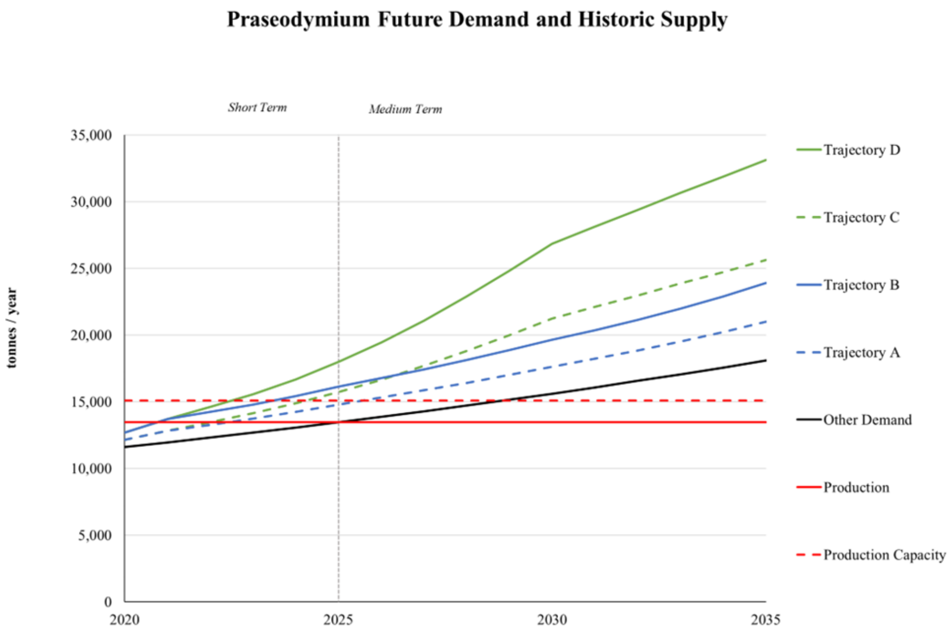

Figure D.17: Praseodymium demand trajectories, current production, and production capacity

D.18 Silicon

Figure D.18 displays the demand of silicon (Si) from 2020 to 2035 against current production and production capacity. The silicon demand trajectories utilized the combined trajectories of three clean energy technologies: lightweighting alloys, solar, and electrical steel. The four different trajectories consist of IEA's STEPS and Net Zero Emission scenarios for low and high scenarios, respectively. The demand for silicon in lightweighting was calculated as the range of silicon present across different lightweighting packages for four lightweighting materials: high-strength steel, advanced high-strength steel, aluminum alloys, and magnesium alloys. This range (low and high material intensities) was then applied to the weighted average mass of light-duty and heavy-duty vehicle types sold by year in the STEPS and NZE scenarios. Projecting silicon demand for solar was created using STEPS with low production yield, STEPS with high production yield, NZE with low production yield, and NZE with high production yield. Electric steel scenarios were taken from the electric steel section (included only energy-related applications for electric steel: power transformers, wind turbines, and electric vehicle motors) and multiplied by 3% for low demand scenarios (Trajectories A and C) and by 5% for high demand scenarios (Trajectories B and D). Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

Non-energy demand for silicon was estimated to be 2020 material demand sourced from the *2018 Minerals Yearbook* as a calculated amount of silicon content from silicon metal and ferrosilicon (U.S. Geological Survey, 2018). Silicon metal was presumed to contain 100% silicon while ferrosilicon is assumed to contain 75% silicon (U.S. Geological Survey, 2018). Silicon demand was projected out with a weighted average CAGR of silicones, polysilicon, and aluminum demand for silicon metal and a CAGR of ferrosilicon growth to project total demand growth until 2020 (U.S. Geological Survey, 2018). From 2020, the non-energy demand of silicon was projected to grow at a CAGR of 3.0%. Silicon production amounts were calculated for 2020 as the silicon content global production amounts sourced through the USGS *Minerals Commodity Summaries 2022* (U.S. Geological Survey, 2022). Because recycling of silicon was deemed insignificant by the USGS, silicon recycling rates are not incorporated into production amounts (U.S. Geolotical Survey, 2022). Production capacity of silicon is an average capacity utilization rate in 2020 for China and the rest of the world applied to 2020 production (Shanghai Metals Market, 2023; 和讯网, 2023).

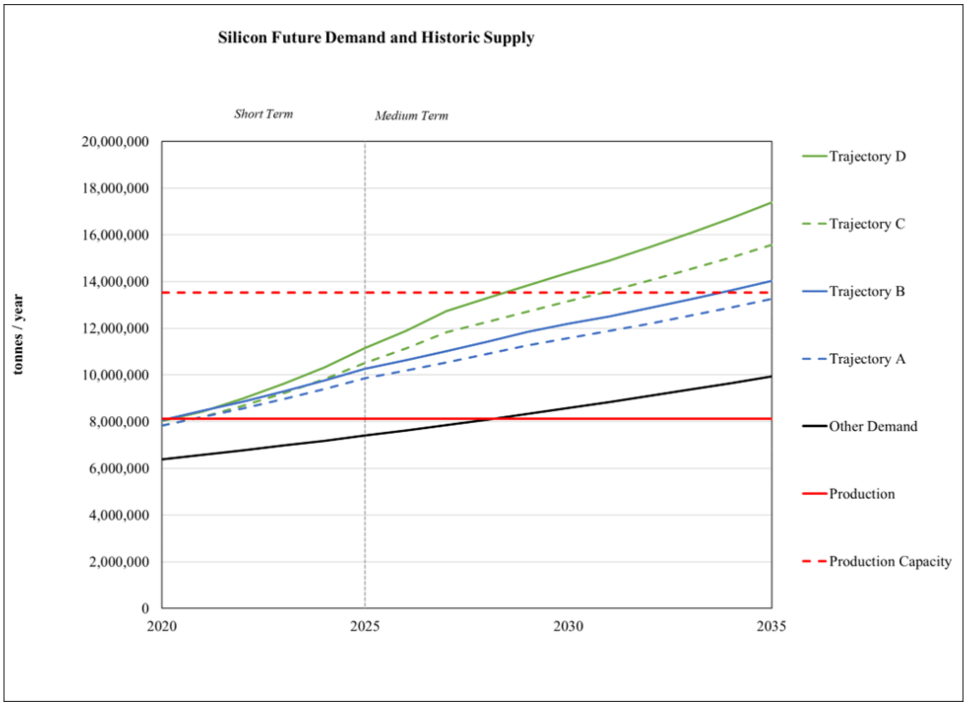

Figure D.18: Silicon demand trajectories, current production, and production capacity

D.19 Silicon carbide

Figure D.19 displays the demand of silicon carbide (SiC) from 2020 to 2035 against current production and production capacity. Different from other materials present in this report, wafer unit instead of mass is used for SiC demand and supply because SiC is an engineered product. As a result, only two trajectories derived from high and low market penetration are presented instead of four. The applications considered for SiC include EV, charging stations, solar, energy storage, rail, motor drive, and wind. The SiC demand utilized in the energy industry on power electronics is 202,801 wafer units in 2020. Trajectory B(A) and D(C) represent SiC demand for high CAGRs of 29% (Chiu and Dogmus, 2022) and a low CAGR of 12% (Technavio, 2023), respectively. Current production was obtained from market reports (Chiu and Dogmus, 2022).

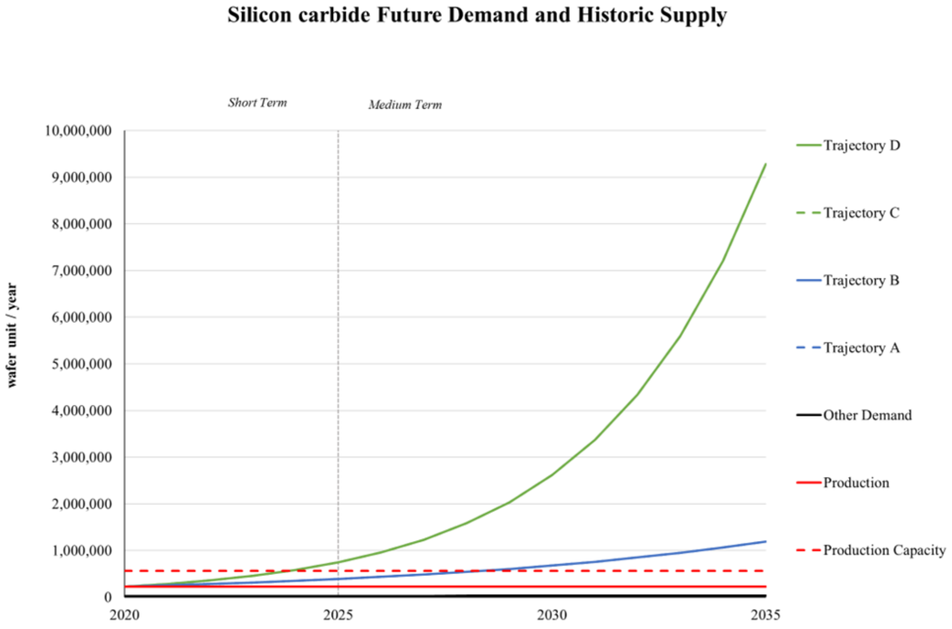

Figure D.19: Silicon carbide demand trajectories, current production, and production capacity

D.20 Tellurium

Figure D.20 displays the demand of tellurium (Te) from 2020 to 2035 against current production and production capacity. The only technology considered for tellurium is cadmium telluride (CdTe) thin-film solar photovoltaic (PV) panel technologies. Tellurium is also used in thermoelectric devices, as a rubber volcanizing agent, and as a catalyst in various chemical industries that make up the non-energy demand portion (USGS, 2022c). The trajectories are defined by the estimated and newly installed solar PV capacity determined from the IEA NZE and STEPS scenario projections, as well as the varied market share of CdTe thin-film solar technologies in the overall solar PV landscape (IEA, 2022b). The tellurium demand of 562 mt/y is assumed to be equivalent to the tellurium supply, as limited data are available on the supply of tellurium. Production capacity is also not reported; therefore, it is assumed that 86% of tellurium that could be recovered is supplied to market, which is consistent with oil and gas resource recovery.

Trajectory A considers the STEPS scenario for solar PV installations with the share of CdTe for newly installed capacity falling from its current 5% to 2% by 2040 at a low material intensity scenario defined further below. Trajectory B considers the STEPS scenario with CdTe rising to 5.5% of new installed capacity with the high material intensity scenario. Trajectory C considers the NZE scenario with the share of CdTe for newly installed capacity falling from its current 5% to 2% by 2040 at a low material intensity scenario. Trajectory D considers the NZE scenario with CdTe rising to 5.5% of new installed capacity with the high material intensity scenario. The two material intensity scenarios are derived from projections provided by the European Commission's Joint Research Center where the material intensity of Te per GW of installed capacity is projected to fall to 20 mt/GW (Alves Dias et al., 2020) in the low case while the high case is assumed as 36 mt/GW as confirmed through personal correspondence with First Solar.

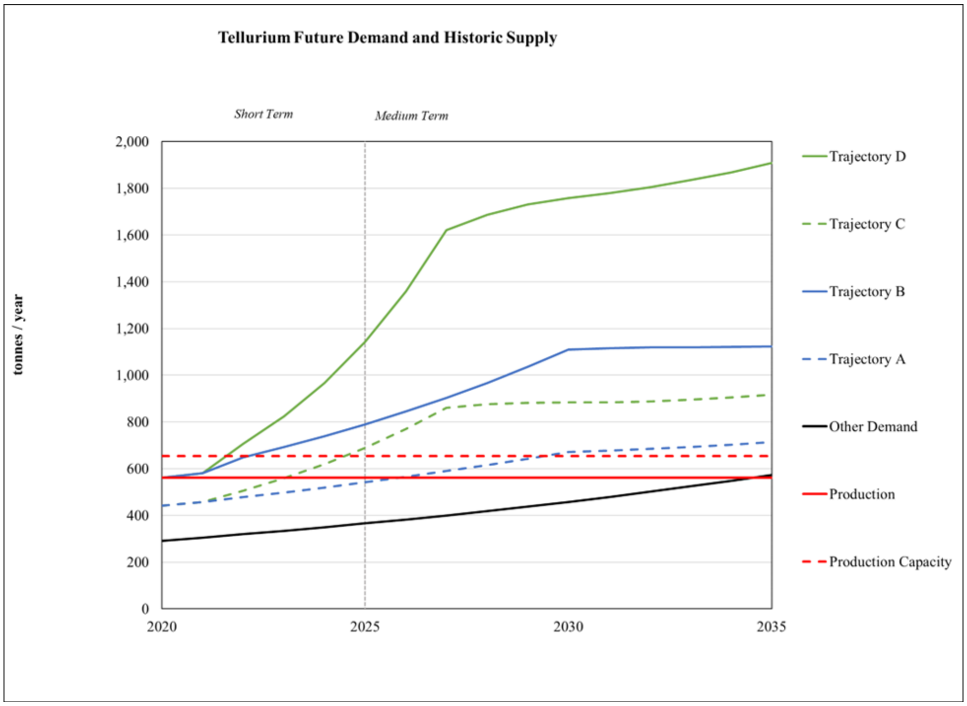

Figure D.20: Tellurium demand trajectories, current production, and production capacity

D.21 Titanium

Figure D.21 displays the demand of titanium (Ti) from 2020 to 2035 against current production and production capacity. The energy technologies considered for Ti were PEM electrolyzers and vehicle lightweighting. We use STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we consider the high and low material intensity of Ti in selected technologies as listed in Appendix B. The non-energy demand curve represents Ti demand for other applications such as aircraft, spacecraft, ships, and gas, and turbine blades. Production was based on 2022 USGS estimates of titanium sponge production and production capacity from the USGS's *Mineral Commodity Summaries 2022*.

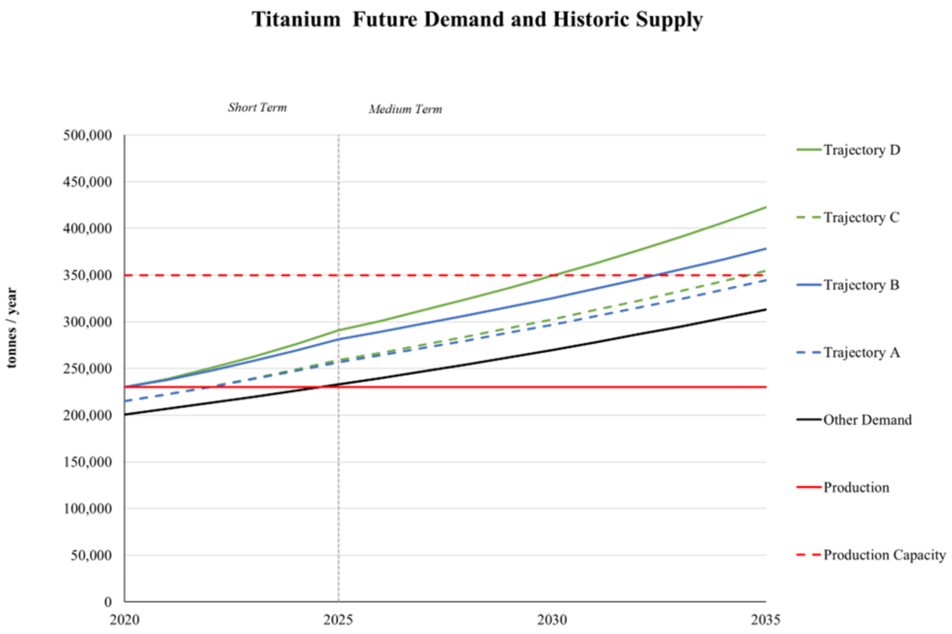

Figure D.21: Titanium demand trajectories, current production, and production capacity

D.22 Uranium

Figure D.22 shows four different demand scenarios for uranium from 2020 to 2035. Two IEA scenarios were utilized to determine the projected nuclear capacity until 2035, including the nuclear fade case (NFC) for low trajectories and the NZE scenario for high trajectories. Additional information on high and low material intensities used to compute each trajectory may be found in Appendix B.

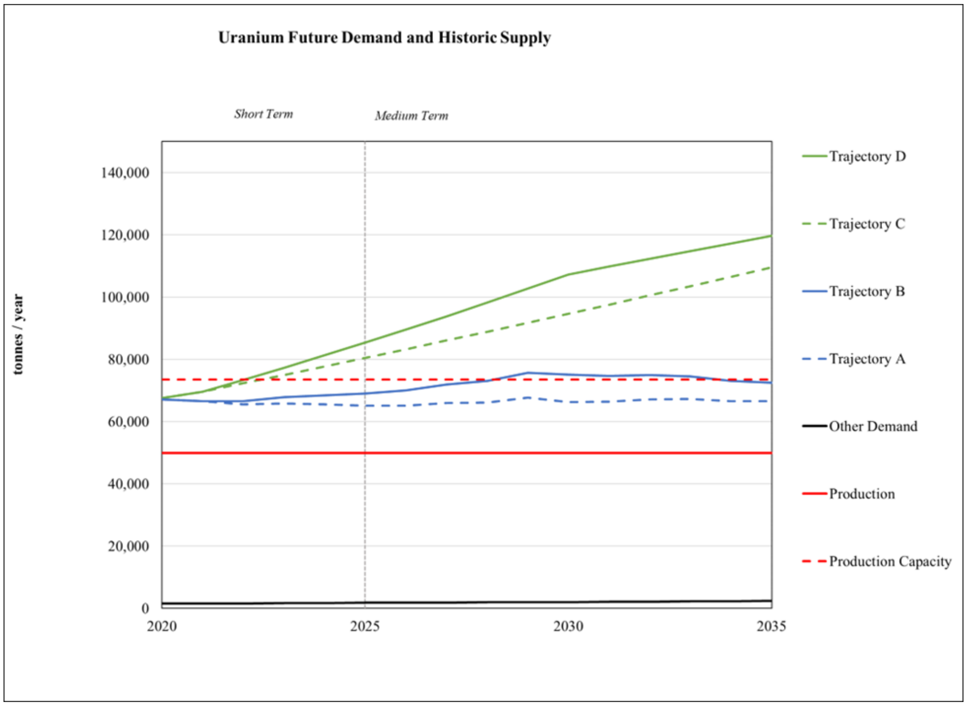

Figure D.22: Uranium demand trajectories, current production, and production capacity

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