Critical Materials Assessment

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Preface

For more than a decade, the U.S. Department of Energy (DOE) has funded basic and applied research and development (R&D) related to critical materials to address the scientific and technological (S&T) challenges that underpin supply chain vulnerabilities. These investments were made possible through the first DOE Critical Materials Strategy in 2010. This included the first DOE Critical Materials Assessment – identifying which materials were critical for clean energy technologies. It also defined the pillars that form the foundation of the DOE research strategy that guided these investments.

The Energy Act of 2020 expanded DOE authorities to address critical materials challenges through a Critical Materials Research, Development, Demonstration, and Commercialization Application (RDD&CA) Program. The Critical Materials RDD&CA Program allows DOE to invest across the entire research continuum and supply chain. Through the Critical Materials RDD&CA Program, DOE implements the DOE Vision and Strategy for Critical Minerals and Materials (CMM):

Vision:

- Develop reliable, resilient, affordable, diverse, sustainable, and **secure domestic critical mineral and materials supply chain**s,
- **support the clean energy transition** and decarbonization of the energy, manufacturing, and transportation economies, and
- **promote** safe, sustainable, economic, and environmentally **just solutions** to meet current and future needs.

Strategy:

- **Diversify & Expand Supply:** Diversify and expand critical mineral and material supply from varying sources while minimizing waste and increasing techno-economic coproduction of materials – to ensure material availability;
- **Develop Alternatives:** Innovate alternative materials and/or manufacturing components – reduce demand and partially offset the need for virgin materials;
- **Materials and Manufacturing Efficiency:** Use and process materials efficiently across the entire supply chain and life cycle – to reduce waste;
- **Circular Economy:** Remanufacture, refurbish, repair, reuse, recycle, and repurpose – to extend the lifetime of materials and partially offset the need for virgin materials;
- **Enabling Activities:** Cross-cutting functions, such as criticality assessments, stockpiling, international engagement, market development, and advanced theoretical, computational, and experimental tools – to accelerate progress.

The 2023 Critical Materials Assessment will enable DOE to set priorities for investments through the Critical Materials RDD&CA, continuing advancements in S&T innovation in combination with expanded focus on de-risking and deploying commercialization technologies to build and transform domestic supply chains.

To learn more about DOE's Critical Materials RDD&CA Program, readers are encourage to visit the following website: https://www.energy.gov/cmm/critical-minerals-materials-program

Acknowledgments

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List of Acronyms and Abbreviations

AC	Alternating current
ADCU	Autonomous driving control unit
AEC	Alkaline electrolyzer
AEMEC	Anion exchange membrane electrolyzer
AFC	Alkaline fuel cells
Ag	Silver
AGR	Advanced gas-cooled reactor
AHSS	Advanced high-strength steel
Al	Aluminum
AlGaAs	Aluminum gallium arsenide
AlGaInP	Aluminum gallium indium phosphide
AlNiCo	Aluminum nickel cobalt
APS	Announced Pledged Scenarios
B	Boron
BAU	Business-as-usual
BEV	Battery-powered electric vehicle
BLDC	Brushless direct current
BWR	Boiling water reactor
CAGR	Compound Annual Growth Rate
CANDU	Canadian heavy water reactor
CCUS	Carbon capture, utilization, and storage
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CLED	Carbon-dot light-emitting diode
CM	Critical materials
CMA	Critical Materials Assessment
CMS	Critical Materials Strategy
Co	Cobalt
CO	Carbon monoxide
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 2019

CTC	Continuously transposed copper
Cu	Copper
CZTS	Copper zinc tin sulfide
DC	Direct current
DFIG	Doubly fed induction generator
DOE	U.S. Department of Energy
DRC	Democratic Republic of the Congo
DRI	Direct reduction of iron
DSSC	Dye sensitized solar cell
Dy	Dysprosium
EESG	Electrically excited synchronous generator
EIA	U.S. Energy Information Administration
EO	Executive Order
EPA	U.S. Environmental Protection Agency
ES	Electrical steel
EU	European Union
EV	Electric vehicle
F	Fluorine
FBR	Fast breeder reactor
FCEV	Fuel-cell electric vehicle
Fe	Iron
Ga	Gallium
GaAs	Gallium arsenide
GaAsP	Gallium arsenide phosphide
GaInP	Gallium indium phosphide
GaN	Gallium nitride
GaP	Gallium phosphide
GCR	Gas-cooled reactor
GDP	Gross domestic product
Ge	Germanium
GE	General Electric
GOES	Grain-oriented electrical steel

GW	Gigawatt
GWe	Gigawatt-electric
HALEU	High-assay low-enriched uranium
HDV	Heavy-duty vehicle
HEV	Hybrid electric vehicle
HHI	Herfindahl-Hirschman Index
HTGR	High-temperature gas-cooled reactor
HVAC	High voltage alternating current
HVDC	High voltage direct current
Hz	Hertz
IAEA	International Atomic Energy Agency
IC	Integrated circuit
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
ICFB	Iron-chromium flow battery
ICFV	Iron-chromium flow battery
IEA	International Energy Agency
IGBT	Insulated-gate bipolar transistor
IGCT	Integrated gate-commutated thyristor
In	Indium
InGaN	Indium gallium nitride
IPM	Internal permanent magnet motor
Ir	Iridium
IRENA	International Renewable Energy Agency
kt	Kilo metric tons
La	Lanthanum
LCC	Line-commutated converter
LCOS	Levelized cost of storage
LDV	Light-duty vehicle
LED	Light-emitting diode
LFP	Lithium iron phosphate
Li	Lithium

Li-ion, LIB	Lithium-ion battery
Li-Fi	Light Fidelity
LMFP	Lithium manganese iron phosphate
LMO	Lithium-ion manganese oxide
LMP	Lithium-metal polymer
LNMO	Lithium nickel manganese oxide
LPT	Large power transformer
LREE	Light rare earth element
LVDT	Low-voltage dry-type
LWGR	Light water graphite-moderated reactor
LWR	Light water reactor
MCFC	Molten carbonate fuel cell
MMC	Modular multilevel converter
Mg	Magnesium
Mn	Manganese
MREO	Mixed rare earth oxides
MOCVD	Metal organic chemical vapor deposition
MOSFET	Metal-oxide-semiconductor field-effect transistor
MOX	Mixed oxide fuel
MPPT	Maximum power point trackers
MSR	Molten salt reactor
Mt	Million metric tons
mt	Metric ton
MVA	Megavolt amperes
MVDT	Medium-voltage dry-type
Na	Sodium
NaS	Sodium sulfur
NAS	National Academy of Sciences
NCA	Nickel cobalt aluminum
Nd	Neodymium
NdFeB	Neodymium iron boron (magnet)
NFC	Nuclear Fade Case

Ni	Nickel
NiMH	Nickel metal hydride
NMC	Nickel manganese cobalt
NOES	Non-grain-oriented electrical steel
NRC	U.S. Nuclear Regulatory Council
NZE	Net-Zero Emissions
OBC	Onboard charger
OEM	Original equipment manufacturer
OLED	Organic light-emitting diode
P	Phosphorous
PAFC	Phosphoric acid fuel cell
Pd	Palladium
PEM	Polymer electrolyte membrane
PEMFC	Polymer electrolyte membrane fuel cell
PEMEC	Proton exchange membrane electrolyzer
PFAS	Polyfluoroalkyl substance
PFSA	Perfluorosulfonic acid
PGM	Platinum group metal
PHEV	Plug-in hybrid electric vehicle
PHWR	Pressurized heavy water reactor
PM	Particulate matter
PMSG	Permanent-magnet synchronous generator
PMSM	Permanent-magnet synchronous motor
PWR	Pressurized water reactor
Pr	Praseodymium
PRS	Political, Regulatory and Social factors
Pt	Platinum
PV	Photovoltaic
QLED	Quantum-dot light emitting diode
RD&D	Research, development and deployment
RE	Rare earth
REMADE	Reducing embodied energy and decreasing emissions

REMIX	Regenerated mixture fuel
REPM	Rare earth permanent magnet
Rh	Rhodium
S	Sulfur
SDS	Sustainable Development Scenario
SF6	Sulfur hexafluoride
Si	Silicon
SiC	Silicon carbide
SMR	Steam methane reforming
SMR	Small modular reactor
SOEC	Solid oxide electrolyzer cell
SOFC	Solid oxide fuel cell
Sr	Strontium
SRM	Switched reluctance motor
SSL	Solid-state lighting
STEPS	Stated Policies Scenario
SWU	Separative work unit
Tb	Terbium
Te	Tellurium
Ti	Titanium
TRISO	TRi-structural ISOtropic particle fuel
TWh	Terawatt-hour
U	Uranium
UF6	Uranium hexafluoride
UHSS	Ultra high-strength steel
UO_2	Uranium dioxide
UO_3	Uranium trioxide
UPS	Uninterrupted power supply
U.S.	United States of America
USGS	U.S. Geological Survey
V	Vanadium
VOC	Volatile organic compound

VRFB	Vanadium redox flow battery
VSC	Voltage source converter
WGI	World Governance Indicator
Y	Yttrium
ZBFB	Zinc-bromine flow battery
Zn	Zinc
Zircaloy	Zirconium alloy
Zr	Zirconium

Executive Summary

The global effort to curb carbon emissions is accelerating demand for clean energy technologies and the materials they rely on. Demand for these materials will only continue to grow, especially as some nations aim to achieve net-zero emissions by 2050. While some major materials like steel, copper, and aluminum are already powering the fossil fuel economy, others are more minor materials with potential supply risks. These risks could jeopardize the ability to reduce greenhouse gas emissions within the desirable timeframe to avoid significant climate change. In some cases, it may be necessary to take action to improve the resilience of these material supply chains and mitigate supply risks. Understanding the importance of individual materials to clean energy and the supply risks associated with them is necessary to identifying which materials may serve as potential roadblocks to a clean energy future.

The U.S. Department of Energy (DOE) issued a series of 13 “supply chain deep dive” assessment reports related to the supply chains supporting various energy technologies in 2022 in response to President Biden’s Executive Order on America’s Supply Chains (E.O. 14017). These reports emphasized that supply chain bottlenecks can occur at any stage of the value chain ― from mining and refining to component and even subsystem manufacturing. The bottlenecks result from a combination of factors such as material availability, equipment availability, workforce availability and quality, logistics, regulatory frameworks, and market conditions. These bottlenecks were worsened during the global Covid-19 pandemic. Its lingering impacts have hindered capacity expansion for material supply chains and prevented product lead-time recovery. One approach to reduce supply chain risks for the United States is to have a strong domestic manufacturing sector with a diverse set of producers. Boosting responsible domestic production would require leveraging the latest science not only in material extraction but also in developing substitutes and fostering recycling, reuse, and remanufacturing.

This report is an updated analysis of previous Critical Materials Strategy (CMS) reports published by the DOE in 2010, 2011, and 2019 based on national and global priorities, technology advancement, and technology adoption trends. Like the CMS reports, this analysis presents the results of a formal material criticality assessment to identify which materials are critical to the continued worldwide deployment of clean energy technologies. The analysis in this report leveraged the DOE supply chain deep-dive assessments to develop the initial list of materials to evaluate.

This report includes engineered materials that were identified as bottlenecks for clean energy deployment in DOE’s deep-dive assessments, namely silicon carbide (SiC) and electrical steel. The use of SiC in power electronics has become more significant, particularly for electric vehicle (EV) inverters. While expansion of SiC wafer manufacturing capacity seems able to keep up with demand, low yield and high cost are key constraints on growth. In addition to engineered materials, this assessment considers a larger set of materials and technologies than previous CMS reports and introduces a formal screening methodology to determine which materials to include in the criticality assessment.

This DOE Critical Materials Assessment (CMA) has been conducted independently of criticality assessments performed by other U.S. government agencies, such as that conducted by the U.S. Geological Survey. This analysis complements the USGS critical minerals determination in three aspects. First, the DOE assessment is performed from a global perspective, whereas the USGS analysis focuses on the importance of minerals to the U.S. economy. Second, this report focuses on the importance of materials to clean energy technologies, rather than to the economy in general. Last, this study is forward looking to 2035 based on clean energy deployment scenarios, whereas the USGS assessment is retrospective. Materials evaluated in this report that do not appear

in the USGS's U.S. Critical Minerals List include copper, uranium, electrical steel, and SiC. A draft version of this report received ~80 public comments related to supporting data and methodological improvement. Those comments have been incorporated as much as possible where appropriate.

Highlights of findings from this 2023 CMA include the following:

- Rare earth materials (neodymium [Nd], praseodymium [Pr], dysprosium [Dy], and terbium [Tb]) used in magnets in EV motors and wind turbine generators continue to be critical. While Dy and Tb are both heavy rare earth elements that serve the same function in magnets, the criticality of Tb is slightly lower than that for Dy in the short term due to the widespread use of Dy in high-grade magnets and Tb's present role as a substitute. Similarly, Pr is critical in the medium term but only near critical in the short term because it is more substitutable in magnets than Nd.
- Materials used in batteries for EVs and stationary storage are now considered to be critical. While cobalt (Co) was found to be critical in this and previous reports, lithium (Li) becomes critical in the medium term due to its broader use in various battery chemistries and the rampant growth of the EV industry. Natural graphite is a new addition in this assessment and is also found to be critical.
- Platinum group metals used in hydrogen electrolyzers, such as platinum (Pr) and iridium (Ir), are critical due to an increased focus on hydrogen technologies to achieve net-zero carbon emissions, whereas those used in catalytic converters, such as rhodium (Rh) and palladium (Pd), were screened out due to the decreased importance of catalytic converters in the medium term.
- Gallium (Ga) continues to be critical due to its use in light-emitting diodes (LEDs). In addition, the use of Ga has increased in magnet manufacturing and in semiconductors in forms such as gallium arsenide (GaAs) or gallium nitride (GaN).
- Major materials like aluminum (Al), copper (Cu), nickel (Ni), and silicon (Si) move from noncritical in the short term to near critical in the medium term due to their importance in electrification.
- Electrical steel is near critical due to its use in transformers for the grid and electric motors in EVs.

Market Evolution since the 2019 Critical Materials Strategy Report

The 2019 CMS report found seven materials to be critical in the medium term (2020–2030), including neodymium, dysprosium, rhodium, gallium, lithium, cobalt, and magnesium (Mg). These materials are used in magnets, batteries, vehicles, and lighting phosphors. Although palladium was found to be near critical in 2019, it is not included in the current assessment. Since 2019, significant market developments have shifted the picture for material criticality. Following are highlights:

The world has witnessed a global surge in adoption of EVs, resulting in increased demand for vital components like lithium-ion batteries, rare earth magnets, electrical steel, and power electronics. Global EV sales increased from 716,000 vehicles in 2015 to 10.6 million vehicles in 2022. China has been at the forefront of this growth, accounting for 60% of the new EV registrations worldwide in 2022, encompassing various vehicle types such as cars, trucks, vans, and buses. The swift growth in EV sales has resulted in increased demand for vital components such as lithium-ion batteries, rare earth magnets, electrical steel in both motors and charging infrastructure, and power electronics. Manufacturers are under significant pressure to ensure availability of these components.

Doubling of offshore wind capacity leads to compounded demand for rare earth magnets. Although offshore wind accounted for less than 7% of global wind capacity in 2022, its growth from 27 gigawatts (GW) in 2019 to 56 GW in 2021 drove the technology's demand share for rare earth magnets. Annual installations grew from 6.2 GW in 2019 to 21.1 GW in 2021. New installations will continue to grow fivefold to sevenfold between

2021 and 2035 depending on low and high deployment scenarios according to International Energy Agency's projection. This growth is due to the deployment of direct-drive turbines that use rare earth magnets to reduce weight and maintenance needs for wind turbines in offshore settings.

Grid stationary storage is growing quickly but needs to increase significantly to reach net-zero emissions (NZE) goals. Deployment is bottlenecked by lithium, nickel, and graphite supplies. From 2019 to 2021, the global installed capacity of grid-scale battery storage grew from 6 GW to 16 GW. A significant expansion in stationary storage, reaching up to 680 GW by 2030, necessitates an average annual addition of about 80 GW. Currently, lithium-ion batteries, especially lithium-iron-phosphate (LFP), dominate the stationary storage market, but flow batteries show potential for competitiveness as the technology matures, potentially reaching 50% of demand capacity by 2030. As redox flow batteries and alternative technologies gain traction, this dependence is expected to become less of an issue for stationary storage.

Global hydrogen demand is expected to increase, leading to a concurrent rise in demand for iridium and platinum in electrolyzers. Historically, hydrogen use has been concentrated in the chemical, refining, and steel industries. In 2021, global hydrogen consumption was 94 million tonnes (Mt). Hydrogen demand is expected to grow in three main areas: (1) decarbonization of long-distance heavy- and medium-duty trucks, air, and marine transport; (2) applications requiring stationary storage; and (3) applications requiring high-temperature heat generation and chemical production, specifically to produce low-carbon ammonia, methanol, and various other chemicals.

Silicon-based power electronics currently dominate the power electronics market but silicon carbide (SiC) and gallium nitride (GaN) are expected to grow significantly. Silicon-based power electronics currently dominate the market, accounting for 96% of the market share by value in 2022 due to their lower production costs and mature technologies. However, the market share of silicon power electronics is expected to decline, reaching 80% by 2028. SiC is projected to reach a 17% market share by 2028, driven primarily by its use in EVs for inverters and charging infrastructure. GaN, while growing in use for consumer electronics and communications, is limited to niche applications due to its higher cost.

The demand for electrical steel has increased due to the need for electric grid expansion and modernization as well as use in EV motors and charging infrastructure. The global power grid market was valued at $271.43B in 2022. This market will grow to reach $414.91B by 2032. There are two key driving factors for the electric grid market. First, renewable energy growth has led to an increase in smaller-scale power plants and distributed grids closer to end users. Renewable energy integration also requires grid expansion and modernization with added sensors, automation systems, and analytical tools to manage energy in real time. Second, demand from manufacturing, health care, and data centers is increasing as a result of urbanization and industrialization. Electrical steel used in EVs requires a higher grade than that used in industrial motors and other automotive motors. Concerns arise related to slow and expensive capacity expansion for EV-grade electrical steel on a global basis.

Light-emitting diodes (LEDs) now dominate more than 50% of the global lighting market share. Traditional lighting sources such as fluorescent, incandescent, and high-intensity discharge lamps are being replaced by LEDs due to their superior performance in terms of energy efficiency, lifespan, versatility, and color quality, as well as reductions in their production costs. Globally, LEDs accounted for more than 50% of the lighting market share in 2020 and 2021. In addition to general lighting, Also gaining in popularity are LED grow lights for indoor farming and advanced lighting systems in automobiles to improve safety and riding experience.

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.

Crystalline silicon remains the dominant technology in the photovoltaic market due to its well-established status and lower production costs. Solar photovoltaics (PVs) currently contribute 3.6% of global electricity generation and 4.5% of U.S. generation. To achieve net-zero carbon emission goals, the share of solar energy supply needs to reach 23% globally and approximately 45% in the United States by 2050. Si-based PV accounted for ~88% of global market share by value in 2021, followed by thin-film PV (9% market share), and others (3% market share). Cadmium-telluride (CdTe) thin-film solar PV is currently accounting for a significant portion of new utility-scale solar projects in the United States but remains around 5% globally, while global production of copper-indium-gallium-selenide (CIGS) has halted.

2023 Criticality Assessment

This assessment uses updated analyses based on national and global priorities, technology advancement, and technology adoption trends. It considers 38 materials used by eight major technologies, of which 23 materials are evaluated for criticality after a screening process. There are three main differences in this report compared to previous versions. First, the definition of materials has been extended from only raw minerals to include a number of engineered materials such as electrical steel and silicon carbide. Second, this assessment introduces a screening process to provide a more selective set of materials and technologies to be assessed for criticality. Last, it introduces a formal scoring rubric with defined thresholds and logic to ensure consistency when scoring each material across several factors.

This report serves as a complementary analysis to other criticality assessments conducted by the U.S. government, such as those conducted by the U.S. Department of the Interior (specifically, USGS). While these assessments differ in scope, approach, and purpose from DOE’s critical material assessments, they provide valuable insights into ensuring secure and reliable supplies of critical minerals. This 2023 report focuses specifically on the potential growth in global demand for these materials in energy technologies, with a narrower focus on key materials that are integral to clean energy technologies with high growth potential. The collaborative nature of these assessments across the U.S. government has played a significant role in shaping the scope and data provided in this report.

Similar to the previous CMS reports, this report evaluates the criticality of materials based on their importance to the energy sector and supply risk. The analysis identifies seven materials, namely dysprosium, neodymium, gallium, graphite, cobalt, terbium, and iridium, as critical in the short term (2020–2025; see Figure ES.1). These materials are used in various applications such as magnets, batteries, LEDs, hydrogen electrolyzers, fuel cells, and power electronics. Additionally, lithium, uranium, electrical steel, nickel, magnesium, SiC, fluorine, praseodymium, and platinum are classified as near critical in the short term. Over the medium term (2025–2035; see Figure ES.2), the importance and supply risk scores for certain materials shift. Specifically, nickel, platinum, magnesium, SiC, and praseodymium become critical, primarily due to their roles in batteries and vehicle lightweighting. Aluminum, copper, and silicon become near critical in the medium term due to increased demand in solar energy technologies, global electrification, and vehicle lightweighting.

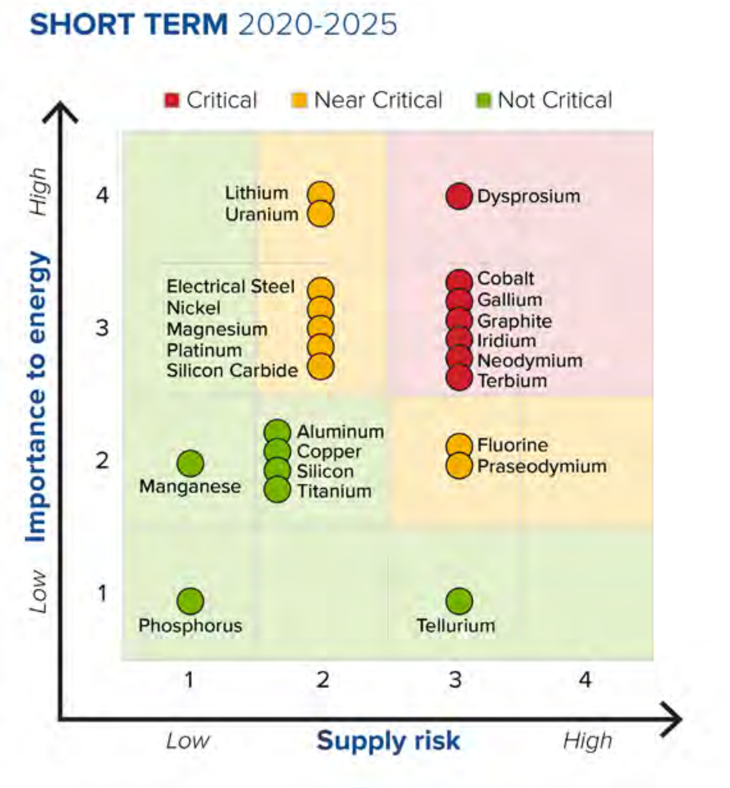

Figure ES.1. Short-term (2020–2025) criticality matrix

Figure ES.2. Medium-term (2025–2035) criticality matrix

Implications and Next Steps

This 2023 CMA serves as the fourth update to DOE's long-standing CMS reports, the first of which was released in 2010. It aims to serve as a guide to the department in prioritizing research, development, and deployment (RD&D) strategies by providing an analysis of the materials most critical to securing a decarbonized clean energy future. This version incorporates a number of notable changes from the previous CMS reports. Leveraging findings from DOE's 2022 supply chain deep-dive reports, this assessment evaluates a much longer initial list of materials, including a number of engineered materials in addition to natural materials. It also introduces a screening methodology to develop a list of key materials to be evaluated for criticality and a formal scoring rubric for the criticality assessment with defined thresholds and logic.

In total, the assessment evaluates an initial list of 38 materials essential to clean energy technologies, 23 of which are evaluated for their criticality after passing the initial screening. Of those, seven are found to be critical for clean energy in the short term, while 13 are found to be critical in the medium term. As the energy sector continues to decarbonize, the list of potential materials essential to clean energy technologies will only increase.

Due to the dynamic nature of material criticality, DOE plans to update the assessment in approximately three years. The update will reflect market conditions, technology advancement, technology adoption trends, production capacity, and the global policy landscape. The update will also help evaluate the effectiveness of DOE's existing RD&D strategy and potential focus areas for future strategy. Inputs from the public and other similar reports will continue to be leveraged for report quality improvement.

It is important to note that while some materials might not be deemed critical in this assessment, certain value chain steps might have bottlenecks that were not examined closely in this report. This limitation is because the scope of this assessment is meant to be broad rather than deep when evaluating criticality among diverse materials using a common framework. DOE will continue to perform deep-dive supply chain studies to provide insights on vulnerabilities across specific supply chains and will use these to inform future assessments.

By taking a global perspective and forward-looking approach, this study outlines four possible trajectories for material demand based on high and low deployment scenarios and material intensities. The criticality of most materials in this analysis is due to high deployment trajectories and high material intensities. As clean energy continues to be deployed globally, future RD&D efforts will focus on reducing material intensity, increasing manufacturing efficiency, improving recycling rates and efficiency, finding better substitutes, and enhancing primary production efficiency. DOE's strategic framework will continue to focus on five pillars: (1) diversify and expand supply from primary sources; (2) develop alternative materials and systems; (3) enhance material and manufacturing efficiency; (4) promote a circular economy through recycling, reuse, and remanufacturing; and (5) use analyses to enable and speed up science discoveries. For each of the critical materials (CMs) identified in this report, DOE will develop an integrated strategy to address material-specific risks. Ultimately, addressing material criticality in the present will help ensure that a clean energy future is possible for decades to come.

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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 of critical infrastructure with national security importance such as energy, communications, transportation, and water systems. 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 concerns about material availability (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.

In 2010, the U.S. Department of Energy (DOE) established a methodology to assess material criticality based on the potential for supply risk for a range of energy technologies, resulting in DOE's *2010 Critical Materials Strategy* (CMS) (DOE, 2010). The assessments were updated in 2011 (DOE, 2011) and 2019 (DOE, 2019). Section 7002(a)(2) of the Energy Act of 2020 (codified at 30 U.S.C. § 1606(a)(2)) authorized the Secretary of Energy to determine critical materials. According to Consolidated Appropriations Act, 2021, Public Law 116-260 (Dec. 27, 2020), Div. Z, Title VII (Congress, 2020), the statutory definition of a "critical material" is:

- Any nonfuel mineral, element, substance, or material that the Secretary of Energy determines:
  - Has high risk for supply chain disruption; and
  - 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](USGS, 2022a).

This statutory definition is consistent with DOE's long-standing methodology to assess material criticality based on *importance to energy* applications and potential for *supply risk*. This CMA report continues DOE's systemic analyses of materials criticality, in part to inform the critical materials determination under the Energy Act of 2020.

One of the two defining factors of the methodology applied in this assessment is "importance to energy." For the purposes of this assessment, DOE interprets energy technologies to be "clean energy" technologies in alignment with the DOE Critical Minerals and Materials Vision and Strategy (DOE, n.d.-b). The anticipated unprecedented increase in demand for critical minerals and materials is driven by the global deployment of clean energy technologies to achieve net-zero emissions (NZE) goals by 2050. The International Energy Agency (IEA) estimated that the demand for critical minerals and material will increase by between 400% and 600% by 2040 to achieve these goals (IEA, 2021b). The specific energy technologies considered in this assessment are described in Chapter 2 of this report and are aligned with the technologies that DOE assessed as part of "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" (Office of Policy, 2022).

Material criticality assessments have also been conducted by other organizations, both within the United States and in other countries. For example, the 2022 *U.S. Critical Minerals List* produced by the U.S. Geological Survey (USGS) evaluates the criticality of minerals based on *economic vulnerability* and *disruption potential* to the United States using historical data from 2018 to 2021 (Nassar & Fortier, 2021; USGS, 2022a). The critical raw material assessment conducted by the European Union (EU) considers *non-energy raw materials* for *economic importance* and *supply risk* to EU countries for the 2016–2020 period (Grohol & Veeh, 2023).

While similar, the DOE assessments differ in several ways. Namely, they are focused specifically on the importance of materials to energy and decarbonization technologies and are performed with an eye to the future. 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 (5–15 years). These trajectories are also global rather than focused only on demand in the United States, accounting for policies of Asian and European countries related to emission goals. Because the United States is part of the global market and supply chains, considering global context helps DOE better understand the competition for materials among countries. With this global perspective, this particular assessment will not dive deeply into trade relations between the United States and other countries, U.S. permitting issues in mining, or U.S. levels of import reliance. Finally, a unique feature of this assessment is that it incorporates selected engineered materials in addition to natural raw materials to address some supply chain bottlenecks that were highlighted in the 2022 DOE supply chain deep-dive assessments for various clean energy technologies in response to Executive Order 14017 (Office of Policy, 2022).

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 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 research, development, and deployment (RD&D) investments and policy engagement. By anticipating criticality, DOE can proactively reduce medium- and long-term material criticality by investing in RD&D that reduces the reliance of energy technologies on critical materials and promotes the diversification of material supply.

This report contains six 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 gives a brief description of technologies and associated materials considered in this report as listed in Table 1.1. Chapter 3 discusses the method for screening and selecting key materials to be evaluated in the overall material criticality assessment. Chapter 4 describes demand trajectories and current production along with the production capacity of each key material that passed the screening in Chapter 3. Chapter 5 details the criticality assessment methodology and discusses the results of the analysis. Chapter 6 concludes the analysis with a discussion on future RD&D strategies.

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 market shares of sub-technologies and calculation of 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.

1.1 Scope and Assessment Process

As in previous reports, this report is global in scope and presents material criticality assessments for both the short term (0–5 years) and the medium term (5–15 years). In addition, this CMA introduces a number of key differences from the criticality assessments conducted in the previous DOE CMS 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 a material's importance to energy and supply risk. In 2022, DOE released 13 reports as part of its one-year response to President Biden's Executive Order on America's Supply Chains (E.O. 14017). These "supply chain deep dive" reports evaluate the potential vulnerabilities of 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 dive reports, 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), the electric grid including transformers and high-voltage direct current (DC) transmission (Nguyen et al., 2022), energy storage (Mann et al., 2022), fuel cells and electrolyzers (Badgett et al., 2022), hydropower including pumped storage hydropower (Uría-Martínez, 2022), rare earth (RE) magnets (Smith, Riddle, et al., 2022), nuclear energy (Finan et al., 2022), platinum group metal catalysts (Smith, Graziano, et al., 2022), semiconductors (Mann & Putsche, 2022), solar photovoltaics (PVs) (DOE, 2022a), and wind energy (Baranowski et al., 2022). The initial list of materials was further refined after consultation with experts from various DOE offices. The full list of materials evaluated includes 38 materials along with their technologies, as shown in Table 1.1.

The set of materials evaluated includes aluminum (Al), boron (B), cobalt (Co), copper (Cu), dysprosium (Dy), electrical steel (ES), 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), terbium (Tb), titanium (Ti), uranium[1] (U), vanadium (V), yttrium (Y), zinc (Zn), and zirconium (Zr). This set of materials excludes indirect materials that are used in manufacturing processes but that do not contribute to the physical composition of components or final products. For example, helium is used in cooling, cleaning, and creating an inert environment for semiconductors, but it is not a physical constituent of semiconductors. While a disruption in the helium supply chain can impact semiconductor production, the scope of this assessment does not extend to indirect materials.

Notably, this set of materials includes a limited set of engineered materials, including electrical steel, gallium nitride, and silicon carbide. This set of engineered materials was selected based on two factors: (1) they were found to have high potential for supply risk in the supply chain deep-dive reports and (2) the elements comprising the engineered materials (such as iron for electrical steel) were unlikely to be found critical on their own, potentially understating the risk posed to deploying energy technologies. There are four main categories

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[1] 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 decision-making, this report has analyzed uranium, including based on its fuel uses, under the same methodology used for other materials.

of energy applications considered in this report, including (1) generation, (2) transmission and distribution, (3) storage, and (4) end-use applications with a focus on decarbonization and energy efficiency.

Table 1.1. Technologies and materials considered in this report.

Energy Application Categories	Technology	Components/ Sub-technology	Materials
Transmission and distribution	HVDC*	Converters, transformers, breakers, and switches	Cu, Ge, Ni, electrical steel, SiC
	HVAC*	Transformers	Cu, electrical steel
Generation	Nuclear	Fuels, moderators	U, Zr, natural graphite, electrical steel
	Solar	PVs	Si, Te, Ga, In
	Wind	Off-shore	Cu, Nd, Pr, Dy, Tb, B, Ga, 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, Tb, B, Fe, Ga
		Batteries	Li, Ni, Mn, Co, graphite, Al, Fe, P, LREEs*
		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, Riddle, et al., 2022), 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 IEA reported that increased fuel prices were responsible for 90% of increased average generation costs for electricity on a global basis (IEA, 2022i). 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, 2022i). 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, 2023b). 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, 2023b). 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 (Li-ion) batteries (or LIBs) and neodymium-iron-boron (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 (i.e., by 35%) and is expected to grow another 12% by 2026 (Czerwinski, 2021). Additionally, high-strength steel alloys are increasingly becoming an integral part of lightweighting of vehicles. In 2021, the average vehicle contained 65% steel, up 5% since 2010 (Hu & 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.

EV sales projected to increase 30–35% among passenger vehicles by 2030 as consumer preferences are expected to shift from ICE vehicles (ICEVs) to EVs; thus, the need for EV lightweighting is expected to grow over the coming years as well (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 ICEVs 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).

Although the EV industry has been adopting and will continue to adopt these technologies, 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 ICEV 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 EVs' 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 added expense. In the fourth quarter 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, 2023a), 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 gigawatt (GW) in 2017 to 93.6 GW in 2021 (GWEC, 2022). 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 (GWEC, 2022; Musial et al., 2022). 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, 2022).

1.2.5 Fuel Cells in Vehicles

Manufacturing and demand for fuel-cell electric vehicles (FCEVs) have 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, 2023a). With higher energy density per weight than batteries, FCEVs can provide the benefits of longer distances between fueling and faster fueling times than EVs of comparable vehicle type. Several countries (e.g., United States, Korea Japan, EU countries) (Asif & Schmidt, 2021; Ko & Shin, 2023) 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 research and development (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 Stationary Storage

The global capacity of installed grid-scale battery storage 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, 2023c). The market will expand at an average annual rate of 29% in the short to medium term up to 2030 (Colthorpe, 2022; IEA, 2023c). However, to meet the ambitious net-zero carbon emissions goals, stationary storage will need to grow by more than 40-fold globally, or up to 680 GW by 2030, requiring average annual additions of about 80 GW (IEA, 2023c). 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 their energy density and cost advantages (Blair et al., 2022; DOE, 2020). 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 megawatt [MW]) vanadium redox flow battery was recently commissioned in 2022 in China (CNESA, 2022). The primary bottleneck for the current battery technology mix remains lithium supply, of which demand is expected to grow by an order of magnitude for the combined EV and stationary storage market by 2030 (IEA, 2023c). 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 metric tons (Mt) (IEA, 2022d). 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 through 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 (TechSci Research, 2022). Globally, LEDs accounted for more than 50% of the lighting market share in 2020 and 2021 (IEA, 2023d). Smart or connected lighting systems in buildings such as business offices, hospitality venues, and industrial sites are growing (TechSci Research, 2022). In addition to general lighting, LEDs are gaining in popularity as grow lights for indoor farming and advanced lighting systems in automobiles to improve safety and riding experience (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 (TechSci 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, 2022b).

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, 2022i) 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, 2022). Despite early market growth in the early 2000s of thin-film solar technologies such as copper-indium-gallium-selenide (CIGS) and cadmium telluride (CdTe) solar cells, market share of thin-film solar cells has declined since that time period (Lee & Ebong, 2017). By 2009, thin-film technology represented 17% of the global solar market, then decreased to 7–8% by 2014 (Lee & Ebong, 2017), and finally plateaued in the ~5–10% range by 2021 (Chowdhury et al., 2020; Efaz et al., 2021; Kim et al., 2021). Of the latest total global solar market, CIGS represented only ~2% of the total solar market (Efaz et al., 2021; Kim et al., 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, 2021b; Solar Energy Technologies Office, 2023).

CdTe thin-film PVs have gained in 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 (U.S. Manufacturing of Advanced Cadmium Telluride Photovoltaics Consortium, 2022). In the United States, CdTe accounts for 40% of the utility-scale market today (Kennedy, 2022). This result is partially due to the antidumping investigation led by the U.S. Department of Commerce that reduced the availability of non-crystalline PV technologies. It was determined that some companies avoided U.S. tariffs on silicon PV by exporting Chinese components to non-tariffed countries like Malaysia, Thailand, Cambodia, and Vietnam (Swanson & 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 in transformers, non-grain-oriented steel (NOES) is typically used in 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 et al., 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 Mt of produced NOES were xEV grade, which caused concern for the automotive sector as EV demand is expected to grow significantly until 2030 (Vittori et al., 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).

In addition to the conventional iron-silicon alloys, amorphous steel is a newer soft magnetic material that has high resistivity, leading to lower energy losses of up to 70% (Metglas Inc., n.d.) at very high frequencies. While it has great potential for both motors and transformers, its main application today is in transformers due to energy efficiency. Amorphous steel made up had a 4.5% share ($2.2B) of global market for soft magnet technologies in 2018 (Eckard, 2020). Its market value is expected to reach $5.4B in 2024. Due to the importance of conventional electrical steel and amorphous steel to the electric grid, both material forms are included in this report under one category of electrical steel. This material category is one of the few engineered materials included in this report for criticality assessment that has not been included in previous reports.

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 & 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). As in 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 & 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%.

SiC and 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 & 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 & 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 (Chiu & Dogmus, 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 & 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™ technology has been used in SiC wafer manufacturing to improve yield (Rosina & 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 Energy Technology Applications of Considered Materials

This chapter provides a brief description of the technologies and associated materials considered in this report as listed in Table 1.1. The goal of this chapter is to explain why these technologies and materials are important as well as how they are used to maintain modern life. Each section provides background information on the importance of each technology to both the global and U.S. economies and infrastructure. They then discuss the current and emerging technology landscape. Each technology is further broken down into its key components and associated materials. There are eight technologies in this chapter including vehicles, stationary storage, hydrogen electrolyzers, solar energy, wind energy, nuclear energy, electric grid, and solid-state lighting. In addition, other electronics that do not support the eight listed technologies are included in the last section.

2.1 Vehicles

2.1.1 Importance of Vehicles to the Global/U.S. Economy and Critical Infrastructure

Access to safe, efficient, affordable, and sustainable transport is important for sustaining populations and economic growth across the globe (The World Bank, 2023). Road vehicles, the focus of this study, transport goods and services across and between countries and connect people to work, healthcare, education, and other essential services.

Vehicles also play an integral role in the global energy system as they are one of the most important users of energy and contributors of greenhouse gases. The transportation sector overall was responsible for more than 26% of all energy use globally in 2021 and nearly 27% of all energy use in the United States in 2022 (EIA, 2023; IEA, 2022b). The sector also contributed 37% of all global carbon dioxide (CO_2) emissions from end-use sectors in 2021 due to the sector's reliance on fossil fuels, of which more than 76% came from road transport applications (IEA, 2023e). As such, the continued adoption of EVs, which have fewer (or zero) tailpipe emissions than ICEs, can significantly reduce the amount of carbon dioxide emitted by the transportation sector overall.

While traditional hydrocarbon-powered vehicles with internal combustion engines (spark ignition gasoline engines and compression ignition diesel engines) (Vehicle Technologies Office, 2013) remain the dominant technology (and will for some time), EV sales globally have continued to increase at a rapid pace. According to the IEA, EV sales accounted for 14% of total vehicle sales in 2022, up from 9% in 2021 — a rate driven largely by consumers in China (IEA, 2023e). This increase in sales has been dominated by purchases of light-duty cars by individuals; however, there has also been growth in sales of medium- and heavy-duty buses and trucks for commercial applications. Importantly, gasoline and diesel-powered vehicles are still expected to be prevalent through 2035, so this assessment also includes discussion of various efficiency-enhancing and emissions-reducing technologies associated with these vehicles.

Vehicle components that may contain critical materials include power-train batteries and fuel cells, catalytic converters, lightweighting alloys and high strength steels, copper wiring, and electronic components (Ortego et al., 2018; Restrepo et al., 2017).

2.1.2 Current and Emerging Vehicle Power Technologies

Several vehicle power technologies exist with varying degrees of technology readiness, commercial availability, and adoption. Broadly, there are two major types of vehicles: those powered exclusively by an internal combustion engine (i.e., ICE vehicles or ICEVs) and those powered partially or fully with a battery

(EVs). ICEVs include gasoline-powered vehicles as well as those fueled by diesel, natural gas, propane, and biofuels. In this study, hybrid electric vehicles (HEVs), which are primarily powered by internal combustion engines, are coupled with ICEVs in the assessments. EVs include plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). The following sections discuss each of these vehicle types in more detail.

2.1.2.1 Internal Combustion Vehicles

Internal combustion engine (ICE) vehicles or ICEVs are powered by an engine that burns fuel, usually gasoline or diesel. ICEVs have been the dominant type of vehicle on the roads for many years but lead to significant environmental impacts. The burning of fossil fuels in these vehicles releases greenhouse gases into the atmosphere, contributing to climate change. ICE vehicles also produce air pollutants including nitrogen and sulfur oxides, particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs), which can have negative impacts on human health and the environment (Dey & Mehta, 2020). For pollution control, ICEVs (as are HEVs and PHEVs) are equipped with filters to reduce PM emissions and catalytic converters to convert CO and VOCs to CO_2 and NO_x to nitrogen and oxygen.

ICE vehicles have been important contributors to global economies for decades. The production and sales of ICE vehicles support jobs in the manufacturing, sales, service, and recycling industries, providing employment for millions of people across the globe. ICE vehicles are also important for emergency services such as police, fire, and ambulance services, which rely on the quick and reliable transportation of personnel and equipment to respond to emergencies.

Nevertheless, ICE vehicles are significant CO_2 emitters. The market share of ICE vehicles, however, is expected to decline as more electric and alternative fuel vehicles become available, affordable, and incentivized by law. Several countries and regions have legislated or proposed actions designed to increase the adoption of zero-emissions vehicles, including financial incentives, grants, tax credits, and revised fuel economy standards (IEA, 2023b). In February 2023, the European Union enacted a law revising CO_2 emissions standards, requiring all new cars and vans sold in the region to be zero-emissions vehicles by 2035 (European Parliament, 2023). Although ICE vehicles will continue to be an important part of the global vehicle market in the medium term, their market share is expected to decline.

While ICE vehicles emit carbon dioxide and other pollutants during operation, reductions in net carbon emissions can be achieved through improvements in efficiency and the use of alternative fuels. Improvements in efficiency through technological advancements such as direct injection and turbocharging can reduce the amount of fuel that ICE vehicles consume and therefore lower their emissions. Some ICE vehicles can run on alternative fuels that emit fewer carbon emissions than gasoline or diesel. For example, natural gas vehicles emit fewer carbon emissions than gasoline or diesel vehicles. Other ICE vehicles run on renewable energy fuels, such as bioethanol or biodiesel.

2.1.2.2 Hybrid Electric Vehicles

Hybrid electric vehicles (HEVs) are powered by an internal combustion engine, which is supplemented by an electric motor that is powered by a battery. In contrast to BEVs and PHEVs, HEVs are not plugged in to charge the battery. Instead, the battery is charged by the internal combustion engine and through regenerative braking. HEVs are equipped with catalytic converters and batteries (nickel metal hydride or lithium ion) and may use lightweighting alloys. One study found HEVs to be 23-49% more fuel efficient than comparable ICEVs, although no positive effects on hydrocarbon emissions and higher carbon monoxide emissions were observed (Carlson, 2013). In this study, HEV demands are not considered separately from ICE vehicles (Argonne National Laboratory, n.d.-b).

2.1.2.3 Plug-in Hybrid Electric Vehicles

Plug-in hybrid electric vehicles (PHEVs) are powered by an electric motor in combination with an internal combustion engine. PHEV batteries are recharged from the electric grid, from the internal combustion engine, and from regenerative breaking. PHEVs may be designed for parallel operation where both the engine and electric motor drive the wheels or series operation ― whereas only the electric motor drives the wheels (Alternative Fuels Data Center, n.d.). PHEVs hold some benefits over other low-emissions vehicle types (Taherzadeh et al., 2020). Compared to BEVs, PHEVs typically offer greater mileage between fueling. With a larger battery pack than HEVs, PHEVs provide the potential for higher levels of fuel displacement and consequently lower emissions.

2.1.2.4 Battery Electric Vehicles

Battery electric vehicles (BEVs) are powered solely by electricity stored in a battery. BEVs use an electric motor, usually a traction motor, to propel the vehicle and are powered by rechargeable batteries that are charged using an external power source, such as a charging station or a home charging unit. They typically have a range of 100–300 miles on a single charge, depending on the battery size and the driving conditions. They emit no tailpipe emissions and are therefore considered zero-emissions vehicles – in contrast with ICE vehicles and HEVs. By reducing greenhouse gas emissions and dependence on fossil fuels, BEVs can help mitigate the negative impact of transportation on the environment.

BEVs are becoming increasingly popular as the technology improves and the cost of batteries decreases. According to the U.S. Energy Information Administration (EIA), as of the fourth quarter of 2021, electric vehicle sales accounted for 3.4% of all light-duty vehicle sales in the United States (EIA, 2022a), and nearly 12% of cars sold in February 2023 were either BEVs or PHEVs (as shown in Figure 2.1). While they are typically more expensive than gasoline-powered vehicles, the cost of ownership over time can be lower due to lower maintenance and fuel costs. Some of the challenges associated with BEVs include limited driving range, long charging times, and a lack of charging infrastructure in some areas. However, these issues are being addressed as the technology improves and more charging stations are installed.

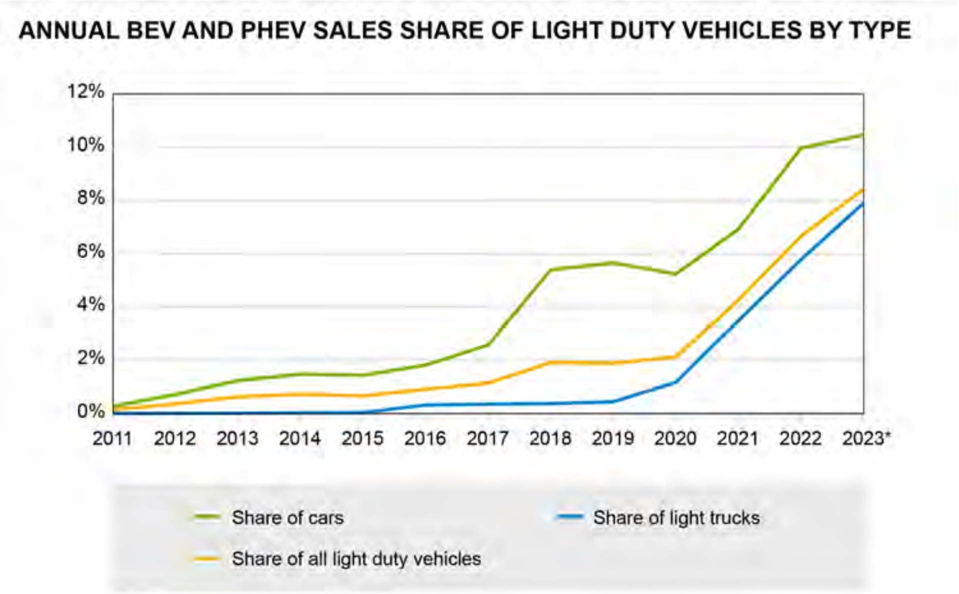


Figure 2.1. Historical share of cars, light-duty trucks, and light-duty vehicles from 2011 to 2023 (Argonne National Laboratory, n.d.-b).

The growing market for BEVs creates new economic opportunities, such as the development and production of new technologies, the expansion of charging infrastructure, and the creation of new jobs in the manufacturing and service sectors. In addition, the increased adoption of BEVs can lead to lower fuel costs for consumers, which can stimulate economic activity and drive demand for new products and services. Adoption of BEVs can also help reduce dependence on foreign oil and improve energy security, which is critical for economic stability and national security. As a result, many countries and regions are investing in the development and deployment of BEVs, with the aim of fostering a more sustainable and prosperous future.

BEVs contribute to the energy system in the United States in several ways. Primarily, they rely on electricity from the grid (which may include renewable energy sources) instead of gasoline or diesel, reducing the demand for fossil fuels and helping to reduce greenhouse gas emissions and air pollution. They also act as a form of distributed energy storage, which can help to stabilize the grid and reduce the need for expensive upgrades to the electrical infrastructure. As more renewable energy sources like wind and solar are added to the grid, BEVs can help to balance fluctuations in supply by charging during times of excess supply and discharging during times of high demand. They can also provide backup power during power outages, which may improve the resilience of the electrical grid.

BEVs contribute to decarbonization by reducing emissions, encouraging renewable energy growth, and increasing efficiency. EVs emit significantly less greenhouse gases compared to traditional gasoline-powered vehicles, producing zero emissions at the tailpipe, meaning they do not release any pollutants or harmful gases into the air. EVs are more energy-efficient than gasoline-powered vehicles in that they require less energy to travel the same distance, resulting in less fuel consumption and reduced emissions.

2.1.2.5 Fuel Cell Electric Vehicles

Fuel cell electric vehicles (FCEVs) are zero-carbon emissions technologies with the potential to significantly contribute to the decarbonization of the transportation sector. FCEVs are being developed and deployed by several automakers and are seen as a promising technology for advancing zero-emissions transportation. In

2021, more than 50,000 FCEVs were registered globally, with 90% of these vehicles concentrated in Korea, the United States, China, and Japan (Samsun et al., 2022). Global sales of FCEVs, however, currently trail behind those of BEVs and PHEVs. Demand for BEVs, in particular, is expected to significantly exceed demand for FCEVs through 2035 (IEA, 2023b).

FCEVs are powered by hydrogen. In an FCEV, the fuel cell generates electricity through a chemical reaction between hydrogen and oxygen, which produces water vapor and electricity as by-products. The electricity is then used to power the electric motor. Compared to gasoline- and diesel-powered vehicles, benefits of FCEVs include zero carbon emissions during operation and quiet operation on the road. The life-cycle carbon reduction potential of FCEVs, however, relies on the expansion of no-carbon production of hydrogen (for example, hydrogen produced by water electrolysis fueled by renewable electricity) (Kelly et al., 2022).

On the road, FCEVs, compared to BEVs, benefit from faster refueling times (3–5 minutes), longer distances between refueling (as much as 600 km), and greater longevity (>200,000 km) (Pollet et al., 2019). These advantages could be particularly important for medium- and heavy-duty trucks, trains, buses, and maritime applications (Cullen et al., 2021). Additionally, governments are investing in hydrogen production and fueling infrastructure with the objective to spur FCEV demand (Moreira & Laing, 2022).

At present, FCEVs are the major end-use product for fuel cell technology and the focus of this analysis. FCEVs are predominantly equipped with polymer electrolyte membrane fuel cells (PEMFCs). PEMFCs rely on platinum for the cathode and anode and graphite for the bipolar plate and gas diffusion layers (Badgett et al., 2022). Lesser amounts of cerium are used to improve fuel cell durability (Moreira & Laing, 2022).

The capital and operating costs for FCEV production are currently higher than for battery electric vehicles. Contributors to the relatively higher costs are, at present, low production volumes and the use of platinum catalysts. R&D efforts focused on reducing (or replacing) the platinum content in FCEVs have and are expected to continue to contribute to lowering FCEV costs (Reverdiau et al., 2021).

2.1.3 Overview of Components and Materials Used in Vehicles

2.1.3.1 Electronics, Heat Dissipation, and Wiring

Copper plays a critical role in the functionality, efficiency, comfort, and safety in vehicles. Copper is a preferred material for electronics in vehicles due to its excellent electrical conductivity and thermal conductivity. While aluminum is a competitor in electrical and thermal conduction applications in vehicles, vehicle manufacturers prefer copper because less material is needed for electrical applications and heat transfer is improved in thermal applications (Wood Mackenzie, 2019). Cu is a prevalent material in vehicles and can be found in multiple systems and components in both ICE vehicles and EVs. These systems include the braking system, electrical driving controls, gearbox, heat exchangers, and vehicle electronics. In the U.S., ICE vehicles are composed of approximately 23 kg of copper with about 80% of that mass used for electrical components and the remainder for nonelectrical components (Copper Development Association Inc., n.d.-a). EVs use copper in their batteries, traction motors, inverters, wiring systems, and power electronics (Copper Development Association, 2022a; IdtechEx, 2022). Electricity delivery in EVs is done using wiring primarily made of Cu. Evs contain approximately three to four times the amount of copper that an ICE vehicle has, with much of the additional copper coming from the traction motor (ICA, 2022b).

In parallel with EV deployment, autonomous vehicle development also will drive increased copper consumption in cameras, lidars, radars, and the autonomous driving control unit (ADCU) (IdtechEx, 2022). These components have been estimated to comprise six percent of the total copper deployed in an EV

(IdtechEx, 2022). With the shift of the automotive industry toward the electrification and automation of vehicles, copper's importance will continue to increase given its many applications.

It is estimated that BEVs contain 83 kg of copper, HEVs contain 39 kg of copper, and PHEVs contain 60 kg of copper (Copper Development Association, 2022a). Additionally, as vehicle size increases, such as for a bus, the amount of copper required for a BEV increases by a factor of eleven to sixteen when compared to an ICE bus. This range yields copper requirements for a BEV bus at 369 kg and 89 kg for a hybrid electric bus (Copper Development Association, 2022a).

2.1.3.2 Catalytic Converters

Vehicles equipped with ICE and diesel engines emit carbon dioxide and toxic gases. To meet vehicle emission regulations, these engine exhausts are processed in onboard catalytic converters before discharging to the atmosphere. Catalytic converters oxidize hydrocarbons to carbon dioxide and water, oxidize carbon monoxide to carbon dioxide, and reduce nitrogen oxide to nitrogen and oxygen gases (Kritsanaviparkporn et al., 2021).

Platinum group metals (PGMs), specifically palladium, platinum, and rhodium, serve as catalytic agents for these conversions. Catalytic converters are classified as three-way (Pd, Pt, and Rh) catalyst agents for internal combustion engines and two-way (Pd and Pt) catalyst agents for diesel engines. The specific PGM contents of catalytic converters vary by country, vehicle type, and manufacturer and have evolved over time in response to vehicle emission policies and product development.

Recovery of PGM from end-of-life catalytic converters provides an important supply source of Pt, Pd, and Rh. Historical global PGM demand for auto-catalysts and recycled supply are provided in Table 2.1.

Over time, the demand for catalytic converters is expected to decline as gasoline- and diesel-fueled vehicles are replaced by full electric vehicles – BEVs and FCEVs. The IEA's pathway to net-zero energy sets milestones of no new ICE car sales and 50% of truck sales electric by 2035 (IEA, 2023b). These goals will lead to a decline in Pt, Pd, and Rh demands for this application. In the short term, however, catalytic converter demand is projected to grow to meet increasing global sales of ICE and diesel engine vehicles.

Table 2.1. Global demand for PGMs in the manufacture of catalytic converters and recovered PGM from end-of-life catalytic converters (Johnson Matthey, 2022).

	Catalytic Converter PGM Demand (tonnes)			Catalytic Converter PGM Recycled (tonnes)		
	Platinum	Palladium	Rhodium	Platinum	Palladium	Rhodium
2017	95.3	262	25.8	28.8	73.3	9.6
2018	87.5	274.8	28	41.5	81.6	10.3
2019	80.7	300.2	32.2	43.2	90.6	11.1
2020	63.6	264.5	29.8	35.9	83.6	10.5
2021	73.1	259.4	29.4	38.4	90.0	11.5

2.1.3.3 Non-traction Motors

Non-traction motors exist in all vehicle types. They are low-power motors, also known as auxiliary motors, that perform various tasks in a vehicle, ranging from starter motors, electric power steering, oil and fuel pumps, electric seat adjustment, mirror adjustment, window, and sunroof motors. On average, there are 35 to 45 auxiliary motors in a car (Vittori et al., 2021). Small and basic vehicle models have about 20 motors while larger and luxurious models have up to 100 motors to provide enhanced driver comfort (Vittori et al., 2021). Like other electric motors, rotors (the moving part) and stators (the stationary part) are two mechanical components, and magnets and armature are two electrical parts. Together, the mechanical and electrical parts form a magnetic circuit of the motors.

Typical electric motors have rotors or stators made from soft magnetic materials associated with copper windings. When permanent magnets are used for stators and rotors, the motors are called permanent magnet motors. The magnets for permanent magnet motors are typically made of materials such as neodymium-iron-boron (NdFeB) magnets or ferrite with strong magnetic properties. Soft magnetic materials associated with windings or permanent magnets create magnetic fields to produce a torque that causes the rotor to rotate (Hughes & Drury, 2019). Most auxiliary motors in vehicles use ferrite magnets to save costs. Where high performance, weight, or space saving are required, NdFeB magnets are used to reduce up to 50% of the size and 40% of the weight compared to ferrite magnet motors (Honkura, 2006). However, the amount of NdFeB magnets used in auxiliary motors are not as significant as in EV traction motors, ranging from 16 g to 125 g/vehicle (Nguyen et al., 2020; Nguyen et al., 2019). As a result, NdFeB magnets are not considered for auxiliary motors in this report. More discussion on NdFeB magnets can be found in the traction motor discussion in Section 2.1.3.4.

The discussion of copper wiring above includes copper in auxiliary motors. Therefore, the discussion here focuses on electrical steel (ES) of non-traction motors. Electrical steel is an iron-silicon alloy that contains 1.5%–6% silicon (Si) by weight (Eckard, 2020). Silicon helps reduce the eddy currents in the transformer core, leading to better electric resistivity. However, high Si content makes the alloy brittle and hard to process. New manufacturing methods allow for 6% of Si content by weight or higher. Most applications require a silicon content of from 1.5% to 3% (Eckard, 2020). There are two main categories of electrical steel, including one that is grain-oriented (GOES) and another that is non-grain oriented (NOES). GOES is mainly used for non-rotating applications like transformers, whereas NOES is used for rotating equipment such as electric motors, generators, and high-frequency converters. NOES used in vehicle auxiliary motors is of a lower grade compared to NOES in EV traction motors. This result is due to both lower power requirement and cost-savings needs of auxiliary motors.

2.1.3.4 Traction Motors in Electric Vehicles

Electric, hybrid, plug-in hybrid, and fuel cell electric vehicles all require traction motors to convert electrical energy to mechanical energy. Various types of electric motors are used in these vehicles, with each exhibiting a unique set of characteristics, benefits, and trade-offs including its size, weight, power, range, cost, and performance requirements (everythingPE, 2023). These motor types, including alternating current (AC) induction motors, permanent magnet synchronous motors (PMSMs), DC brushed motors, brushless direct current (BLDC) motors, switched reluctance motors (SRMs), and internal permanent magnet (IPM) motors, each utilize unique principles to generate torque and propel the vehicle. The AC induction motor utilizes the interaction between the stator and rotor magnetic fields to generate torque. The PMSM takes advantage of the interaction between the permanent magnets mounted on the rotor and the electromagnets on the stator. The BLDC motor uses electronic commutation to control the current flowing through the windings. The SRM utilizes the interaction between magnetic fields in the stator and rotor to generate torque, and the IPM motor uses permanent magnets to generate the magnetic field in the rotor (everythingPE, 2023). The most commonly used electrical vehicle motor available today is a rare earth permanent magnet (REPM) synchronous drive motor using NdFeB magnets. Premium induction motors have about 2.1% lower efficiency, reducing mileage and driving range for electric vehicles (Newkirk et al., 2021). Brushed DC series motors require more maintenance (Karthik, 2019). Permanent magnet synchronous drive motors with alternative types of magnets require heavier magnets to deliver the same amounts of power.

The base materials for NdFeB magnets are neodymium (Nd), iron (Fe), and boron (B). Praseodymium (Pr) is often substituted for some of the Nd in the magnet by using didymium, a mix of Nd and Pr, in place of some or all of the Nd. A number of additions to improve magnetic properties are also included, including dysprosium (Dy), terbium (Tb), and gallium (Ga). Dy, Tb, and Ga can all be used to increase magnet coercivity, which allows it to perform in higher-temperature environments, which is key for use in vehicle motors. Dy is most frequently used, while Tb and Ga are sometimes added in smaller quantities (Huang et al., 2022).

As the global push for higher torque density and lower-cost traction motors intensifies, research is looking in the direction of the use of non-heavy rare earth (non-HRE) permanent magnet materials in traction motors. Researchers at DOE's Oak Ridge National Laboratory and National Renewable Energy Laboratory propose a dual three-phase winding configuration driven by a segmented dual three-phase drive for Dy-free motors (Raminosoa et al., 2020). Earlier, a study led by DOE Ames Laboratory investigated a simplified process for anisotropic mixed rare earth (Nd-based) magnets and little or no Dy, bulk processing improvements for RE-free magnets (alnico), and advances in "super-AlNiCo" (tetragonal Fe-Co) with theoretical/synthesis efforts focused on design of other AlNiCo additions (Anderson, 2012).

In addition to permanent magnets, similar to non-traction motors, NOES is widely used as a motor core material in the electric propulsion systems of EVs (including hybrids and plug-in hybrids) as it offers high efficiency and meets high-power motors' requirements (Fujimura et al., 2019). Unlike the ordinary motor, an EV traction motor's requirements include high torque characteristics to enable quick starting of the vehicle and powerful hill climbing, and a high revolution characteristic for high top speed (Wakisaka et al., 2013).

2.1.3.5 Lightweighting Alloys

The use of lightweighting alloys in vehicles helps to reduce overall vehicle weight, thereby increasing vehicle efficiency and reducing the energy required to propel the vehicle. Lightweighting also allows manufacturers to build structures that use the minimum number of materials necessary to provide the same strength and durability as conventional materials. Different materials have different properties that can reduce the weight of vehicles while still maintaining the structural design of the vehicle. The choices that manufacturers make between different materials affects how much mass is reduced, component strength, and costs. For example, original equipment manufacturers (OEMs) must decide between using a less dense material such as magnesium to reduce equipment's weight while understanding that magnesium does not provide the corrosion resistance provided by aluminum. The development of lightweighting material compositions is a complex effort, and material selection optimization methods are being developed so that traditional materials can be replaced by more lightweight vehicle materials. Three of the main lightweight alloys — magnesium, aluminum, and high-strength steel alloys — are discussed here due to their current commercial viability and their use in projecting material demand in vehicles.

2.1.3.5.1 Magnesium Alloys

Magnesium plays an important role in lightweighting alloys for automobiles and is the lightest metallic construction material available. Elements added to magnesium to create the alloy often include manganese, aluminum, zinc, and silicon (North American Die Casting Association, n.d.). Aluminum is a commonly used alloying element, which strengthens and hardens the alloy while also widening the melting range, which makes it easier to cast (ASM International, 2017). Rare earth elements such as cerium and lithium are combined with magnesium to help improve the corrosion resistance and create ultra-light structural alloys (ASM International, 2017). Zinc is the second most effective and commonly used alloying metal, which increases room temperature strength, increases fluidity in casting, and can help improve corrosion resistance when combined with nickel and iron impurities (ASM International, 2017). Magnesium alloys have a density of 1.7–2.0 g/cm^3, which is approximately 30% less than that of aluminum and 75% lighter than steel (Czerwinski, 2021). Magnesium alloys have excellent fluidity and less susceptibility to hydrogen porosity, which allow these alloys to have better castability over other cast metals such as aluminum and copper.

Despite the fact that it can be easily molded into appropriate castings, magnesium presents some barriers in high-volume vehicle applications. For example, magnesium provides challenges associated with manufacturing, processing, assembly, in-service performance, and cost (Joost & Krajewski, 2017). It also presents corrosion and stiffness issues as compared to aluminum or steel and corrodes in galvanic contact with automotive materials, making it undesirable for certain parts of the automobile (Luo, 2013). Additionally, magnesium sheet strengths are needed in order to match the stiffness of high-strength aluminum alloys (Joost & Krajewski, 2017). For these reasons, magnesium alloys make up less than 0.5% of the weight of the average vehicle (Joost & Krajewski, 2017).

2.1.3.5.2 Aluminum Alloys

Aluminum alloys are often classified into two categories: wrought compositions and cast compositions. Wrought composition aluminum alloys are created through combining aluminum with other elements, such as manganese, silicon, copper, and magnesium (Fabricating and Metalworking, 2014). The alloys are created by smelting pure aluminum ingots with alloying elements, which are then cast into large slabs (Clinton Aluminum, 2020). The alloy is then rolled, forged, or extruded into its final shape. Cast alloy production, on the other hand, is produced when the aluminum is melted together with alloying metals in a furnace and poured into a pre-made mold of the final product (The Federal Group USA, 2020). Many alloys are heat treated in order to increase the strength and hardness of the wrought and cast alloys, known as “heat-treatable” alloys (ASM International, 2016). Heat treatment increases the strength of aluminum alloys through solution heat treatment, quenching, and age hardening (ASM International, 2016).

The properties of aluminum alloys allow them to be attractive not only to the automobile industry but to other transportation modes as well. Aluminum alloys are the second most used materials in structural metals only behind steel (Davis, 2001). With a density of approximately 2.7g/cm^3, it is denser than magnesium but approximately one-third the density of steel. The less dense properties of aluminum, coupled with the high strength properties of some of its alloys, enable its use in the lightweight construction of structures such as space vehicles, aircraft, and automobiles. Unlike magnesium, aluminum resists the oxidization that causes steel to rust away (Davis, 2001). The thin oxide layer of aluminum clings tightly to metal and is colorless and transparent, which means that discoloration and flaking of the rusting process of iron and steel do not occur with aluminum (Davis, 2001). Additionally, aluminum’s barrier oxide film that is bonded to its surface allow it to be an excellent material for corrosion resistance (Davis, 2001). Pure aluminum is readily forgeable into intricate shapes, making it an ideal material for automobile construction. However, alloying aluminum with elements such as copper, magnesium, and silicon to increase strength can decrease the forgeability of the alloy (Davis, 2001).

2.1.3.5.3 High-Strength Steel Alloys

Ferrous alloys are often not classified as lightweight materials, but the automobile industry is turning toward using low-density steel in order to reduce the weight of transport vehicles. Manganese is primarily used as an alloy in the production of steel, which increases both the strength and flexibility for use in automobile production. All commercially available steel contains manganese due to its ability to reduce the cooling rate during hardening, reducing ductility and enhancing yield (AZO Materials, 2016). Almost 90 percent of the consumption of manganese is used in the steel industry as manganese removes oxygen and sulfur when iron ore is converted into iron (Cannon, 2014). Approximately 6 to 9 kilograms of manganese are used per ton of steel where 30% of the material is used during refinement of iron ore and 70% is used as an alloy in steel manufacturing (Cannon, 2014). While the predominant use of manganese is in steel, some non-metallurgical applications of manganese include battery cathode production, electronics, additives in fertilizers and animal feed, and colorant for automobile undercoat paint (Cannon et al., 2017).

Steel presents properties that enhance the sustainability of production as well as manufacturability that allow it to be more affordable and cleaner than materials like aluminum. For example, the steel recycling process is less expensive than that of aluminum and results in increased environmental benefits, such as the reduction of CO_2 (Czerwinski, 2021). To reduce the weight of steel for the automobile industry, “low-density steel” that consists of iron, manganese, aluminum, and carbon are often used (Czerwinski, 2021). Aluminum is an essential alloying element in the reduction of steel density, given that a 1% weight addition of aluminum results in a 1.3% reduction in density. However, adding aluminum to steel introduces changes in the steel microstructure, which can lead to poor ductility and brittleness (Czerwinski, 2021). In recent years, the introduction of advanced high-strength steels (AHSS) and ultra-high strength steel (UHSS) has led automakers to build vehicles with thinner sheets that are both strong and lightweight (Czerwinski, 2021).

2.1.3.6 Batteries

The vast majority of EVs in operation today rely on lithium-ion batteries for energy storage. Lithium-ion batteries come in many varieties, but the types most commonly used in EVs include nickel manganese cobalt (NMC), nickel cobalt aluminum (NCA), and lithium iron phosphate (LFP) batteries, which are named for the cathode material that is used. NMC batteries are most commonly used in electric vehicles produced in the U.S. and Europe, followed by NCA batteries, while LFP batteries are more common in EVs produced in China. Each of these battery chemistries has distinct advantages. NMC and NCA batteries have higher energy density than LFP, which allows vehicles to have longer ranges for a given amount of battery weight and volume. They also perform better at low temperatures, and thus may be more attractive for car buyers who live in cold climates. LFP batteries, on the other hand, require fewer expensive materials, have a longer cycle life that allows them to maintain their full level of charge for longer, and have lower risk of fires.

These battery types each use different materials in the battery cathodes. NMC cathodes include lithium, nickel, manganese, and cobalt. The ratio of nickel to manganese and cobalt can vary, with common varieties of NMC, named for their molar ratio of nickel to manganese to cobalt, being NMC 333, 532, 622, and 811. NCA cathodes include lithium, nickel, cobalt, and aluminum. LFP cathodes include lithium, iron, and phosphorus. In addition to these cathode materials, there are different options for materials to use in the anode. The most common anode material is graphite, but silicon can also be substituted for some or all of the graphite in the anode. The electrolyte uses lithium, phosphorus, and fluorine. Figure 2.2 shows materials used in three main battery components, including anode, cathode, and electrolyte.

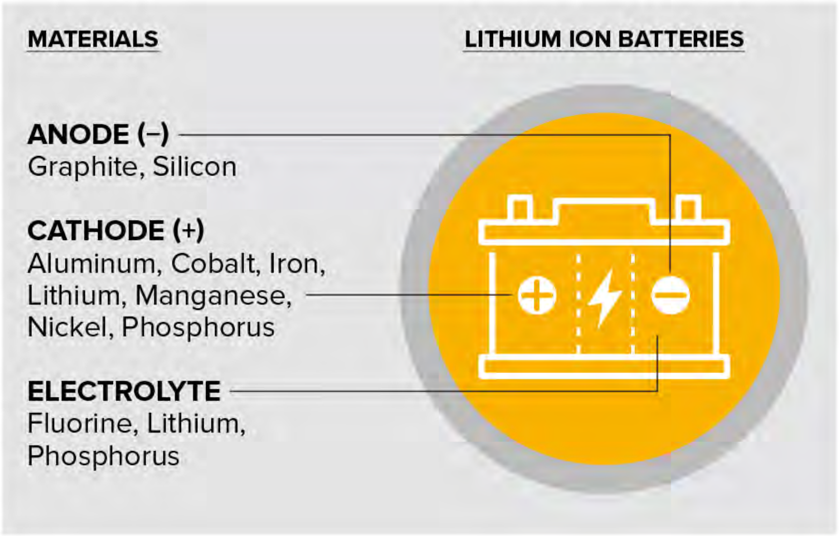
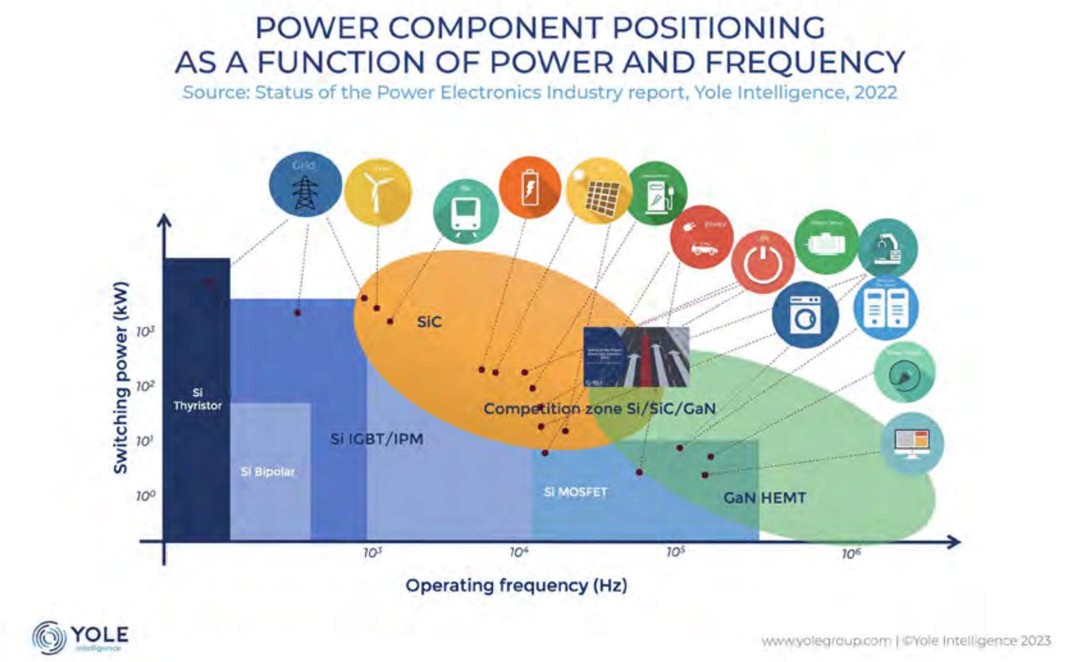


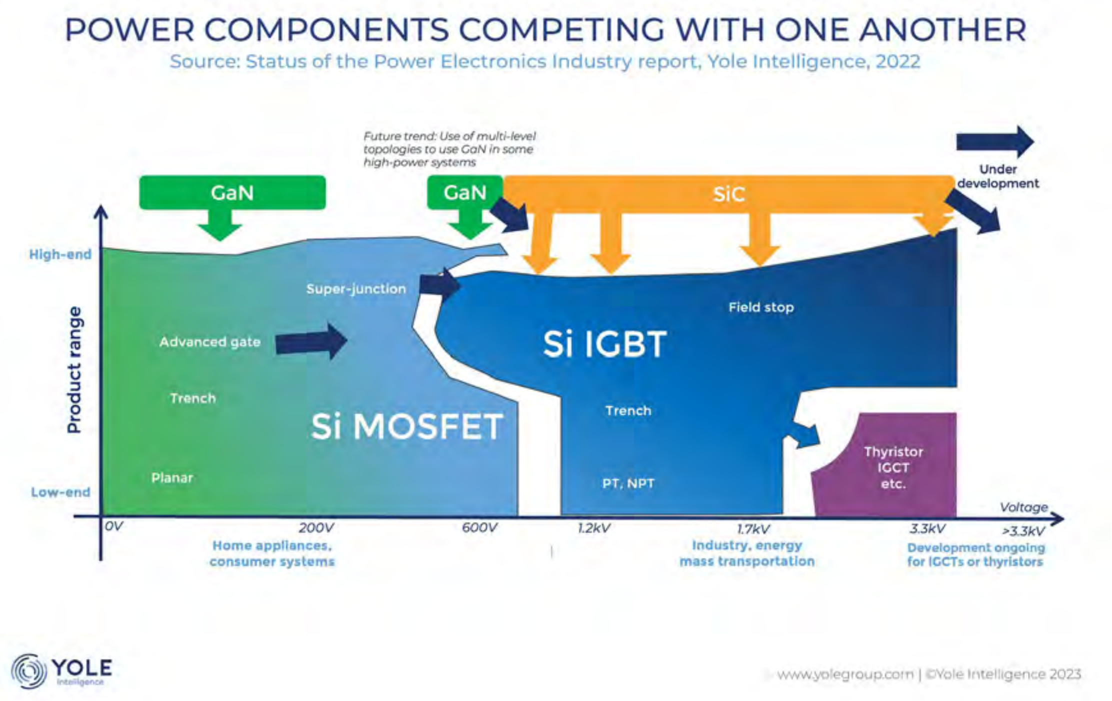
Figure 2.2. Materials used in lithium-ion battery components.

2.1.3.7 Power Electronics in Electric Vehicles

Power electronics are key components of various technologies powering our modern lives. They are present in energy systems (solar PV, HVDC, wind, battery energy storage systems and EV charging), communications (both in infrastructure and servers), industrial equipment (pumps, motors, robots, and security cameras), transportation (EVs, rail, auxiliary and thermal automotive components), consumer electronics (home appliances, audio systems, computers, mobile and gaming devices), and medical equipment (Chiu & Dogmus, 2022). By material, there are three power electronics categories including silicon (Si), gallium nitride (GaN), and silicon carbide (SiC). Of these three materials, Si-based electronics dominated the power market at 93% market share in 2022, followed by SiC at 6% market share and GaN at 1% market share (Rosina & Villamor, 2022). These market shares were calculated from the total market value of $47.8 billion in 2022 by all device types, with an overall compound annual growth rate (CAGR) of 4.4% until 2027 (Rosina & Villamor, 2022). Overall, Si-based electronics perform well at high switching power and voltage at various operating frequencies (Figure 2.3). A major advantage of wide-bandgap semiconductor material including SiC and GaN, compared to traditional semiconductor material Si, is the higher operating frequency and higher switching power. GaN electronics work well at very high frequencies but at medium switching power and low voltage. SiC can perform well at high switching power, relatively high frequency, and high voltage. The competition zones among these three power electronic types are also shown in Figure 2.3.


POWER COMPONENT POSITIONING AS A FUNCTION OF POWER AND FREQUENCY

Source: Status of the Power Electronics Industry report, Yole Intelligence, 2022


POWER COMPONENTS COMPETING WITH ONE ANOTHER

Source: Status of the Power Electronics Industry report, Yole Intelligence, 2022

Figure 2.3. Performance of Si, SiC, and GaN power electronics. Top: based on switching power and operating frequency; bottom: based on voltage (Rosina & Villamor, 2022).

Specific to automotive application, power electronics are widely used in all vehicle types. The automotive sector accounted for 32% of the power electronics market value in 2022 (Rosina & Villamor, 2022). In traditional ICEs, power electronics are mainly used in the engine control unit and other electrical controlled accessory systems. In EVs, power electronics play a more important role including in traction motor control, onboard/offboard charging (Nademi & Zhang, 2020), and battery management system controls (Zhang et al., 2022). Currently, SiC-, Si-, and GaN-based power electronics are all used at various levels in the EV industry. Although SiC-based and GaN power electronics modules provide higher performance, which is preferred by the EV industry, Si-based ones are still widely used today due to low cost.

Si-based power electronics are widely used in EVs, with 66% market share in this application in 2022 (Rosina & Villamor, 2022): they are cost effective with a trade-off of lower operating switching frequency of less than 20 kHz (Zhang et al., 2019). Si-based power modules, motor control electronics, and chargers, which could be up to 3.3 kV or higher, are generally less expensive compared to those that are SiC based, making them a cost-effective but still reliable choice for many EV applications. SiC-based motor controllers can enable higher switching frequency of up to 40–85 kHz (Zhang et al., 2021; Zhang et al., 2018). SiC-based power electronics offer higher voltages and power, higher operating temperatures, faster switching, better efficiency, and a smaller form factor (Wolf Speed, 2019) compared to traditional Si-based power electronic inverters/rectifiers. SiC can withstand operating at 1.2 kV or even 1.7 kV, which is essential for charging a typical EV battery pack at 400 V or 800 V. They enable faster switching speeds, leading to reduced power losses and more efficient energy conversion in EVs (Morya et al., 2019). Owing to the higher operation frequency, using SiC-based charging systems also reduces the size and weight of charging infrastructure with higher power density. Therefore, SiC could also potentially be beneficial to a high power charger given the less space/size needed for the power electronics equipment. For those reasons, SiC devices accounted for 33% market share of EV application in 2022. Specific energy applications of SiC power electronics include 600 V/1200 V inverters, 600 V/1200 V onboard chargers, 600 V/1200 V metal-oxide-semiconductor field-effect transistor (MOSFET) for automotive components, 1200 V charging stations, and 1200 V for motor drive (Ayari & Chiu, 2022; Chiu & Dogmus, 2022). The EV industry is a major driver of SiC power electronics, accounting for 69% of the SiC devices market in terms of dollars and 65% in terms of wafer quantity in 2022 (Chiu & Dogmus, 2022).

As of 2022, a 6-inch wafer is the mainstream size for SiC produced by leading manufacturers. There is an initial volume of 8-inch wafers in 2022 mainly for qualification of wafer quality, newly installed production lines, and tooling. A few wafer suppliers, such as Wolfspeed, GTAT, Coherent Corp (formerly II-VI), and SK Siltron CSS have demonstrated 8-inch wafers. Wolfspeed, STMicroelectronics, Onsemi, and ROHM are qualifying or demonstrating 8-inch platforms with their internal wafer supplies (Chiu & Dogmus, 2022). The wafer cost still accounts for a significant part of the SiC device. Reuse of various finished quality levels of wafers according to different acceptable power level device (i.e., a lower-quality wafer for those applications with lower application requirements) could also be an option to reduce SiC wafer manufacturing cost. Due to its high costs, SiC adoption in non-EV markets is still limited.

Also used in EVs but at a lower market adoption of 1% is gallium nitride (GaN) (Ayari & Chiu, 2022). Like SiC, GaN is a wide-bandgap semiconductor. The major difference between GaN and SiC is that GaN can operate at a much higher frequency but lower switching power and voltage than SiC. Small power applications of GaN devices used in the EV market include onboard chargers (OBCs) and direct current (DC) to DC conversion (Ayari & Chiu, 2022). OBCs between 3–11 kW and bidirectional DC/DC converters between 12–48 V are of interest to EV manufacturers. GaN is also used in e-bikes and e-motorcycles that are not considered in this report. Overall, GaN plays a small role in the EV industry.

2.1.3.8 Fuel Cells in Vehicles

Today, operational FCEVs are powered by the conversion of hydrogen to electricity in polymer electrolyte membrane fuel cells (PEMFCs). Major components of PEMFCs are the electrodes (anode and cathode), catalysts, ion-exchange polymer membrane (commonly Nafion), serpentine flow fields, perfluorosulfonic acid (PFSA) proton conductor and binder, and carbon-based bipolar plate and porous transport layers (Muthukumar et al., 2021). Vehicle fuel cell materials considered in this analysis are platinum (anode and cathode catalysts) and graphite (bipolar plate and porous transport layers). Pt and graphite are the FCEV materials considered in this assessment.

FCEV fuel cell sizes are reported in power units, commonly kW. Power range estimates assumed for this study were derived for fuel cell passenger cars, light-duty vehicles, medium-duty vehicles, and heavy-duty vehicles as reported in Cullen et al. (Cullen et al., 2021). Specifically, assumed power estimates are: 100 kW for cars, 150 kW for vans, 186 kW for buses, and 300 kW for trucks.

2.2 Stationary Storage

2.2.1 Importance of Stationary Storage to the Global/U.S. Economy and Critical Infrastructure

Stationary energy storage systems enhance the energy efficiency, reliability, and resilience of the electric grid, industrial operations, and other critical infrastructure for the U.S. and global economy. This family of technologies support the seamless integration of intermittent renewable energy sources into the grid, thereby reducing carbon emissions and bolstering grid and industrial process resilience to disruptions by offsetting peak demand and providing emergency backup power. They can also stimulate economic growth by creating jobs, supporting the development of new energy markets, and reducing dependence on oil imports for energy.

2.2.2 Current and Emerging Technologies

Technologies for stationary storage are diverse and rapidly evolving and are distinguished both by their principal operating mechanisms and by their energy to power density ratios. Stationary storage technologies include electrochemical systems such as lithium-ion batteries, redox flow batteries, and lead-acid batteries; mechanical systems such as pumped hydro storage and compressed air storage, and chemical/thermal/thermo-chemical systems such as hydrogen, molten salts, and phase-change materials. Lithium-ion batteries are the most common type of electrochemical stationary storage and are known for their high efficiency, long lifespan, and broad range of applications. Although redox flow batteries can last longer and cost less to install than lithium-ion batteries, they have lower efficiency and thus higher operating costs. Lead-acid batteries have the lowest capital cost per kWh, but their inferior cycle life and low efficiency lead non-competitive levelized cost of storage (LCOS) compared to other battery systems. Pumped-hydro storage is an inexpensive, mature technology for long-duration storage, but it requires large footprints for land and water. Compressed air energy storage is more nascent. Like hydro, it is particularly cost competitive for long-duration storage but also requires a large land footprint or underground caverns. Hydrogen is an emerging and versatile option for high-density energy storage, while molten salts headline energy storage options that are ideal for integration with concentrated solar thermal systems (Viswanathan et al., 2022).

There are a number of current and emerging battery chemistries for stationary energy storage, and the choice of chemistry depends on a number of factors, including energy density, lifespan, roundtrip energy efficiency, cost, and safety, as well as life cycle environmental impacts. Lithium-ion dominates battery energy storage applications, adopting different chemistries such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). While lead-acid batteries used to be a cost-effective alternative to lithium-ion, they have fallen behind in the competition with LFP and are expected to lose their advantage to NMC by 2030. Flow batteries, such as vanadium redox flow batteries (VRFBs), zinc-bromine flow batteries (ZBFBs), and iron-chromium flow batteries (ICFBs), constitute emerging alternatives to lithium-ion batteries, which offer the advantage of decoupling energy and power, allowing for scalability and potentially longer cycle life. Although ZBFBs have a higher efficiency and better lifespan than VRFBs, the technology is less mature. Other emerging battery storage technologies include sodium-based batteries like

NaS and NaNiCl, which show potential for large-scale grid application, and zinc-based batteries, including zinc-air and nickel-zinc, which are being developed for their superior safety and low cost (Viswanathan et al., 2022). The best battery chemistry for a particular application will depend on the specific requirements of that application. Table 2.2 gives a summary of advantages and disadvantages of each battery chemistry.

Table 2.2. Summary of advantages and disadvantages of major battery chemistries.

Battery Chemistry	Advantages	Disadvantages
Lithium-ion	Competitive installation cost and LCOS, high energy density, long lifespan, efficient	Safety concerns, money lost in recycling LFP batteries
Vanadium redox flow batteries	Long lifespan, competitive installation cost for long-duration systems, storage duration easily adjustable	Less efficient, limited operating range
Zinc-bromine flow batteries	Safe, low system integration cost, may leverage infrastructure for lead-acid	Less efficient, not yet demonstrated at large scale
Lead-acid batteries	Low capital cost per kWh, established supply chain and recycling practice	Less efficient, low cycle life, high LCOS
Sodium-sulfur batteries	Competitive efficiency and lifespan	Safety concerns, high operating cost

2.2.3 Overview of Components and Materials Used in Stationary Storage Technologies

This assessment considers various types of batteries for stationary storage as well as the conversion of hydrogen into electricity using fuel cells.

2.2.3.1 Components of Batteries Used for Stationary Storage

Lithium-ion batteries have four major components, including cathode, anode, electrolyte, and separator. The cathode comprises of a mixture of lithium and other materials such as cobalt, nickel, manganese, iron, phosphorus, and aluminum. These materials determine the energy density, safety, and thermal stability of a battery. The anode is primarily composed of graphite that allows lithium ions to move freely to drive battery function. A silicon-based anode is showing promise but faces challenges due to large volume changes. The electrolyte, typically a lithium salt dissolved in an organic solvent, enables ion transport between the cathode and the anode. The separator, typically a polymer material such as polyethylene, separates the anode and cathode to preclude short-circuiting. Other components include current collectors, which aid electron flow, and binders, which enhance stability and conductivity.

Like lithium-ion batteries, flow batteries also comprise a cathode, an anode, an electrolyte, and a separator. Across different flow battery technologies, materials used in flow batteries include vanadium, zinc, bromine, nickel, chromium, iron, graphite, and other carbon-based electrode materials. Vanadium is the most common cathode material for flow batteries. It is a transition metal that can exist in four different oxidation states, which makes it a versatile material for flow batteries, as it can be used to store a wide range of energy densities. Iron chromium is also relatively common. While it is less expensive than vanadium, it has a lower energy density. Zinc bromine is the least common cathode material for flow batteries. It has a higher energy density than vanadium but it is more expensive.

2.2.3.2 Fuel Cells for Stationary Hydrogen to Electricity Conversion

Stationary fuel cells are being developed and commercialized to serve as dispatchable generators for electricity grids; combined heat-and-power systems; and as back-up power sources for commercial, residential, industrial, energy, and military applications (Cigolotti et al., 2021). Stationary fuel cell technologies include proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), and solid oxide fuel cells (SOFCs) (European Commission et al., 2019). SOFC technologies, evaluated in this study, are expected to capture the largest share of demand for stationary applications (Badgett et al., 2022).

2.3 Hydrogen Electrolyzers

2.3.1 Importance of Hydrogen to the Global/U.S. Economy and Critical Infrastructure

Hydrogen has widespread uses as an energy carrier and chemical reactant in a variety of applications. Historically, hydrogen demand has been concentrated in the chemical, agrochemical, refining, and steel industries. Ammonia production is the largest consumer of hydrogen, followed by methanol production and direct reduction of iron. In refineries, hydrogen is used to remove impurities, such as sulfur, from oil (Noussan et al., 2021) and to upgrade heavy oil feeds (Gai et al., 2022). In 2021, global hydrogen consumption was 94 million Mt (IEA, 2022d).

Hydrogen is also an important pillar for decarbonization, particularly for applications that capitalize on its high mass energy density and light weight (Oliveira et al., 2021). However, most hydrogen production technologies today rely on carbon feeds (often methane) and generate carbon dioxide emissions, which may or not be emitted to the atmosphere. While DOE defines “clean hydrogen” as any process that contributes less than or equal to 4 kg of CO_2 equivalent per kg of hydrogen (Hydrogen and Fuel Cell Technologies Office, 2022), hydrogen “labels” distinguish production routes based on their relative contribution to decarbonization:

- Grey: produced from hydrocarbons without carbon capture and storage.
- Blue: produced from hydrocarbons with carbon capture and storage, or water electrolysis powered by carbon-based chemicals.
- Green: produced by water electrolysis, powered by renewable electricity or other routes that do not produce carbon dioxide.

The “hydrogen economy” is centered on hydrogen production, distribution, and usage in multiple economic sectors including transportation, energy, environmental, manufacturing, and residential. To meet decarbonization goals, hydrogen demand is expected to increase, particularly for sectors that are difficult to decarbonize, such as heavy- and medium-duty trucks; synthetic fuels for air and marine transport fuels; energy storage; and high-temperature heat. Hydrogen demand for other applications, including electricity, chemicals, and buildings, are also forecasted to increase in the IEA NZE scenario. Additionally, usage of hydrogen to produce low-carbon ammonia, methanol, and other chemicals is expected to increase. As shown in Figure 2.4, the U.S. Department of Energy’s “H2@Scale” initiative envisions hydrogen produced from renewable, nuclear, and fossil fuels with carbon capture and storage to supply energy to all economic sectors.

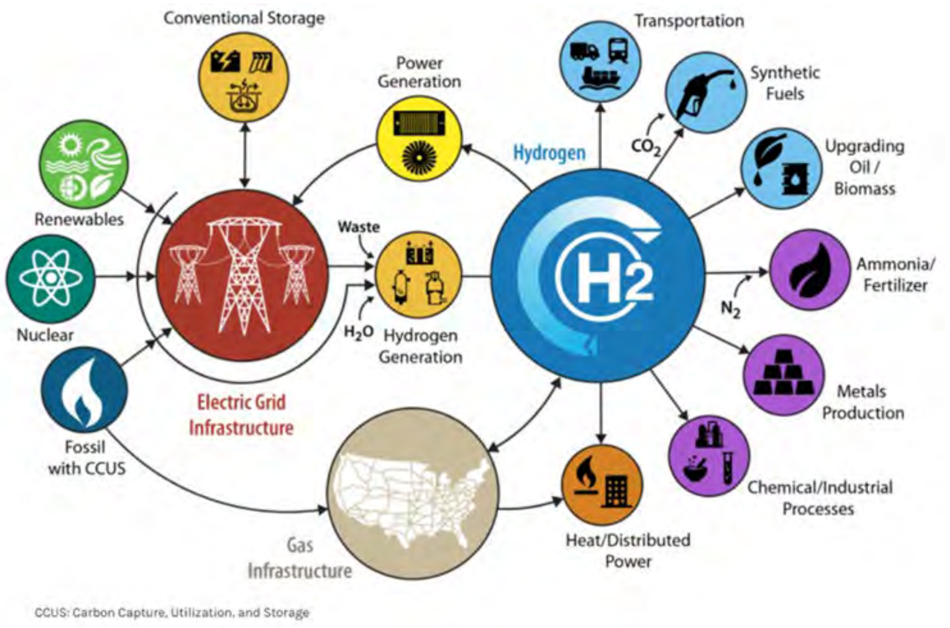


Figure 2.4. DOE's Vision for hydrogen at scale (DOE, n.d.-e).

2.3.2 Current and Emerging Technologies

Today, most hydrogen is produced by steam methane reforming (SMR). Less common hydrogen production routes include auto-thermal reforming, methane pyrolysis, and biomass or coal gasification (DOE, 2023). Low-carbon hydrogen production technologies include water electrolysis powered by renewable or nuclear electricity; fossil fuel reforming with carbon capture, utilization, and storage (CCUS); and reformation or gasification and pyrolysis of bio-liquids such as ethanol, sugars, and bio-oils (*Fuel Cells and Hydrogen Production*, 2018). Hydrogen production technologies being researched in laboratories include photoelectrochemical water splitting and microbial electrolysis (DOE, n.d.-c). This study focuses on the most mature low-carbon technology, namely, water electrolysis. Several electrolysis technologies are already commercialized or are under development, including both low- and high-temperature technologies. Low-temperature technologies include alkaline electrolyzers (AECs), proton exchange membrane electrolyzers (PEMECs), and anion exchange membrane electrolyzers (AEMECs). Of these, only AECs and PEMECs are currently commercialized, while AEMECs are still in the research stage. High-temperature technologies include solid oxide electrolyzer cells (SOECs) and molten carbonate electrolyzers. SOECs are currently in the demonstration stage, while molten carbonate electrolyzers are still in the research stage.

AECs account for the majority of commercialized electrolyzers. The technology is challenged, however, by low current densities, corrosive conditions, and low cycling capability (Grigoriev et al., 2020; Iyer et al., 2022). PEMECs are considered one of the most promising prospects for large-scale hydrogen generation due to their wide operational range of current densities, high turndown ratio, compact size, excellent dynamic response, and the possibility to operate at high pressure (Osman et al., 2022). Currently, however, the technology is more expensive than alkaline electrolyzers (Ouimet et al., 2022).

SOEC technologies are more nascent but show promise for achieving high current densities, high efficiencies, and, most significantly, the potential to support reversible operations for energy storage (Holm et al., 2021). The high operating temperatures of SOECs, however, challenge material stability and durability. Anion exchange membrane and molten carbon electrolyzers are not considered in this analysis, as these technologies are in the early stage of research and development.

2.3.3 Overview of Components and Materials Used in Hydrogen Electrolysis Technologies

The major components of electrolyzer cells are metal electrodes and associated catalysts (anode catalysts for the oxygen evolution reaction and cathode catalysts for the hydrogen evolution reaction); the electrolyte (promoting ion conductivity); and a thin, ion-conductive separator. Operational and material properties of the three electrolyzer types are shown in Table 2.3.

PEMEC technologies rely on platinum for the cathode, iridium for the anode, and titanium sponge for the anode gas diffusion layer and bipolar plate (Badgett et al., 2022). Significant research is ongoing to reduce the iridium content in PEMECs by approaches including substituting iridium with ruthenium; alloying or doping with less rare metals; modifying catalyst supports; and varying the chemical form and morphology of the iridium catalyst (Fu et al., 2023). Another emerging concern for PEMEC technologies is their reliance on polyfluoroalkyl substance (PFAS) chemicals, which are long-lasting in the environment, have harmful health effects, and are at risk of being banned (EPA, 2023b).

Given the early emergence of SOEC technology and several different chemistries being researched, this study’s material intensities for SOECs are based on the composition reported in the DOE report, “Water Electrolyzers and Fuel Cells Supply Chain” (Badgett et al., 2022). SOEC materials evaluated include lanthanum, strontium, cobalt, nickel, yttrium, and manganese.

Note that this analysis does not consider materials required to build and support the infrastructure for the hydrogen economy. To meet projected demands for hydrogen, low-cost hydrogen transportation (e.g., pipelines, gas and liquid trucking) and storage technologies (e.g., absorptive or chemical carrier materials; compressed gas, cold/cryo, liquid hydrogen storage, salt caverns, and lined hard rock storage) also need to be developed, designed, and commercialized (DOE, 2023; Liu et al., 2022; Moreira & Laing, 2022). Transportation options include pipelines and tube trailers for hydrogen gas and cryogenic tanks for liquefied hydrogen. Other options, particularly for long distance transport, are conversion of hydrogen to ammonia or bounding with liquid organic hydrogen carriers. Hydrogen storage technologies include pressurized containers and salt caverns. The material criticality implications of these technologies are currently uncertain.

Table 2.3. Hydrogen electrolyzer technologies (Iyer et al., 2022).

Current Status	AEC	PEMEC	SOEC
Technology status (IEA, 2023a)	Mature, state-of-the art TRL 9	Commercial TRL 9	Research and development TRL 7
Operating temperature (°C)	60–90	50–100	650–1000
Efficiency (%)	60–80	80	>99
Lifetime (h)	60,000–90,000	30,000–90,000	500–2000
Current density (A/cm2)	0.2–0.6	0.0–3.0 (up to 20)	0.0–2.0
Cathode catalyst	Ni foam Ni-stainless steel Ni-Mo ZrO_2-TiO_2	Platinum	Ni-YSZ Ni-GDC cermet (gadolinia-doped ceria)
Anode catalyst	Ni_2, CoO_4, $LaSrCoO_3$, Co_3O_4	Iridium oxide (Ruthenium oxide, though with reduced stability)	$(La,Sr)MnO_3$, $(La,Sr)(Co,Fe)O_3$
Electrolyte	20–40 wt.% Potassium hydroxide (KOH) (aqueous)	Perfluorinated sulfonic acid (PFSA)	Yttria-stabilized zirconia(YSZ) Sc_2O_3-ZrO_2 MgO-ZrO_2 CaO-ZrO_2
Separator material	ZrO_2 on polyphenylsulfone Asbestos Polysulfone-bonded poly-antimonic acid NiO Polysulfone impregnated with Sb_2O_5 polyoxide	Polymer membrane	Ceramic
Current distributor	Nickel	Titanium	Ferritic stainless steel

2.4 Solar Energy

2.4.1 Importance of Solar Energy to the Global/U.S. Economy and Critical Infrastructure

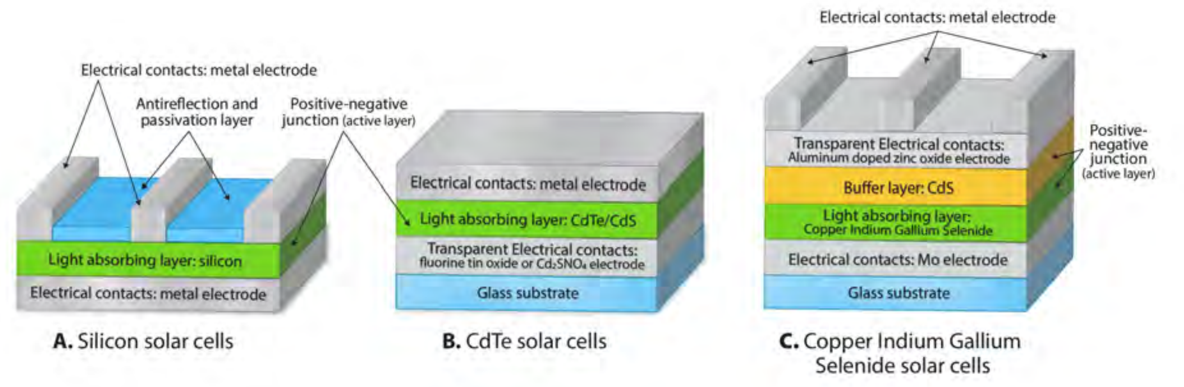
In 2021, more than 1,000 terawatt-hours (TWh) of global energy was generated by solar power (Bojek, 2022). An increase of 179 TWh from 2020 showed a growth in generation of 22% (Bojek, 2022). Solar photovoltaic (PV) contributed to 3.6% of global electricity generation (Bojek, 2022) and to 4.5% of the U.S. electricity generation (Solar Energy Industries Association, 2022). However, with ambitious goals to achieve NZE, the share of the solar energy supply will need to reach 23% globally (IEA, 2022i) and ~45% in the United States by 2050 (DOE, 2021). The high growth of solar in the United States comes from federal policies like the solar Investment Tax Credit, declining costs, and increasing demand (Bojek, 2022). However, high soft costs including installation labor, customer acquisition, permitting, inspection, and interconnection remain a major challenge for growth.

The global solar market was highly valued at between $146 billion (Grand View Research, 2021) and ~$168 billion (Fortune Business Insights, 2021b). Its market value has grown by 6% in 2021 despite supply chain disruptions from the COVID-19 pandemic. Currently, the solar market is dominated primarily by crystalline silicon (~88%) followed by thin-film PV at 9%, including by cadmium-tellurium (CdTe), amorphous silicon, and copper indium gallium selenide solar cell (CIGS) and other unspecified PV devices at 3% (BCC Publishing, 2022).

The most recent Russian–Ukraine invasion has spurred sanctions on Russian fossil fuels (European Commission, 2023). Given supply shortages and price increases, some have turned to renewables to supplement energy needs (Nadig, 2023). The invasion spurred a record in wind and solar production in Europe, which offset 11 billion euros of natural gas in 2022 (Bove, 2022). In 2022, an extra 40 GW of solar was installed, which represents a 45% gain from 2021 (Myllyvirta, 2023). Despite increased renewables production, it was not enough to offset the loss of natural gas from Russia. The European Union has resolved to achieve energy independence from Russia, part of which involves an extra 1,236 GW of wind and solar by 2030 (Myllyvirta, 2023).

2.4.2 Current and Emerging Technologies

This report focuses on silicon, CdTe, and CIGS solar cells, which use silicon, tellurium, and indium/gallium, respectively. Regardless of the device generation, all PV devices rely on a light-absorbing layer to generate an electron-hole pair (also known as the active layer), as shown in Figure 2.5. An internal electric field generated within the absorbing layer separates the electron-hole pair and drives them to separate metal contacts known as electrodes (i.e., anodes and cathodes). Once in the electrodes, the electrons and holes may be used to perform work (i.e., powering electronic circuits) before returning into the solar cell to repeat the process.



A. Silicon solar cells

B. CdTe solar cells

C. Copper Indium Gallium Selenide solar cells

Figure 2.5. Cross structure schematic of A. Silicon solar cells, B. CdTe solar cells, and C. CIGS solar cells.

Traditional silicon panels are made from many silicon wafers that are hundreds of microns thick and linked together within a panel enclosure. These are the most common commercially available solar panel today. Thin-film panels are made using vacuum deposition techniques. These films typically range from hundreds of nanometers to a few microns thick. Thin-film materials include organic materials, copper zinc tin sulfide (CZTS), CdTe, CIGS, and perovskites. These materials typically absorb light much better than silicon but suffer from a variety of other problems such as higher internal losses, use of rare materials, and poor stability. Once solved, however, many hope thin-film devices will become a lower-cost alternative to displace silicon. A large variety of manufacturing methods can be used depending on the materials in the device.

2.4.2.1 Current Technologies

2.4.2.1.1 Silicon Solar Cells

Silicon is the most popular PV 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 Publishing, 2022), which consumed about 4.0% of total mined silicon that year. While past projections consistently overestimated silicon's decline in the PV market (Dimmler, 2012; van Sark et al., 2007; Weckend et al., 2016), the continued dominance of silicon demonstrates its importance to the PV industry. Much of silicon's success was due to low-cost production from China, which put all U.S.-based silicon solar cell manufactures out of business (Basore & Feldman, 2022). The historical trend of maintaining 87% market share is not likely to fluctuate significantly, especially given that newer technologies like CdTe and CIGS tend to be dominated by smaller manufacturers.

Although silicon itself is highly abundant, silicon solar cells rely on screen-printed metal contacts that contain silver (Ag). Ag represents about 10% of the cost of the cell, and the global PV industry consumes about 10% of the world's production of Ag (Bellini, 2021a). Although consumption of Ag in the future will increase as global PV manufacturing expands, it is not likely that the availability of Ag will become a constraint because the amount of Ag required per cell is decreasing with time. The amount of Ag required for the most common type of silicon solar cell, now 80 milligrams per cell, is expected to drop to 50 milligrams per cell over the next 10 years (Fischer et al., 2023). Furthermore, Ag is the most likely component of PV modules to be recycled in the future, and less expensive alternatives to Ag are being actively investigated.

2.4.2.1.2 CIGS Thin-Film Solar Cells

CIGS solar cells contain both gallium and indium in its composition. CIGS cells account for only less than 1% of global solar production in 2021 (Fraunhofer Institute for Solar Energy Systems ISE, 2022). The largest CIGS manufacturing plant in the world is located in Japan but terminated its CIGS line in 2021 in favor of manufacturing silicon solar cells instead (Bellini, 2021c). From 2000 to 2021, the percent market share of CIGS technology has fluctuated between 0–2.5% but has currently fallen to 0.0% for utility-scale projects. Current CIGS production satisfies small niche applications, such as defense and unmanned aerial vehicles (Ascent Solar, 2023). Complex fabrication procedures, which unforgivingly affect device efficiency and quality, use of rare materials, and lower efficiencies for large area devices (ranging from 14–19%) (Diermann, 2021; Sinetech Energy, 2022) inhibit CIGS cells from competing effectively against silicon solar cells.

2.4.2.1.3 CdTe Thin-Film Solar Cells

Tellurium (Te) is used in CdTe thin-film solar cells within the active layer. Aside from CdTe thin-film solar PV, tellurium is utilized in thermoelectric devices, as a rubber vulcanizing agent, a metal alloy, and as a catalyst. To date, CdTe has been the only thin-film solar cell technology that has been able to compete with mainstream silicon devices.

Global CdTe thin-film solar PV utilization has increased from negligible levels in the mid-2000s to over 6 GW per year in 2020. The rise of CdTe thin-film solar technology can be attributed to its low cost, ease of manufacturing, and optimal bandgap for light absorption (Nassar et al., 2022). The current demand for CdTe thin-film solar cells varies significantly both globally and domestically. It is estimated that CdTe thin-film solar PV supplies 40% of the U.S. utility-scale PV market and 5% of the world market (U.S. Manufacturing of Advanced Cadmium Telluride Photovoltaics Consortium, 2022). Due to the overall projected growth for solar PV installations, total production in GW of CdTe solar panels is expected to grow. However, industry expert projections forecast that CdTe market share for new installations will remain around 5% globally (First Solar, 2022) for the high scenario and 2% for the low scenario (Solar Energy Technologies Office, 2023).

2.4.2.2 Emerging Technologies

2.4.2.2.1 Perovskites

Perovskites are a special class of materials defined by their crystal structure and have been used for many different applications. A recent and popular application for perovskites is solar cells. The efficiency of perovskite solar cells rapidly grew from 3.8% efficiency in 2004 to 25.2% in 2021 (Kim & Kim, 2021). The most popular lead-halide perovskite crystal used for solar applications has excellent electrical properties, very high light absorption, low-cost fabrication, and low weight. These benefits have convinced many that perovskites will play a significant role in the future of commercial solar technology. Regardless of the technology’s success, the unique properties of the lead-halide crystal should be studied to understand what makes it such a good material for solar applications. Grasping these fundamentals could lead to more efficient and environmentally friendly engineered PV materials.

A solar cell’s semiconductor bandgap sets the colors of light that it is able to absorb. The bandgap of perovskites can be tuned to absorb different colors of light, which makes them excellent candidates for tandem solar cell devices. Tandem solar cells attempt to overcome light absorption limitations by stacking two complementary light-absorbing layers on top of each other. For example, a two-layer tandem device may have a top layer that absorbs blue light and a bottom layer that absorbs red light. More layers in a tandem device directly translates to higher potential device efficiencies, but that gain occurs at the expense of greater fabrication complexity and cost. Silicon-perovskite tandems have been popular because the silicon layer is not affected by the perovskite deposition and both materials have excellent PV properties. Efficiencies of 32.5%

have been achieved (Zheng et al., 2023) for small area devices, which still leaves plenty of room for improvement toward this combination's theoretical efficiency limit of 43% (Werner et al., 2018; Zheng et al., 2023) .

The main drawbacks of perovskites are the low stability and the use of lead within the crystal structure. Device encapsulation has been the main approach to the lead issue as lead-free perovskite alternatives suffer from low efficiency (Chen et al., 2023). Perovskite degradation and instability occurs from environmental variables such as heat, moisture, oxygen, and light (Duan et al., 2023). Current research on device stability explores stabilizing additives and device encapsulation to block out moisture and oxygen. Devices kept under inert atmospheres have lasted for more than 10,000 hours (Y. Li et al., 2021). By adding stabilizing monolayers inside the device (to prevent interlayer diffusion), some have reported accelerated aging tests, which predicted device lifetimes of 20 years (Zhao et al., 2022). For large area modules, the best results (for a silicon-perovskite tandem) to date maintained 75% of the original 21.7% model efficiency after a 500-hour test (Xiao et al., 2022). To compete with silicon devices, acceptable degradation rates ultimately depend on initial device efficiency. For example, a 24% efficient device needs a 21-year life vs. a 27% efficient device needs to last only 15 years to be cost competitive with silicon (Čulík et al., 2022). Some believe that, with a strong research thrust on device stability and large area device fabrication, these challenges could be solved within 5–10 years—and thus commercial tandem perovskite-silicon devices would become available on the market (Duan et al., 2023).

2.4.2.2.2 Organic Solar Cells

Organic solar cells use a variety of different semiconducting polymers to make solar cells. Generally, semiconducting polymer devices are lightweight, mechanically flexible, and have excellent light absorption properties that can be tuned to absorb a larger range of light wavelengths. For example, some polymer solar cells can be used as power-generating windows by absorbing invisible light and allowing visible light to pass through (Sun & Jasieniak, 2017). The main drawback of polymer solar cells is non-ideal electrical properties of polymers and device stability. The performance of larger area devices is very sensitive to fabrication defects. The current record for small area device efficiency, reported in 2022, was 19.1% (Zhu et al., 2022). Conversely, larger area devices can range from 1% to 5.5% efficiency with corresponding lifetimes of 17,500 hours and 2,000 hours, respectively (Park et al., 2020). Small area devices of 10% efficiency have demonstrated more than 34,000 hours of battery life (X. Xu et al., 2020). Other small area devices (12% efficiency) under accelerated age testing were estimated to last for more than 30 years (Liu et al., 2021). For polymer solar cells to compete with silicon, the performance gap between small- and larger-scale fabrication needs to shrink.

2.4.2.2.3 Other Technologies

Dye-sensitized solar cells (DSSCs) and quantum dot solar cells are another unique class of solar cells that have shown significant improvements in device power conversion efficiency, although these are still well below other thin-film approaches.

2.4.3 Overview of Components and Materials Used in Solar Energy Technologies

2.4.3.1 Silicon Solar Cells

The fabrication of silicon solar cells starts with silicon ingots, which are cut into thin wafer slices using a diamond wire saw. The cutting process typically incurs a 33%–40% loss of silicon material as kerf waste (IEA, 2020b; J. Li et al., 2021). The wafers are then polished, textured, and doped (i.e., a high-temperature gas diffusion process designed to introduce functional impurities) (Basore & Feldman, 2022). Additional fabrication steps depend on the type of silicon solar cell being manufactured but may include various coating treatments (e.g., surface passivation and anti-reflection layers), wet chemical etching, and laser etching (Basore & Feldman, 2022). Electrodes are screen-printed on the wafers to form an individual solar cell followed by quality control inspections. The cells are then linked together inside a laminated panel to be sold to customers. Approximately 3 grams of silicon per watt are used to make a silicon solar cell (IEA, 2020b).

2.4.3.2 CIGS Thin-Film Solar Cells

Materials of interest in CIGS thin-film solar cells include both indium and gallium. These thin-film cells only require a thickness of a few microns in comparison to crystalline-silicon cells, which requires about 200 microns (Salhi, 2022). Despite requiring small amounts of material, the vacuum deposition/co-evaporation fabricating methods normally used to fabricate CIGS cells waste about 20% to 60% of the material (Hibberd et al., 2010; Uhl et al., 2012) and increase fabrication costs on a mass production scale (DOE, n.d.-a). Another production method is known as a precursor reaction process, where deposition of copper, indium, and gallium occurs through sputtering or electroplating (DOE, n.d.-a). Once deposited, selenium is annealed to the deposited layer in the form of hydrogen selenide or gaseous selenium (DOE, n.d.-a).

Once the CIGS layer is deposited through either of the two methods described above, cadmium sulfide is deposited through a chemical bath deposition to form the junction (DOE, n.d.-a). Next, zinc oxide is deposited through sputtering or chemical vapor deposition (DOE, n.d.-a). Molybdenum is deposited through sputtering on the back contact of the cell (DOE, n.d.-a). Lastly, the CIGS cell resides on a glass substrate comprised of soda lime glass which increases performance of the cells due to its similar thermal expansion properties and through sodium diffusion to the CIGS layer (DOE, n.d.-a).

2.4.3.3 CdTe Thin-Film Solar Cells

In CdTe thin-film solar cells, CdTe composes an active layer of several microns thick with an approximately 47% Cd and 53% Te matrix. Material intensity for Te has fallen sharply over time due to decreases in thickness and improvements in the module design of CdTe panels. Older CdTe solar PV cells had Te material intensities ranging from 60–100 tonnes/GW (McNulty & Jowitt, 2022; Redlinger et al., 2015). The current material intensity of Te, approximately 36 tonnes/GW, has been demonstrated by the U.S. producer First Solar (First Solar, 2022) and is expected to continue to trend downward to 20–27 tonnes/GW by 2040 (Alves Dias et al., 2020). A further discussion on Te intensity in CdTe thin-film solar PV can be found in Appendix B.

2.4.3.4 Power Electronics

Solar inverters (or grid-tie inverters) are one of the primary power electronics components used in solar systems to convert the DC generated by solar panels into AC for electric grid integration and transmission. Typically, the maximum power point trackers (MPPTs) control strategy is used in inverters to adjust panel voltage and to maximize the energy conversion efficiency of the solar panel. For some large solar power plants or solar farms, these inverters can be aggregated up to several hundred megawatts. Examples of large solar projects in the U.S. include a NextEra project with a capacity of 250 MW and a Roadrunner project with a capacity of 450 MW (Roy et al., 2022).

For solar inverter applications, wide bandgap devices such as GaN or SiC might offer potential advantages with higher switching frequency and efficiency, but they are still in the early stages of development and deployment. The solar industry does not have critical size or fast dynamic response requirements for power electronics compared to the EV industry (Roy et al., 2022; Zhang et al., 2019). Therefore, silicon-based power electronics inverters remain the solar industry standard due to their established performance, cost-effectiveness, and infrastructure. Si-based electronics accounted for 76.0% of PV and energy storage applications in 2022, followed by SiC-based electronics at 23.6% (Chiu & Dogmus, 2022; Rosina & Villamor, 2022). SiC electronics have been used for both residential and commercial PVs, at power levels of 10 kW to 200 kW (Chiu & Dogmus, 2022). SiC power-switching modules rated at 1.2 kV offer higher power and lower losses. GaN penetration for PV and energy storage inverters is still limited, contributing 0.4% market share in 2022 (Ayari & Chiu, 2022).

2.5 Wind Energy

2.5.1 Importance of Wind Energy to the Global/U.S. Economy and Critical Infrastructure

Wind energy uses turbines to convert kinetic energy from wind into electricity. Because wind energy is renewable and does not emit greenhouse gases to produce electricity, the technology is critical to reducing carbon emissions from the electricity sector to meet climate goals. Projections are that more than 100 GW of wind capacity will be added annually through 2030 (BloombergNEF, 2022). The global wind energy market is projected to be worth about $174.75 billion by 2030 with a compound annual growth rate (CAGR) of 9.4% over the 2021–2030 period (Precedence Research, 2021b). This expected wind boom is the result of aggressive decarbonization targets throughout the world, with a focus on offshore wind. The U.S., for example, set its goal of deploying 30 GW of offshore wind by 2030, which will unlock a pathway to 110 GW by 2050 (The White House, 2021).

Onshore wind energy is the power generated by wind turbines located on land and driven by natural movement of the air, while offshore wind farms generate electricity from wind blowing over the seas. Offshore turbines are generally considered more efficient because of the higher speed of winds, greater consistency, larger size, and lack of physical interference that the land or human-made objects can present. Figure 2.6 shows different types of offshore turbines.

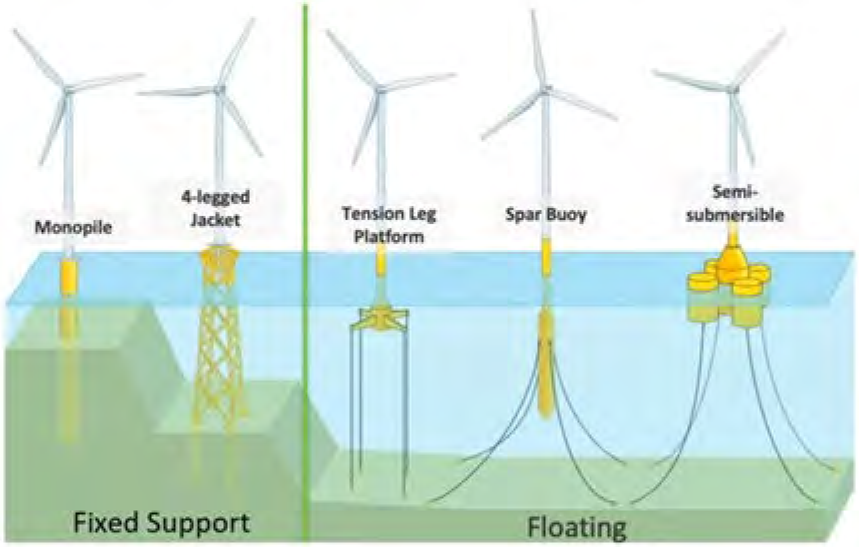


Figure 2.6. Support structures for offshore wind turbines (NREL, 2020).

Wind power has grown rapidly over the past two decades. According to the International Renewable Energy Agency (IRENA), the global capacity of installed wind generation increased by a factor of 98 between 1997 and 2018, growing from just 7.5 GW to 733 GW (IRENA, n.d.). Between 2010 and 2020, onshore wind capacity grew from 178 GW to 699 GW, while offshore wind grew from just 3.1 GW to 34.4 GW, respectively (IRENA, n.d.). These increases in capacity led to an increase by a factor of over 5.2 in total generation between 2009 and 2019 to reach 1412 TWh (IRENA, n.d.).

In the United States, there are more than 500 manufacturing facilities specializing in various wind turbine components (blades, towers, and generators) and turbine assembly (Wind Energy Technologies Office, n.d.). According to DOE's Wind Energy Manufacturing Office, modern wind turbines are increasingly cost effective and reliable, and advancements in composite materials, automation, and manufacturing processes have helped domestic manufactures dramatically increase productivity (Wind Energy Technologies Office, n.d.).

2.5.2 Current and Emerging Technologies

Wind turbine markets have trended toward larger turbines that can generate more power from a single turbine. Average nameplate capacity per wind turbine reached 3 MW for newly installed turbines in the U.S. in 2021, and new 15-MW and 16-MW models of offshore wind turbines are nearing commercial availability (Musial et al., 2022). As offshore turbines have become more common, new mounting structures such as floating turbines have begun to be deployed commercially only recently (Musial et al., 2022).

The most common type of generator used in onshore wind turbines is a double-fed induction generator (DFIG). This generator requires a gearbox to translate lower-speed rotation of turbine blades to the higher rotation speeds required for the generator. Direct-drive generators avoid the use of a gearbox and can be used with permanent magnet synchronous generators (PMSGs) or electrically excited synchronous generators (EESGs). The use of direct-drive PMSGs can increase efficiency and reduce maintenance needs relative to DFIG turbines due to the lack of a gearbox (Osmanbasic, 2020). However, a PMSG requires a large and expensive permanent magnet. A third alternative is a hybrid generator, which combines a simplified gearbox to increase generator speed with a smaller permanent magnet generator. In the offshore sector, direct-drive PMSG turbines are the leading choice with about 60% of the market worldwide due to lighter and more efficient attributes as well as lower maintenance costs, whereas the onshore wind market is currently dominated by gearbox-DFIGs, with about 70% of the global market (IEA, 2021b).

2.5.3 Overview of Components and Materials Used in Wind Energy Technologies

Wind turbines are made up of foundations or substructures, towers, nacelles, hubs, blades, cables, and substations (OpenEI, n.d.). These structures contain electrical components, including wiring, power electronics, and generators, which are typically either DFIGs or PMSGs.

2.5.3.1 Wiring

Copper is indispensable to the appropriate functioning and efficiency of wind turbines, playing a central role in the inner workings of generators, grounding the towers, and carrying the electrical current where it needs to go (Copper Development Association, 2010). Cu needs for wind power depend on the turbine type: gearbox or direct drive. For the two most commonly used gearbox wind turbine types, the DFIG and PMSG require about 2.9 tons/MW and 2.4 tons/MW, respectively (IEA, 2021b). For the direct-drive wind turbine type, PMSG and EESG require about 4.5 tons/MW and 6.5 tons/MW (IEA, 2021b). These intensity numbers are applicable only to onshore installations. In addition to generators, Cu is also used in other parts of onshore installation, including magnet wire for transformers, cables, and busbars for switchgear. In terms of percentages, 21% of Cu goes into cables within the tower, 20% into cables for interconnecting towers, 19% into the turbine transformer, 13% into switchgear, 11% into the generator and power electronics, 9% into ground wires and connectors, 4% into the step-up transformer, 2% into cables from the tower to the pad transformer, and 1% into control wiring (Broehl & Gauntlett, 2018). More Cu is needed in offshore installations given the need for longer cabling (IEA, 2021b). The Cu content in offshore turbines can range from about 8 tons/MW to 9.5 tons/MW (Copper Development Association, 2022b; IEA, 2021b).

2.5.3.2 Generators and Transformers

There are two major components in a wind turbine that contain electrical steel: the generator and the transformer (ArcelorMittal, n.d.-b). In a wind farm, each turbine contains its own step up generator that takes the low-voltage output from the wind turbine generator and transforms it into a medium voltage (Ayers & Dickinson, 2011). Medium-voltage transformers are preferred for use in the turbine. These transformers are responsible for electricity delivery to the wind farm substation before the voltage is stepped up with another transformer to a high voltage for connection with the existing electricity network (EWEA, n.d.). Generally, medium-voltage transformers such as those found in wind turbines require grain-oriented electrical steel (GOES) as part of the transformer core (U.S. Department of Commerce, 2020). GOES is found in stationary equipment such as transformers where the magnetization direction occurs in only one direction (Hayakawa, 2022).

Typically, the generators found in wind turbines require nongrain-oriented electrical steel (NOES) (ArcelorMittal, n.d.-a; Heller et al., 2022). NOES is found in rotating electrical machines such as electrical motors and generators. In wind turbine generators, high-speed machines such as those of gear drive turbines require lower-loss electrical steels (ArcelorMittal, n.d.-a). Low-speed machines such as direct-drive machines require highly permeable electrical steel grades (ArcelorMittal, n.d.-a).

The PMSGs commonly used in offshore turbines rely on large NdFeB magnets. Direct-drive PMSG turbines use the largest magnets, estimated at 650 kg/MW, while PMSGs with gearboxes use smaller magnets, estimated at 200 kg/MW (DOE, 2019; Imholte et al., 2018). Materials contained in these magnets include Nd, Pr, Dy, Fe, B, Tb, and Ga. Nd, Pr, Fe, and B make of the base of the magnet, while Dy, Tb, and Ga can be added to increase performance and stability at high temperatures. Wind turbine generators typically operate at temperatures that require some addition of Dy, Tb, and/or Ga, although the temperatures are lower than in EV motors, leading to different material requirements.

2.5.3.3 Power Electronics in Wind Turbines

Onshore wind uses power electronics components including power converters that serve three functions: (1) control the power flow between the wind turbine and the grid, (2) regulate voltage or current depending on different control strategies, and (3) improve power quality for grid integration such as reactive power compensation and fault ride-through capability (Roy et al., 2022). Most of the power electronics devices, materials, and control strategies used in onshore wind farms are also needed for offshore wind farms. The only difference is that offshore wind farm integration requires modular multilevel converters (MMCs) for high-voltage direct current (HVDC) transmission technologies to ensure long-distance and high-power energy transmission from offshore wind farms to onshore sites. MMC-HVDC is a popular converter topology (Zhang & Nademi, 2020).

The wind market is dominated by onshore installation, which is highly subsidized and very cost competitive (Chiu & Dogmus, 2022). Silicon-based, insulated-gate bipolar transistors (IGBTs) are the leading power electronic devices used at wind farms, accounting for 99.8% of market value for this application due to its established technology, cost effectiveness, and higher-rated voltage and power density. While SiC is a promising wide-bandgap semiconductor material, its target is the onshore market at voltage levels of 1.7 kV to 3.3 kV. For offshore applications, the voltage requirement is 3.3 kV to 6.5 kV, for which SiC devices will require time to catch up (Chiu & Dogmus, 2022). SiC market penetration for wind application is still limited at 0.2% in 2022.

2.6 Nuclear Energy

2.6.1 Importance of Nuclear Energy to the Global/U.S. Economy and Critical Infrastructure

Nuclear energy represents an important part of the current clean energy economy in that it produces no carbon dioxide during operation (EIA, 2022e; IEA, 2022i). As of 2022, nuclear power accounted for about 10% of electricity generation in the world (IEA, 2022h) and ~18% in the United States (EIA, 2022f). However, uncertainty surrounds nuclear power's future due to variations between different countries' approaches and mindsets toward nuclear power (IEA, 2022h). Typically, nuclear power is used as a base load energy source due to its low-cost fuel and steady-state power generation (Penn State, 2022). Base-load energy sources are not typically designed to respond to fluctuations in consumer energy demand as the best economic outcome results from maximum capacity utilization (Pepin, 2018).

2.6.2 Current and Emerging Technologies

The current global nuclear reactor portfolio as of 2021 consists mainly of two types of reactors: light water reactors (LWRs) and pressurized heavy water reactors (PHWRs), which together represent 96% of the global reactor fleet by reactor count (IAEA, 2022b; World Nuclear Association, 2022a, 2022c). Within the category of LWRs, several different designs are currently deployed around the globe, including the pressurized water reactor (PWR), the boiling water reactor (BWR), and the light water graphite-moderated reactor (LWGR), which represent 69%, 14%, and 2.5% of the global reactor fleet, respectively (IAEA, 2022b; World Nuclear Association, 2022c). The remaining operating designs include the gas-cooled reactor (GCR), the high-temperature gas-cooled reactor (HTGR), and the fast breeder reactors (FBRs).

Emerging technologies in the nuclear industry typically revolve around a term known as "advanced reactors" (Nuclear Innovation Alliance, 2022). These advanced reactors include designs such as small modular reactors (SMRs), molten salt reactors (MSRs), micro-reactors, and HTGRs (Nuclear Innovation Alliance, 2022). One of the key changes in some of the newer reactor designs is the fuel type that is being utilized. In many designs, high-assay low-enriched uranium (HALEU) is required as the input fuel (Nuclear Innovation Alliance, 2022). HALEU is a fuel type that has been enriched to yield 5%–20% U-235 compared to the conventional 3%–5% enrichment used in today's reactors (DOE, 2022b). However, one of the major challenges moving forward will be the availability of HALEU fuel—although that discussion is outside the scope of this assessment.

2.6.3 Overview of Components and Materials Used in Nuclear Energy Technologies

There are seven components commonly found in most types of nuclear reactors, including (1) fuel, (2) moderator, (3) control rods or blades, (4) coolant, (5) pressure vessel or pressure tubes, (6) steam generator, and (7) containment (World Nuclear Association, 2022c). The following discussions will focus on the first two components and their essential materials.

2.6.3.1 Nuclear Fuels

Uranium is the most common fuel source in nuclear reactors (EIA, 2022d) and mainly consists of two isotopes, U-235 and U-238. Of these two, only U-235 is capable of producing energy through the fission process used in nuclear reactors (World Nuclear Association, 2022d). In nature, U-235 is typically found at a concentration of about 0.7% with the remaining 99.3% being mostly U-238 (World Nuclear Association, 2022d). However, in order for uranium to be used as a nuclear fuel, the U-235 concentration needs to be increased or "enriched" through a process known as enrichment (World Nuclear Association, 2022d). Typical reactor designs such as light-water reactors (LWRs), which make up the largest market share of reactor designs at 85% (World Nuclear Association, 2022a), require U-235 concentrations to be between 3%–5% (World Nuclear Association, 2022d).

The primary production of nuclear fuel can be summarized as follows: (1) mining of natural uranium, (2) conversion of uranium, (3) enrichment of uranium, and (4) fuel fabrication (World Nuclear Association, 2021b, 2022b, 2022d, 2022e). The mining of natural uranium involves several steps, with the end product in the chemical form of U_3O_8, also known as yellowcake uranium (World Nuclear Association, 2022e). Once mined, the uranium needs to go through a process known as “conversion” to transition to a form suitable for the subsequent enrichment process (World Nuclear Association, 2022b). The conversion process yields a product of uranium hexafluoride (UF_6) (World Nuclear Association, 2022b). Estimates of 2020 global conversion capacity were 62,000 metric tons (mt) of uranium from five companies with only 51% of that capacity being utilized (World Nuclear Association, 2022b). Once converted to UF_6, uranium can undergo the enrichment process to yield the required U-235 concentration (World Nuclear Association, 2022d). The uranium enrichment market consists of only three major producers operating their largest facilities in France, Germany, the Netherlands, United Kingdom, United States, and Russia (World Nuclear Association, 2022d). Because uranium enrichment is a multifaceted process that involves multiple variables to achieve the desired uranium output, production capacity is not simply measured in mt uranium. Instead, a unit known as separative work units (SWUs) is used to define enrichment capacity (World Nuclear Association, 2022d). SWUs are a measurement that encompasses the energy required for enrichment and the level of enrichment, the starting enrichment value, the final enrichment value, and the final tails assay value (World Nuclear Association, 2022d). Globally in 2020, enrichment capacity was reported as 60.2 million SWUs/year with approximately half of the capacity being located in Russia. Finally, the uranium arrives at the fuel fabrication facility in two possible forms: UF_6 or uranium trioxide (UO_3) (World Nuclear Association, 2021b). Fuel fabrication requires the conversion of the UF_6 or UO_3 into UO_2 (uranium dioxide) where the UO_2 can be made into ceramic pellets before being loaded into fuel rods (World Nuclear Association, 2021b). Fuel fabrication capacities are also reported in different units than the previous stages as capacity is now a function of pellet manufacturing rather than U-235 enrichment levels (World Nuclear Association, 2021b). LWR fuel fabrication capacity estimates are 12,645 mt/year, 13,913 mt/year, and 15,476 mt/year for conversion, pelletizing, and rod assembly, respectively (World Nuclear Association, 2021b). PHWR fuel fabrication capacity is 5,476 mt/year for rod assembly. Other fuel fabrication processes exist, for example: mixed oxide (MOX) fuel, regenerated mixture (REMIX) fuel, TRi-structural ISOtropic particle (TRISO) fuel, etc. However, these have smaller capacities and are not explicitly considered for this assessment (World Nuclear Association, 2021b).

Additional fuel types include MOX fuel, which consists of plutonium recovered from used reactor fuel and mixed with depleted uranium (World Nuclear Association, 2017). MOX fuel accounted for about 5% of the nuclear fuel used in 2017 (World Nuclear Association, 2017) and can be used as a full fuel load by three U.S. reactors and Canadian heavy water (CANDU) reactors (World Nuclear Association, 2021d). Additionally, all later Russian light-water reactors and western reactors can use up to 30% MOX in their total fuel composition (World Nuclear Association, 2021d).

2.6.3.2 Cladding

Most nuclear fuel requires a rigid, metallic structure in the form of rods or tubes that form the outer layer of a nuclear fuel rod (NRC, 2021a). This structure is referred to as the “cladding” of the fuel. Cladding prevents fuel corrosion and the fission products’ escape into the environment. Common cladding materials include aluminum, stainless steel, and zirconium alloys (zircaloys) (NRC, 2021a). Zircaloys are used as the nuclear fuel cladding in nearly all light- and heavy-water nuclear reactor cores because of their low capture cross section to thermal neutrons and their good corrosion resistance (Onimus & Béchade, 2012; Zircon Industry Association, 2023). Zirconium (Zr) is commonly found in nature with 1–3 wt.% hafnium, which for nuclear applications needs to be reduced to under 100 ppm hafnium in order to be qualified as nuclear grade (Xu et al., 2015). Once purified, Zr can be alloyed into nuclear fuel cladding. Common Zircaloys include Zircaloy-2, Zircaloy-4, ZIRLO ®, and M5® (NRC, 2014). Zircaloy-2's composition includes 1.5% tin (Sn), 0.15% iron (Fe), 0.1% chromium (Cr) and 0.05% nickel (Ni) in addition to Zr. This alloy is used in BWRs and CANDU reactors (Allegheny Technologies Incorporated, 2015). Zircaloy-4, containing 1.5% Sn, 0.2% F,e and 0.1% Cr, is used in PWRs and CANDU reactors (Allegheny Technologies Incorporated, 2015).

2.6.3.3 Moderators

A moderator in a nuclear reactor is a material like water, heavy water, or graphite that is used to slow down the neutrons in the reactor core from their high velocities (NRC, 2021b). By decreasing the speed of the high-velocity neutrons, the likelihood of fission is increased (NRC, 2021b). Most nuclear reactors utilize water as a moderator (World Nuclear Association, 2022c). PWRs, BWRs, and PHWRs make up approximately 94% of the global reactor fleet and utilize water and heavy water as a moderator, respectively (IAEA, 2022b; World Nuclear Association, 2022a, 2022c). Graphite is used as a moderator in gas-cooled reactors (GCRs); advanced gas-cooled reactors (AGRs), which are a subtype of GCRs; light-water graphite-moderated reactors (LWGRs), and high-temperature gas-cooled reactors (HTGRs) (EDF Energy, 2023; World Nuclear Association, 2022c). However, the physical structure of graphite for moderation can be divided into two separate mechanisms. First, GCRs, AGRs, and LWGRs utilize a physical graphite structure in the reactor core, whereas HTGRs utilize graphite as part of the fuel source by encasing uranium with graphite in hexagonal blocks or spherical pebbles (World Nuclear Association, 2021a). It is important to note two key differences between these two mechanisms. First, the former requires graphite on a one-time basis, during construction, and the latter requires graphite on a continual fuel consumption basis. Second, GCRs, AGRs, and LWGRs typically use synthetic graphite for moderators and reflectors, and only HTGR reactors require natural graphite in their fuel design.

2.7 Electric Grid

2.7.1 Importance of Electric Grid Technologies to the Global/U.S. Economy and Critical Infrastructure

The electric grid is a critical infrastructure that powers the global economy. Energy is generated at the power plants (coal, gas, wind, solar, hydropower, nuclear, etc.), then converted to high voltage for long-distance transmission at the step-up substations. It is subsequently converted to lower voltage at step-down substations before being distributed to industrial, commercial, and residential users. The global power grid market was valued at $271.43B in 2022. This market will grow at a CAGR of 4.37% to reach $414.91B by 2032 (Polaris Market Research, 2023). These market values accounted for values of components such as cables; transformers; switchgears; and variable speed drives that are used for generation, transmission, and distribution. The U.S. grid encompassed ~7,300 power plants, about 146,000 miles of high-voltage power lines, millions of low-voltage power lines, and transformers to serve 145 million customers in 2016 (EIA, 2016). It was estimated that $1.5 trillion to $2 trillion is required to modernize and $4.8 trillion to replace the U.S grid (Business Insider, 2017).

There are two key driving factors for the electric grid market (Polaris Market Research, 2023). First, renewable energy growth due to net-zero carbon emissions targets and the need for energy resilience has led to the growth of smaller-scale power plants and a distributed grid closer to end users. Renewable energy integration also requires grid expansion and modernization with added sensors, automation systems, and analytical tools to manage energy in real time (Polaris Market Research, 2023). Second, demand from manufacturing, health care, and data centers is increasing as a result of urbanization and industrialization. Because earlier sections already discussed renewable energy sources such as solar, wind, and hydrogen, which are typically integrated into the grid as distributed renewable energy sources, this section focuses on the large-scale and macro transmission grid.

2.7.2 Current and Emerging Technologies

The traditional grid is run on alternating current (AC), which widely exists and is a major component of the U.S. grid. However, with the critical need of integrating more renewable energies into the grid, the HVDC grid becomes increasingly important for nationwide macro grid interconnection (Acevedo et al., 2021). HVDC technology provides highly efficient ways to receive, transmit, and deliver a large amount of renewable energy over long distances. Globally, HVDC is the major electric power transmission technology for long-distance and high-power grid network connection. However, its market share in terms of installation capacity is still small compared to HVAC as shown in Figure 2.7.

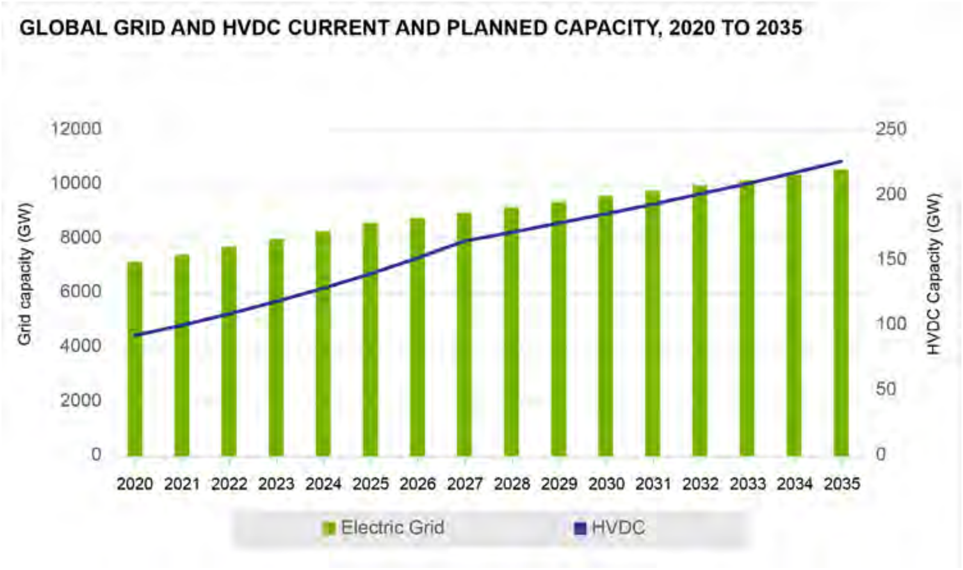


Figure 2.7. Global grid and current and planned HVDC capacity levels until 2035

Compared to high-voltage AC power system networks, HVDC transmission has the following advantages:

- HVDC technology is more economical for long-distance and high-power electricity transmission. It does not require reactive power compensation to boost the power factor compared to AC transmission as the distance increases. Typically, HVDC networks become more cost effective for longer distances compared to AC systems. However, there is not a universal rule of thumb on what the minimum distance should be. While one source indicated 400 miles (GE, 2016), another source mentioned 124 miles (EIA, 2018) for onshore projects. HVDC's preferred feature of long-distance transmission is especially vital for renewable energy to grid integration because large-scale renewable energy harvesting sites — such as offshore wind farm, onshore wind farm, offshore hydrogen harvesting, and solar — are typically in rural or other locations far away from energy demand centers. Thus, HVDC's advantage in terms of long-distance transmission is critical to integrating renewable energy to the grid.
- HVDC technology creates a decoupling and controllable connection terminal with AC/DC converter stations. As a result, the power grid's resilience and security increase compared to the pure AC power grid when having a wide-region AC grid outage or failure (EIA, 2018).
- HVDC technology has better voltage stability compared to the AC grid for long-distance transmission. AC transmission voltage is affected by parasitic capacitance/inductance along the transmission line, but DC transmission does not have this shortcoming (Zhang & Nademi, 2020).

HVDC is a globally emerging technology and the major technology to enable long-distance transmission and integration of renewable energy to the grid. There were about 350 HVDC projects installed and planned globally in 2022 (Transformer Technology, 2022). The global HVDC market value was approximated at $7.8 billion in 2020 with projections to reach $17.4 billion by 2030, a CAGR of 8.6% from 2022 to 2030 (Market Research Future, 2022). Germany and the Netherlands plan to achieve 20 GW and 11.6 GW of production capacity in 2030, respectively, using offshore MMC-HVDC platforms and 525-kV undersea transmission cable systems (Tennet, 2022). In China, tens of ±1,100-kV, ±800-kV, and ±500-kV HVDC systems with over 100 GW capacity are operated across the nation to deliver electricity from the rural northwest areas to economic centers in southeast regions (Yuki, 2021). In the United States, there are only about 20 GW of current or planned onshore HVDC capacity. Two projects constructed and operated before 2000 are using line commutated converter (LCC) HVDC technology while most of the latest HVDC projects are using MMC-HVDC technology. Domestic HVDC capacity is projected to grow to around 39 GW by 2030 (Tariq, 2022), exhibiting a CAGR of 7.7%. The global capacity is estimated to grow at a CAGR of 8.6% from 2021 to 2030 (Market Research Future, 2022).

At the component level, within the HVDC station, DC breakers used for cutting high DC current when there is a grid failure is an emerging technology with applications in multi-terminal HVDCs. Cutting DC current is very challenging from a technology standpoint compared to AC breakers. Therefore, the DC breaker is still in the prototype research and development stage. In 2020, Europe and Asia successfully performed some HVDC breaker (switchgear) prototype tests (Jia et al., 2020; PROMOTioN, 2020). Globally, Hitachi Energy is the leading HVDC breaker manufacturer, successfully achieving 350 kV/20 kA DC current cutting in 2020 for the EU PROMOTioN HVDC project (PROMOTioN, 2020).

2.7.3 Overview of Components and Materials Used in Electric Grid Technologies

The main components in the AC/DC hybrid grid include transformers, converters, AC/DC switchgear (breakers), and transmission lines connecting AC or DC power stations, or submarine cables with offshore wind farms via HVDC converter stations. Materials used in transmission and distribution lines, transformers, converters, and breakers/switches are discussed below.

2.7.3.1 Distribution and Transmission Lines

There are two major categories when it comes to carrying electricity: transmission lines and distribution lines. Transmission lines refer to the wiring system that transports bulk electricity at high voltages across long distances (PG&E, n.d.). These lines conduct electricity from power generating sources to a substation and consist of thicker-diameter material than distribution lines (Circuit Globe, 2016). Distribution lines are the wiring system that delivers electricity to neighborhoods and communities over shorter distances (PG&E, n.d.). They carry electricity from a substation to the end consumers and are thinner in diameter than that of transmission lines (Circuit Globe, 2016). These transmission lines can be deployed as overhead lines or as underground/subsea lines, which require different material selection based on application (Circuit Globe, 2016; PG&E, n.d.). In the future, overhead line deployment is expected to comprise a larger share compared to underground and subsea deployment, because underground and subsea lines require greater material content per unit length compared to overhead line (IEA, 2021b).

Because of differing performance and structural requirements, different materials are required for these applications. Although copper possesses greater electrical conductivity properties than aluminum, its cost and weight can be significant enough to make it an unviable option (IEA, 2021b). For instance, overhead transmission lines typically utilize aluminum (F. Ridley Thrash, 2003; Harbor Energy Solutions, 2020; IEA, 2021b). However, copper can be used for subsea and underground transmission lines due to the mitigation of weight concerns (IEA, 2021b).

Estimates from 2021 indicate that approximately 150 million tonnes of copper and 210 million tonnes of aluminum are in operation today in the electric grid (IEA, 2021b). With projected deployment of clean energy technologies, both distribution and transmission line expansions are expected to grow, leading to increased copper and aluminum demand.

2.7.3.2 Transformers

A transformer in the electric grid is a passive device that transmits electrical power and can be used to change the voltage from one system to another (Baggini et al., 2023). Transformers function based on electromagnetic induction, which means that as alternating current (AC) passes through a winding, the magnetic field generated can induce an AC voltage in a nearby winding (Arrow, 2018). Transformers typically contain two windings, the primary (where input voltage is applied) and the secondary (which receive the output voltage) windings. However, it is possible for multiple primary and/or secondary windings depending on the design and requirements of the transformer (Saini, 2022). These windings are wrapped around a core made of electrical steel.

Transformers vary in application and size, which can dictate the design requirements and material selection. Similar to the case with distribution and transmission lines, two main applications of transformers exist, which are known as distribution transformers and power transformers. Distribution transformers are designed to step down high-level voltages delivered by distribution lines into the usable, low voltages for consumers (Electrical Technology, 2012). Distribution transformers also do not necessarily function at maximum load throughout the day but have fluctuating loads due to end users’ behaviors (Electrical Technology, 2012). Power transformers are designed to both step up voltages from power-generating sources into transmission lines and also step down those same high voltages to be used at distribution substations (Electrical Technology, 2012). Contrary to distribution transformers, power transformers are designed to operate at nearly maximum load every day due to continuous operation (Agarwal et al., 2022). In addition to application differences, sizes of transformers vary widely. Power ratings for power transformers can vary with large power transformers (LPTs) being defined as having a power capacity rating of over 100 megavolt-amperes (MVA) (Nguyen et al., 2022). A distribution transformer is generally defined as a smaller-capacity power transformer. In the U.S., a distribution transformer is defined as having an input voltage of 34.5 kV or less, an output voltage of 600 volts or less, and a rating of operation for 60 Hz (United States Code, 2018).

Transformers consist of several key components such as the core, winding, conservator, tap changer, cooling system, bushings, and tank housing (Nguyen et al., 2022). For this assessment, the key components of concern are the core and winding which consist of electrical steel and copper, respectively (Nguyen et al., 2022). Electrical steel, including both GOES and amorphous steel, is used as the core material for transformers (Hayakawa, 2022; Nguyen et al., 2022). However, their applications in distribution and power transformers vary. Amorphous steel is commonly used in distribution transformers due to its lower no-load energy losses (Najafi & Iskender, 2018). Amorphous steel has the potential to lower core losses up to 60-70% when compared to GOES (Dabbs, 2023). However, this material is more brittle and has lower saturation magnetization compared to GOES, leading to lower efficiencies when required to operate at constant full load (Dempsey, 2023; Hirzel, 2014). This technical drawback can be compensated for by using more core material and copper winding to increase efficiency. However, this increases transformer size and therefore cost (Hirzel, 2014). Amorphous core liquid immersed distribution transformers are broadly installed in Canada (McCoy et al., 2020). BC Hydro, has 90% - 95% of their installed overhead transformers as liquid immersed amorphous core transformers (McCoy et al., 2020). The U.S. DOE recently published amended energy conservation standards that would require liquid-immersed, low-voltage dry-type (LVDT) and medium-voltage dry-type (MVDT) distribution transformers to increase energy efficiency (Energy Efficiency and Renewable Energy Office, 2023). To achieve that goal, distribution transformer cores would likely need to utilize more amorphous steel.

Transformer windings are made from aluminum or copper (Olivares-Galván et al., 2010). Winding material selection comes down to several factors such as transformer cost, material availability, weight, and size (Olivares-Galván et al., 2010). As transformer size and power increase, the likelihood that a winding will be copper increases due to the weight and size savings provided by copper over aluminum (Copper Development Association Inc., n.d.-b). In very small applications, copper is favored as well, given that aluminum requires a larger cross sectional area of wire in order to deliver the same performance as copper (Hammond Power Solutions, n.d.). However, aluminum is the predominant material for windings in low-voltage, dry-type transformers, especially in North America (Benadum, 2020; Csanyi, 2010). Also increasing in likelihood with size and power is the usage of copper continuously transposed cable (CTC), which is the winding used in LPTs (Dubey, 2017; Nguyen et al., 2022). CTC can be made from aluminum, but approximately 94%–98% of CTC produced is made from copper (Dubey, 2017). CTC provides many benefits to transformers such as reduced eddy current losses, improved cooling in the system, and improved short circuit stability (Dubey, 2017).

Last, with the development of HVDC transmissions systems, transformers still play a vital role by integrating a rectifier or inverter (converter station) with the transformer. As coupling components between AC grids and DC systems, HVDC transformers adapt the voltage and generate the necessary phase shift (Siemens-Energy, n.d.). This allows conversion of the DC system to an AC system or vice versa before the voltage and current are modified by the transformer (Siemens-Energy, n.d.). More details on the converter station can be found in Section 2.7.3.4. Additionally, HVDC systems require special circuit breakers and switches, which are discussed in the next section.

2.7.3.3 Breakers and Switches

Because HVDV works at very high voltages, typically between 50 kV and 1100 kV (Hingorani, 1996; Liu & Li, 2021), circuit breakers and contact devices with high current and voltage rating are ideal for use as HVDC components. Some of the key components of an HVDC converter station include converter, AC switchyard, DC filter, and DC breaker (Nguyen et al., 2022). Compared to other circuit breakers, the sulfur hexafluoride (SF6) high-voltage circuit breaker has been found to be effective for use in high-voltage applications like HVDC. SF6 uses sulfur hexafluoride gas as the arc-quenching medium and can be used for voltages from 144 to 765 kV or above. The external casing of the breakers is made of steel, glass polyester, and thermoset composite with copper, tungsten, and silver electrical contacts (Eaton, 2021; Nasrallah et al., 2007). The operating mechanism is made of copper, iron, and steel (Nguyen et al., 2022). High-voltage disconnector switches for HVDC are made of galvanized steel with aluminum tube assemblies and earth-fixed contacts (GE Digital Energy, n.d.).

Another widely used materials for electric breakers and contact devices is the silver-nickel alloy, which can contain amounts of nickel from 5% up to 30% (Efficient Power Conversion (EPC), n.d.). Nickel (Ni) is a hard and durable material that can withstand wear and tear and can also reduce friction. Due to its high electrical conductivity and corrosion resistance, Ni is ideal for plating the base metal of the HVDC breakers and switches. Typical plating thickness for Ni is 0.03 cm (Bead Electronics, 2022), although this thickness can vary between 0.005 to 0.03 cm (Advanced Plating, n.d.). Multiplying the Ni density with the area of the switchgear and Ni plating thickness, a switchgear unit can require between 0.88 kg and 5.3 kg of Ni depending on the minimum and maximum plating thickness, respectively. Based on the author's knowledge, each HVDC project can have 100 to 300 switchgear units requiring a minimum of 88 kg and a maximum of 1586 kg of Ni for plating purposes in an HVDC project. Ni is also used in HVDC as an alloying element in stainless steel to enhance material properties. Around 69% of global Ni production is used to produce stainless steel (Nickel Institute, n.d.) with Ni content varying from 5% to 12% (Tamura & Johansson, 2022). Stainless steel is used in the grading electrode of the HVDC thyristor cooling water pipes (Li et al., 2019). Grading electrodes help achieve even voltage distribution around the inner and outer wall of the pipe and can also prevent leakage current flowing in the water and causing aluminum heatsink corrosion. There are around 800 electrodes in an HVDC project with each rod weighing 0.01 kg (Li et al., 2019). The combined weight of the stainless-steel electrodes in a project is around 9 kg of which 0.45 kg to 1.09 kg could be Ni depending on the minimum and maximum alloying percentages (Li et al., 2019). A typical HVDC project can be of 3 GW capacity. Combining the overall Ni use from both plating and in stainless steel, each HVDC project can require a minimum of 88 kg and a maximum of 1587 kg of Ni.

2.7.3.4 HVDC Converters

HVDC converters are the key power electronics equipment to convert electricity from AC to DC for HVDC long-distance transmission. Technically, HVDC converters can be divided into two categories, voltage source converters (VSCs)—especially modular multilevel converters (MMCs)—and line-commutated converters (LCCs). An MMC consists of tens to hundreds of converter modules aggregated together with high-power rating and flexible voltage, current, active power, and reactive power control capability. LCCs are made with thyristors switches that can only be turned on, thus affording limited control capability but with higher transmission power capacity. The main advantage of a VSC compared to LCC systems is its smaller footprint, reactive power control, lower risk of commutation failure, and better connectivity to weak AC systems (Annakkage, 2015). On the other hand, an LCC system is more mature, economical, and has higher power capacity. Most of the recent global multi-terminal HVDC projects and those for offshore wind farm integrations are using MMC technology, taking advantages of power flow control flexibility. On the other hand, LCC HVDCs are mainly used in extremely high-power transmission scenarios; for example, the current world's highest 1100-kV HVDC project is using LCC (Nguyen et al., 2022).

Regarding subcomponents, each MMC converter consists of six arms, where each arm includes an arm inductor and tens to hundreds of MMC submodules. For each submodule, an insulated-gate bipolar transistor (IGBT) is the key component, which is currently made of silicon material. Germanium was used as a semiconducting base material in early power electronics before the 1970s. Recently, germanium electronics have been replaced by silicon power electronic devices (Przybilla et al., 2009). The forward voltage of the germanium tube P(positive)-N (negative) junction is 0.3 V, while the silicon tube is 0.7 V, which is a great advantage for germanium. However, the structure of germanium crystals is unstable at higher temperatures compared to silicon (Kolodzey et al., 2016; Przybilla et al., 2009). In addition, silicon has a much lower production cost. Nowadays, silicon is the main base material for diodes, thyristors, IGBTs, and metal–oxide–semiconductor field-effect transistors (MOSFETs). Silicon carbide is substitutable with silicon IGBT although at higher costs, and it is not widely used in HVDC converters by major manufacturers.

2.8 Solid State Lighting

2.8.1 Importance of LED Lighting to the Global/U.S. Economy and Critical Infrastructure

Solid-state lighting (SSL) refers to solid-state electroluminescence and comprises several related technologies like light emitting diodes (LEDs), organic light emitting diodes (OLEDs), quantum-dot light emitting diodes (QLED), and carbon-dot light emitting diodes (CLED) (Industrial Light & Power, n.d.; Kim et al., 2012).

LEDs are a rapidly emerging form of lighting that are highly energy efficient, using at least 75% less energy than incandescent lighting and lasting up to 25 times longer (DOE, n.d.-d). LEDs are one of the most efficient forms of lighting with performance around 111 lumens per watt, outperforming conventional lighting technologies such as linear fluorescents (103 lumens/watt), compact fluorescents (61 lumens/watt), halogens (15 lumens/watt), and incandescent bulbs (13 lumens/watt) (IEA, 2022g). Additionally, LEDs are projected to improve in luminous efficiency with projections suggesting that 142 lumens/watt could be achieved by 2030 (IEA, 2022g). Despite LEDs being more expensive at the time of purchase, cost savings are achieved through their higher luminous efficiencies and through their longer life times—3 to 5 times longer than compact fluorescents and 30 times longer than incandescent (DOE, n.d.-d). 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, and accounting for 30% of the U.S. lighting market share (Elliott & Lee, 2020). In 2020, 47% of survey respondents consuming residential energy reported usage of LEDs for most or all of their indoor lighting (EIA, 2022c). LEDs are anticipated to represent the majority of U.S. lighting installations by 2035 (Energy Efficiency and Renewable Energy Office, 2022). Globally, LEDs already represented 50% of the global lighting market in 2021 (IEA, 2022g), and in certain scenarios such as IEA's NZE scenario, will represent 99% of the global lighting sales by 2030. Smart or connected lighting systems in buildings such as business offices, hospitality venues, and industrial sites are growing (TechSci 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; TechSci Research, 2022).

2.8.2 Current and Emerging Technologies

Significant growth is expected in the U.S. and the world for LED lighting (Elliott et al., 2019; IEA, 2022g). The most significant advancement or emerging technology in the coming years is the increased efficiency expected from LEDs (IEA, 2022g). Since 2010, the average efficiency of LED lighting has improved by about 6–8 lumens/watt each year (IEA, 2022g). Both the DOE and IEA are projecting significant improvements in efficiency with general-purpose LEDs achieving 136–142 lumens/watt by 2030 (Elliott et al., 2019; IEA, 2022g).

Concurrently, as SSL is increasingly used for lighting purposes, deployment of Light Fidelity (Li-Fi) as an alternative wireless network to Wireless-Fidelity (Wi-Fi) is emerging (Khorov & Levitsky, 2022; Sanusi et al., 2020). Li-Fi is projected to experience significant growth in the coming years (Mordor Intelligence, 2023; Precedence Research, 2021a). Li-Fi functions by utilizing light sources, in most cases LEDs, in order to transmit data through small changes in light intensity that are imperceptible to the human eye (Agarwal et al., 2022; Sharma et al., 2016). Li-Fi is driving the LED market due to its better speed, security, and efficiency compared to Wi-Fi (TechSci Research, 2022).

2.8.3 Overview of Components and Materials Used in LED Lighting Technologies

LEDs have three main supply chain stages: (1) LED die, (2) LED package, and (3) LED lamp (Lee et al., 2021). LED die manufacturing consists of growing the LED wafer by metal organic chemical vapor deposition (MOCVD) (Lee et al., 2021). LED package manufacturing involves taking the LED die and depositing phosphor material to convert the LED emission to a variety of different color options (Lee et al., 2021; PhosphorTech, n.d). Finally, the LED lamp manufacturing consists of taking LED packages and mounting them to printed circuit boards and then inserting them into a lamp housing (Lee et al., 2021).

Gallium is a key component in most current LED technologies as part of the LED die supply chain stage (Lee et al., 2021; Song et al., 2022). Most types of LEDs consist of p-type and n-type doped gallium nitride (GaN) layers. However, a multitude of other gallium-based technologies can be utilized such as gallium arsenide

(GaAs), aluminum gallium arsenide (AlGaAs), gallium phosphide (GaP), gallium indium phosphide (GaInP), aluminum gallium indium phosphide (AlGaInP), indium gallium nitride (InGaN), or gallium arsenide phosphide (GaAsP) (Electronics Hub, 2021; Gaffuri et al., 2021).

2.9 Microchips

2.9.1 Importance of Microchips to the Global/U.S. Economy and Critical Infrastructure

Semiconductors, sometimes referred to as integrated circuits (ICs) or microchips, are made from pure elements, typically silicon or germanium, or compounds such as gallium arsenide. Semiconductors are an essential component of electronic devices, enabling advances in communications, computing, healthcare, military systems, transportation, clean energy, and countless other applications (Semiconductor Industry Association, n.d.). In 2020, more than 932 billion chips were manufactured around the world, which grew to 1.15 trillion chips in 2021, a growth rate of 23% over that period. The value of the global microchip industry was estimated to be $626 billion in 2022 (ASML, 2022).

2.9.2 Current and Emerging Technologies

Current microchip technology is largely based on high-purity silicon where transistors are etched or deposited on silicon wafers to form integrated circuits. The transistors in these circuits act as tiny electrical switches at the nanometer scale that can turn the current on or off (TU Wien, 2022). These changes in electrical signals allow information to be processed and stored in logic chips and memory chips.

Microchips were first invented in the early 1960s, and either silicon or germanium was used as the semiconductor material. Silicon has historically dominated due to the inability of germanium semiconductors and transistors to tolerate elevated temperatures. However, the compound semiconductor silicon-germanium has decisive advantages over today's silicon technology in terms of energy efficiency and clock frequency achievement. In other words, silicon-germanium semiconductors can operate a circuit more times per second than a silicon semiconductor. This translates to greater processing power that can be achieved at lower energy requirements if silicon-germanium semiconductors are utilized instead of their silicon counterparts (TU Wien, 2022). Although the market penetration of such technology is still low with an estimated market value of $8 billion, or about 1% of the value of the total microchip market, the sector is expected to grow with a 10.8% CAGR for high-frequency and power electronics applications (Global Industry Analysts Inc., 2023).

2.9.3 Overview of Components and Materials Used in Microchips

Current chip technology is largely based on silicon (TU Wien, 2022). Total germanium use is low in microchip applications. Approximately 1% to 2% of global germanium production is estimated to go into microchips, and no data were available on specific material intensity of germanium in these applications (IBM, n.d.). Germanium is less useful than silicon due to its thermal sensitivity and cost, but it is still alloyed with silicon for use in some high-speed devices. IBM is a primary producer of these devices (IQS Directory, n.d.). Optical interconnects made with gallium use light to connect and share signals between microchip components with higher efficiencies and less heat generation.

3 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 subcomponent 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 only 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 5. 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, subtechnologies 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 subtechnologies were grouped 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 subtechnology (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), subtechnologies/components (e.g., direct-drive generators and rare-earth magnets), and materials (e.g., Nd, Pr, Dy, etc.).

3.1 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 subtechnology 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 growth in neodymium demand implied by the growth of this specific technology.

Table 3.1 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 5. 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 its 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 3.1. 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. Subtechnology/ component importance	Market share of specific subtechnology 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 subtechnology/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.

3.1.1 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 Emissions Scenario (NZE), Sustainable Development Scenario (SDS), and the Announced Pledged Scenarios (APS). For example, the 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, 2022i). 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, 2022a). 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/subcomponent 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.

3.1.2 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 materials in solar PV technologies (silicon, CdTe, and CIGS) do not have the same levels of importance. Currently, silicon PV has a market share of ~88% (BCC Publishing, 2022) compared to CdTe at 5% (U.S. Manufacturing of Advanced Cadmium Telluride Photovoltaics 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.

3.1.3 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 mt, (b) a specific energy application accounts for 20 mt of demand, and (c) is currently projected to account for 80 mt 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 the following: relevant energy scenarios as mentioned in Section 3.1.1, market share of sub-technologies as mentioned in Section 3.1.2, material intensities, current 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, which is higher than the technology importance metric but lower than the sub-technology importance metric. This weight reflects the fact 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.

3.2 Screening Results

Figure 3.1 summarizes the screening scores received by 38 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, 23 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 3.2 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 Chapter 5. Lower-risk materials with associated technologies and factors contributing to their lower scores are listed in Table 3.3. Scores shown in both tables are the highest scores for each material. Detail on the scores of all materials and applications can be found in Appendix C.

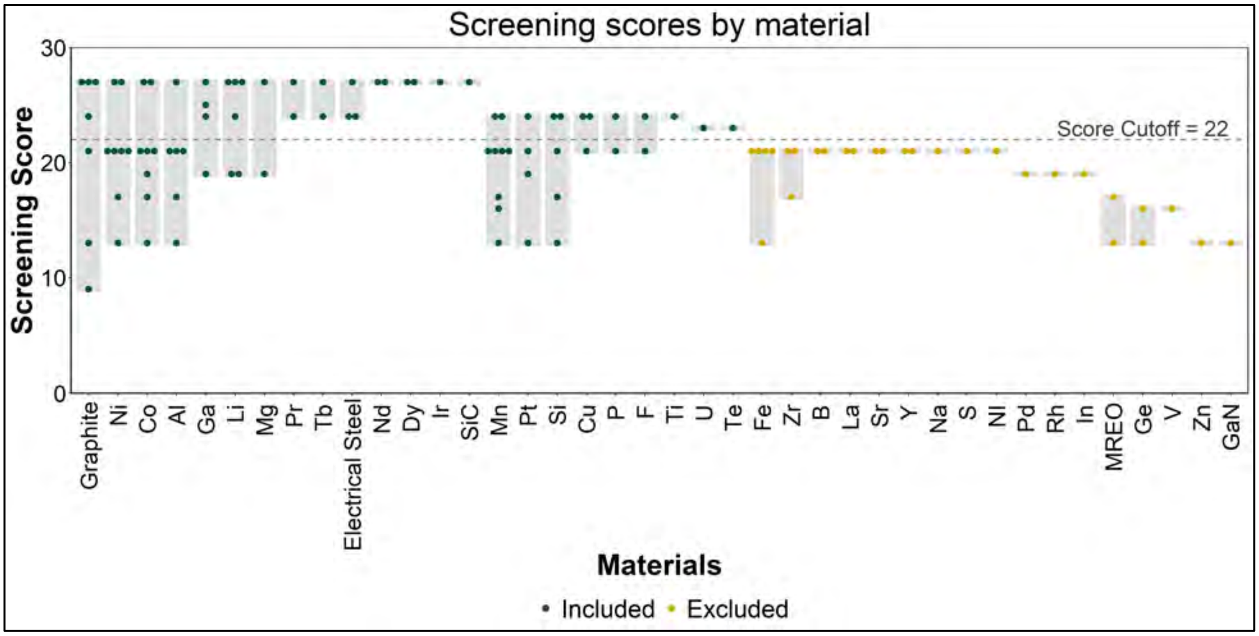


Figure 3.1. Summary scores of 37 materials. Materials with scores above the cutoff line are key materials.

Table 3.2. 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
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

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Iridium	PEM* electrolyzers	27	CAGR 87% of H_2; 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%)
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 & Villamor, 2022)
Terbium	Wind turbines Electric vehicles	27	CAGR 13%–40%; high adoption of offshore turbines and EVs, and high additional demand
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, 2021a) – electric vehicles, 7–15% additional demand
Fluorine	LIBs	24	Broad usage in electrolyte across all LIB chemistries; 40% CAGR of BEV+PHEV vehicles; 19% additional material demand for EVs
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

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Phosphorous	LIBs (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
Platinum	PEM electrolyzers	24	CAGR 87% of H_2, 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, 2022i), 133% additional Te demand 4%–5% share in global solar market, 30%–40% in U.S. solar market (Kennedy, 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 3.3. 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	Solid oxide fuel cells and electrolyzers	21	87% CAGR, <1% additional demand
Strontium	Solid oxide fuel cells and electrolyzers	21	87% CAGR, <1% additional demand
Yttrium	Solid oxide fuel cells and electrolyzers	21	87% CAGR, <1% additional demand

Material	Highest Risk Technology	Score for Highest Risk Technology	Factors Contributing to Scores
Zirconium	Solid oxide fuel cells and electrolyzers	21	87% CAGR in NZE, <1% additional demand
Indium	Solar	19	Low adoption, 9% market share (BCC Publishing, 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
Germanium	Microchips	16	Low adoption rate (<1%), low additional material demand (<1%)
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

4 Demand Trajectories and Current Production Capacity of Key Materials

This chapter describes demand trajectories and current production along with the production capacity of each key material that passed the screening in Chapter 3. These estimates provide the basis for two metrics used in assessing criticality in Chapter 5. The first metric is “energy demand” under the “Importance to Energy” dimension where these trajectories provide the energy demand share of each material when compared against other demand. The second metric is the “basic availability” metric under “Supply Risk” dimension where the gaps between current production capacities and future demand trajectories are quantified for various key materials. Details about the usage of these metrics are described in Chapter 5.

The chapter is organized as follows. Section 4.1 describes the process and methodology for deriving four demand trajectories for each material. Section 4.2 discusses high and low growth trends of energy technologies or applications discussed in Chapter 2 including vehicles, energy storage, hydrogen, solar, wind, nuclear, electric grid, LED lighting, and power electronics. Section 4.2 also discusses assumptions regarding high and low market shares of sub-technologies. For example, solar trajectories are broken down into Si, CdTe, and CIGS technologies with high and low market shares. The section also lists high and low material intensities. More details about market share assumptions and material intensity calculations can be found in Appendix B. Section 4.3 outlines the aggregation of demand trajectories of various applications for each material in alphabetical order. This section also presents recent production and production capacity of key materials.

4.1 Methodology Overview

Demand trajectories were developed for each material that passed the screening in Chapter 3. For each material, four trajectories were developed using high and low market penetration and material intensity assumptions for different energy technologies/applications, shown in Table 4.1. The goal of these trajectories is not to predict the future, but to outline various possibilities of material demand that can inform RD&D strategies. Low energy technology deployment is compiled from various sources, including the Stated Policies Scenario (STEPS) from the International Energy Agency (IEA) and similar low (or business-as-usual) scenarios by other agencies and market reports. STEPS is a conservative scenario, in that it considers that governments may not reach all announced goals based on their current policy landscape (IEA, 2022i). The high deployment scenarios for energy technologies include the IEA’s net-zero scenarios (NZEs) or Sustainable Development Scenario (SDS), as well as high deployment scenarios produced by other agencies. NZE scenarios show a pathway to achieve net-zero CO_2 emissions by 2050 (IEA, 2022i) while the SDS scenarios aim to meet the Paris Agreement goal of achieving net-zero emissions by 2070 (IEA, 2019b). Specific market share and material intensity assumptions are detailed in Appendix B. In some cases, the IEA’s Announced Pledges Scenario (APS) is used when the SDS or NZE are absent. The APS assumes that countries will fully implement their policies to achieve emissions goals by 2030 and 2050 (IEA, n.d.). The SDS scenario was employed by IEA in 2021 but was abandoned in 2022 in favor of the APS. While the climate outcomes of the APS and SDS are similar (i.e., below 2^0C), the two scenarios differ in other outcomes.

As shown in Table 4.1, Trajectory A is derived from low technology deployments combined with low market share and low material intensities. This trajectory shows a business-as-usual (BAU) market penetration scenario with an improved material intensity. Trajectory B uses the same low deployment scenario as Trajectory A, but with a high (or more current) material intensity. This trajectory is in line with a completely BAU scenario. Trajectories C and D account for high technology deployments and high market shares of sub-technologies. Trajectory C considers low (improved) material intensity, and Trajectory D evaluates high (or standard) material intensity. Trajectory C is the most ambitious scenario where technology deployment is accelerated but material intensity is the lowest. Trajectory D is the worst-case scenario where high deployment takes place, but current material intensity is maintained. When a material is considered for multiple energy technologies, the aggregated trajectory is the sum of all of the same trajectories across all technologies for the material. For example, Trajectory A for one material with many end-use applications in clean energy applies the Trajectory A assumptions across all of those technologies.

Non-energy demand is assumed to have a growth rate of 3%, reflecting the global average economic growth as discussed in Chapter 3. 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 Section 4.3 show demand from the considered energy technologies combined with other demand to formulate total demand for each key material.

Regarding supply, only current production or capacity is shown here for estimating the gap between current supply and future demand. This is because estimating future supply incurs high levels of uncertainties as discussed in the 2019 CMS report (DOE, 2019). Data on current mineral production is primarily sourced from the U.S. Geological Survey (USGS) Minerals Yearbook. For engineered materials such as power electronics or electrical steel, the assessment relies on estimates from relevant market reports. Estimating future supply is out of scope for this analysis. Where estimates for current production capacity are unavailable, an average 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).

Table 4.1. Formulation of four trajectories based on energy deployments, sub-technology market shares, and material intensities.

Energy Demand Trajectory	Technology Market Penetration		Material Intensity
	Global Energy Deployment Scenarios	Sub-technology Market Share	
A	Low	Low	Low
B	Low	Low	High
C	High	High	Low
D	High	High	High

4.2 Demand Trajectories of Energy Technologies

4.2.1 Vehicles

Consistent sets of vehicle demand trajectories were developed based on IEA’s STEPS and NZE scenarios for four different vehicle categories—cars, vans, trucks, and buses—and for four different types of drivetrains—BEV, PHEV, FCEV, and ICE vehicles. Total sales of all vehicles for 2020, 2021, 2025, and 2030 were estimated based on EV sales and sales shares from IEA (IEA, 2022b). Missing data on truck, van, and bus sales in the U.S. and India were filled in by assuming the same distribution of car to van to bus to truck sales in those countries as in the rest of the world. Values for years in between the years with reported data were filled in by assuming a constant CAGR for each vehicle type between 2021 and 2025 and between 2025 and 2035. Figure 4.1 shows the total vehicle sales projections, which were used for both the STEPS and NZE scenarios.

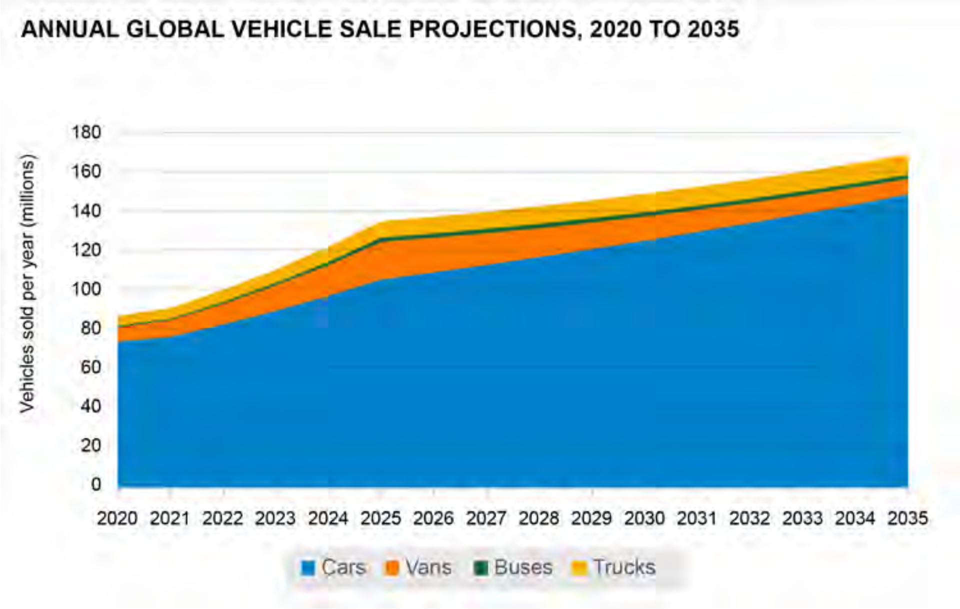


Figure 4.1. Global vehicle sale projections from 2020 to 2035.

For each vehicle type, BEV and PHEV adoption levels for 2020, 2021, 2025, and 2030 for the STEPS scenario were taken from IEA's global electric vehicle outlook (IEA, 2022b). BEV, PHEV, and FCEV sales shares for the NZE scenario for 2030 and 2050 were taken from IEA's *Net Zero By 2050* report (IEA, 2022c). Demand for FCEVs in the STEPS scenario is estimated based on hydrogen fuel use in IEA's STEPS scenarios (see Appendix B, Section B1.7 for details). EV, BEV, FCEV, and ICE vehicle shares of total vehicles of each type for years in between reported data were estimated using separate multinomial logistic functions in 2021–2025 and 2025–2035 for the STEPS scenario, and in 2021–2030 and 2030–2035 for the NZE scenario. Figure 4.2 and Figure 4.3 show the breakdowns by drivetrain of cars in the STEPS and NZE scenarios, respectively. Similar breakdowns were also calculated for vans, buses, and trucks.

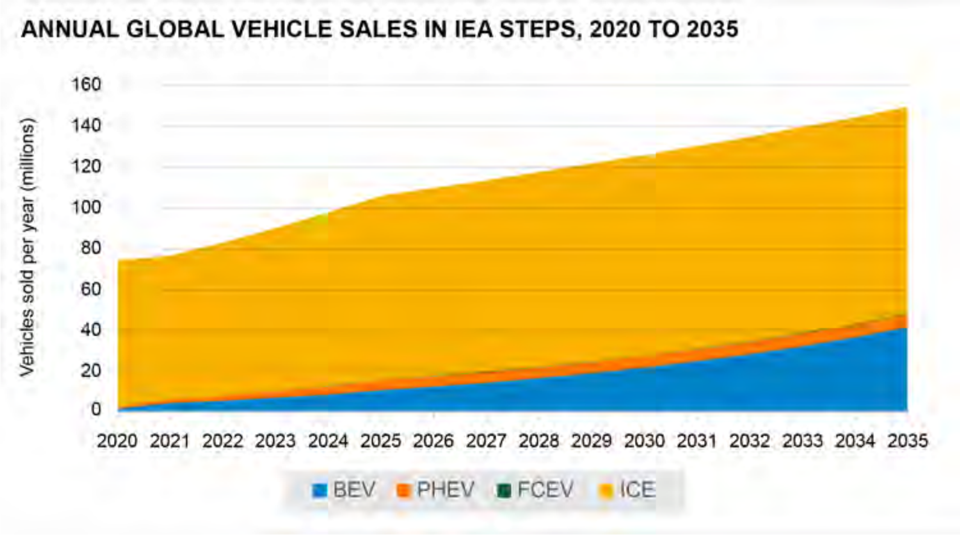


Figure 4.2. Annual global vehicle sales from 2020 to 2035 in the STEPS scenario.

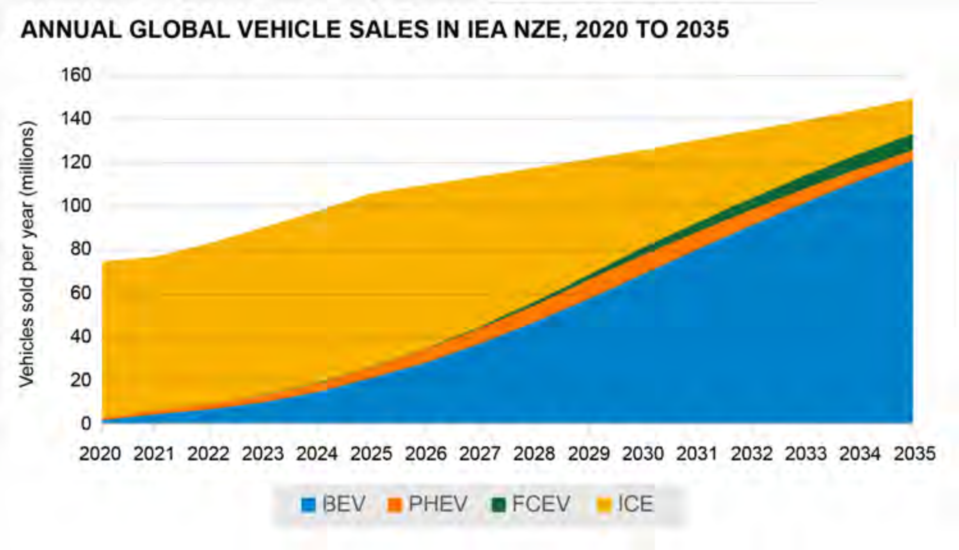


Figure 4.3. Annual global vehicle sales from 2020 to 2035 in the NZE scenario.

4.2.1.1 Electrical Steel

The automotive industry consumes a substantial amount of ES, mostly NOES, amounting somewhere between 1,250 kt (Vittori et al., 2021) and 3,500 kt (Fact.MR, 2023) of expected global ES production in 2023. ES is used heavily in the manufacturing of electric motors, as it produces the electromagnetic field used to turn the rotor. Typically, about 40 kg to 100 kg of NOES are used in building an EV (Steiniger, 2019). While NOES is the ES type used most often in EVs, it should be noted that GOES plays a big role in the EV industry, specifically in transformers of EV charging infrastructure (Vittori et al., 2021). However, this GOES content was calculated as part of the grid and not included here.

Trajectories for ES content were built using the IEA NZE and STEPS scenarios, which provide the expected EV sales until the year 2035 (IEA, 2021a, 2022a). The NZE scenario projects about 138 million EVs while STEPS projects about 45 million EVs by 2035, which include cars, buses, trucks, and vans. To each of these scenarios the NOES values for high and low estimations were applied as mentioned above.

4.2.1.2 Wiring

Similar to ES, the trajectories for Cu content in vehicles were derived from IEA NZE and STEPS until 2035 (IEA, 2021a, 2022a). Each vehicle type has a specific amount of Cu content. HEVs contain 38 kg, PHEVs contain 60 kg, BEVs contain 83 kg, hybrid electric buses contain 89 kg, and battery electric buses contain 370 kg (Copper Development Association, 2022a). The Cu content in ICEs typically range between 8 kg to 22 kg per vehicle. To obtain high and low Cu content levels for non-ICE vehicle types, a value of ± 5% was used given the lack of data.

4.2.1.3 Catalytic Converters

Internal combustion engines, diesel engines, and hybrid and plug-in electric vehicles are equipped with catalytic converters for pollution control. Catalytic converters contain varying amounts of platinum, palladium, and rhodium. For this study, platinum demand for catalytic converters is considered in the platinum demand trajectories. Palladium and rhodium were screened out in the assessment as reported in Chapter 3.

The IEA STEPS and NZE projections for the number of catalytic converter-equipped vehicles sold from 2020 to 2035 are shown in Figure 4.5 and Figure 4.5, respectively. The low and high platinum material intensities derived for these vehicle fleets are 0.9 and 1.2 g/vehicle, respectively (see Appendix B, Section B1.3).

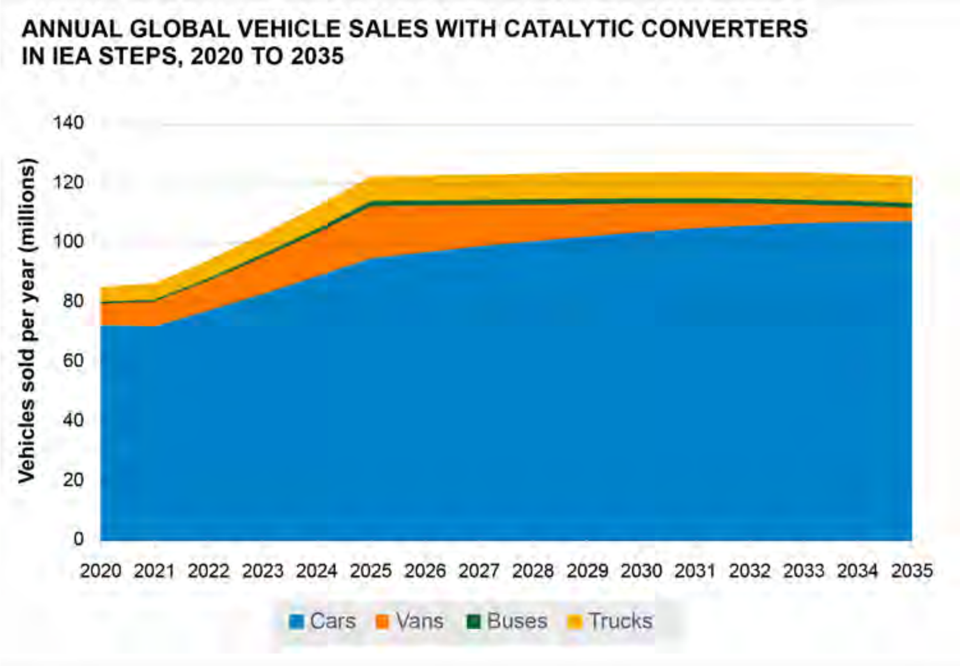


Figure 4.4. Global sales of vehicle with catalytic converters from 2020 to 2035 in the STEPS scenario.

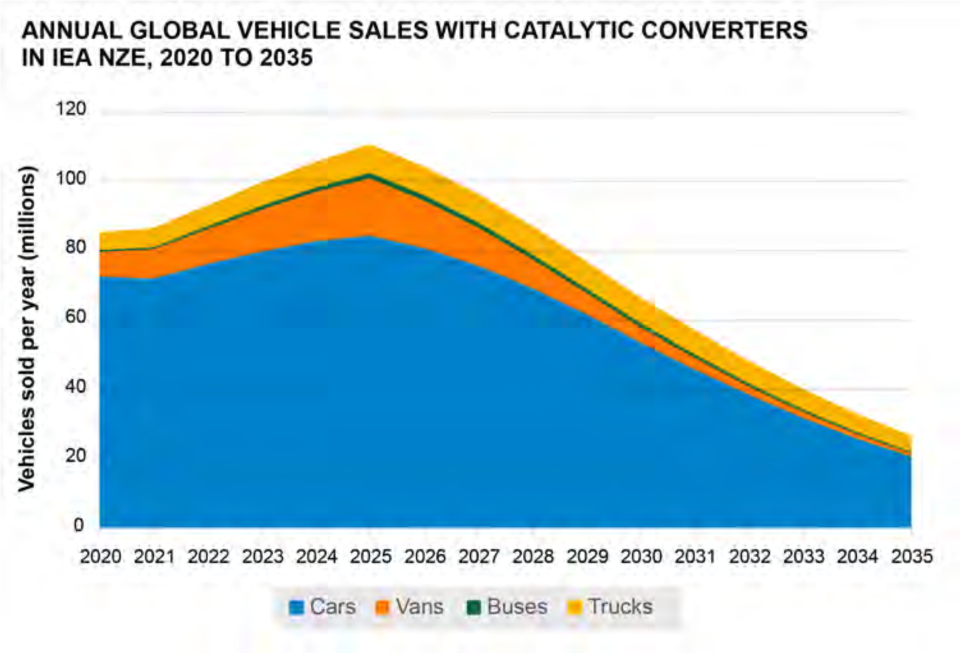


Figure 4.5. Global sales of vehicle with catalytic converters from 2020 to 2035 in the NZE scenario.

4.2.1.4 Vehicle Lightweighting

The four demand trajectories used to calculate vehicle lightweighting materials utilize high-strength steel, advanced high-strength steel, aluminum alloys, and magnesium alloys across different vehicle types. Although materials such as plastics and carbon fiber are used in lightweighting, they were not investigated in this report. The material amounts per vehicle are calculated based upon three lightweighting packages: standard, advanced low intensity, and advanced high intensity. The first is a standard lightweighting package that represents a baseline amount of lightweighting material within a vehicle. The standard package has the least amount of lightweight material within it and mostly consists of mild steel (a ferrous metal made from iron and carbon). There are then two advanced lightweighting packages that represent a low and high lightweighting material intensity. The first advanced lightweighting package is a 10% reduction in vehicle weight and represents the low material intensity. The next represents the high material intensity as results in a 22% vehicle weight reduction (Das et al., 2016).

Each lightweighting package utilized a weighted average vehicle mass for ICE, BEV, HEV, PHEV, and FCV light-duty and heavy-duty vehicles by year. Using each respective year's weighted average mass, lightweighting material percentages for high-strength steel, advanced high-strength steel, magnesium alloys, and aluminum alloys were applied to the vehicle mass to obtain total amounts of lightweighting material per vehicle. With these lightweighting material amounts, actual material amounts per vehicle for magnesium, aluminum, silicon, titanium, and manganese were calculated as a percentage range within high-strength steel, advanced high-strength steel, aluminum alloys, and magnesium alloys. See Appendix B for more information on these ranges. Total material amounts per year were calculated as the amount of material per vehicle for both low and high intensities multiplied by the number of standard lightweighting vehicles and advanced lightweighting cars sold per year.

4.2.1.5 Batteries in Electric Vehicles

The demand trajectories for batteries in electric vehicles were based on separate trajectories for BEVs and PHEVs of four vehicle types: cars, vans, trucks, and buses. The high penetration trajectory was based on IEA's NZE scenario, and the low penetration trajectory was based on IEA's STEPS scenario, as described in Section 4.2.1.

Almost all BEVs and PHEVs currently rely on lithium-ion batteries. Past critical materials strategies also considered nickel metal hydride (NiMH) batteries, which are still being used in some HEVs, although the share of HEVs using NiMH batteries is declining—while at the same time, HEVs have become a small and declining share of the battery market. Alternative technologies such as sodium-ion batteries show promise as possible alternatives to Li-ion batteries, but they are not currently projected to become a significant share of the market by 2035. While they are considered as potential long-run substitutes, they are not included in the battery demand trajectories.

Within the category of lithium-ion batteries are a variety of different types, depending on the cathode and anode material used. The cathodes used most often for EVs are NMC and LFP, followed by NCA. Materials used in Li-ion batteries include Li, Co, Ni, Mn, graphite, Si, F, P and Al, with the material use depending heavily on the type of battery. Li is used in all Li-ion batteries, as are F and Al. Ni, Mn, and Co are all key ingredients of NMC batteries, but are not needed for LFP batteries, while P is used in much higher quantities in LFP batteries. Graphite and Si can be used in the anode of all types of Li-ion batteries, but the amounts of graphite vs. silicon used can vary. Our analysis includes low and high material intensity scenarios based on different mixes of battery types, drawn from the high LFP and high NMC scenarios from Xu et al (C. Xu et al., 2020). For each material, the low material intensity value is taken from the distribution that produces the lowest average material intensity. Battery sizes are also accounted for in the material intensities, with trucks and buses requiring larger batteries than vans and cars, while BEVs use larger batteries than PHEVs. In the high-intensity scenario, the trend toward increasing range in EVs leads to increases in battery size, while in the low-intensity scenario, this trend is offset by improvements in energy efficiency. Details on the assumptions are provided in Appendix B.

4.2.1.6 Magnets in Electric Vehicles

BEVs, PHEVs, FCEVs, and HEVs all have electric traction motors, most of which currently use rare earth permanent magnets (REPMs). Cars such as the Tesla Model 3 and Model Y use induction motors as secondary motors in four-wheel drive vehicles, but use REPM motors as the primary motor (Tesla, 2023a, 2023b). A few models of BMW, Renault, and SMART EVs use brushed EESGs, but these models make up only about 1% of the U.S. EV market (Arena EV, 2022; Argonne National Laboratory, n.d.-b). However, Tesla has announced plans to shift all its vehicles to motors that do not use rare earths (Adamas Intelligence, 2023a). Market shares for REPM motors in EVs are assumed to range from 50%–100% of the EV market through 2035 (see Appendix B for details). High and low demand trajectories for EV, FCEV and BEV trucks, buses, vans, and cars are derived from IEA’s NZE and STEPS scenarios, as described in Section 4.2.1. HEVs made up 6% of U.S. ICE + HEV vehicle sales in 2022 through September (Argonne National Laboratory, n.d.-b), and are assumed to make up 6% of global ICE vehicle use through 2035.

Magnet sizes depend on vehicle power and are generally larger for trucks and buses than vans and cars, and are lower for HEVs than EVs, PHEVs, and FCEVs. Materials used in rare earth permanent magnets include Nd, Pr, Dy, Tb, and Ga. Details on the material intensity assumptions are shown in Appendix B.

4.2.1.7 Fuel Cells in Vehicles

The low and high penetration scenarios for FCEVs are based on the IEA STEPS and NZE forecasts, respectively, for demand growth in fuel cell cars, vans, buses, and trucks as explained in Section 4.2.1.

The IEA STEPS and NZE projections of the number of FCEVs sold by type from 2020 to 2035 are shown in Figure 4.6 and Figure 4.7. The platinum and graphite low and high material intensities (kg/vehicle) for each type of vehicle are reported in Appendix B, Section B1.7.

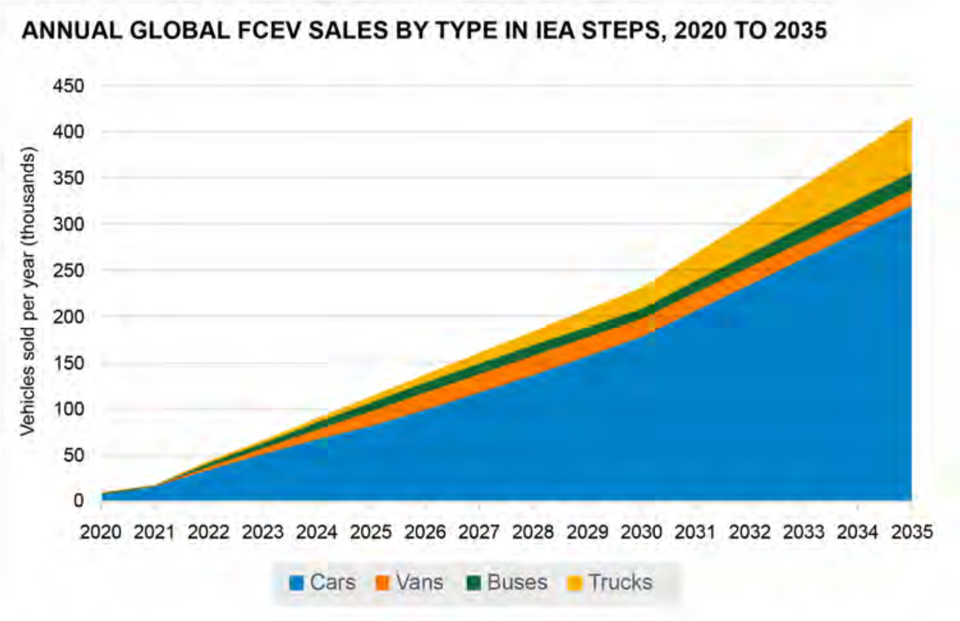


Figure 4.6. Global FCEV sales by type from 2020 to 2035 in the STEPS scenario.

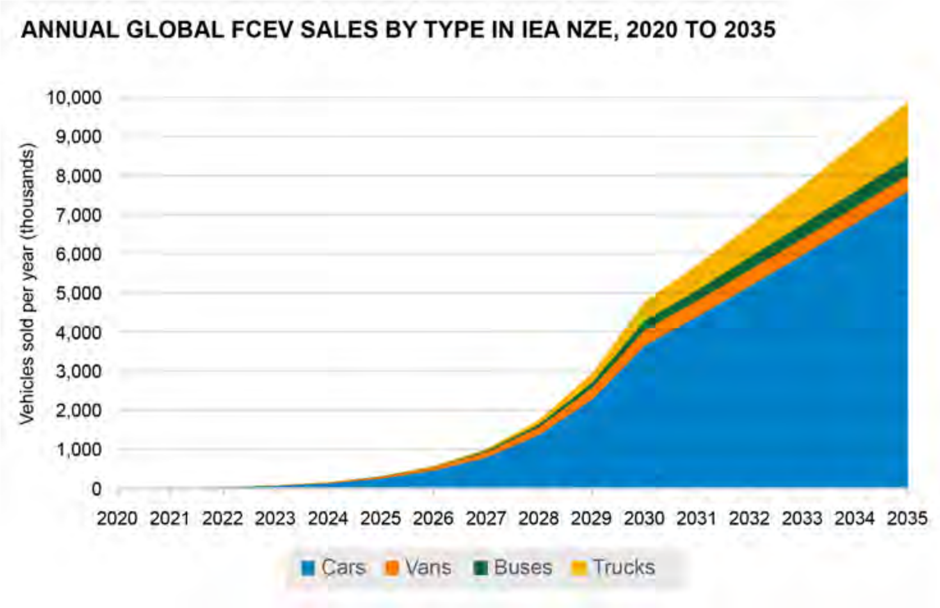


Figure 4.7. Global FCEV sales by type from 2020 to 2035in the NZE scenario.

4.2.2 Stationary Storage

Stationary storage demand trajectories are based on the IEA World Energy Outlook 2022's STEPS and NZE forecasts for grid storage capacity (IEA, 2022i). STEPS projects future demand based on current policies, whereas NZE considers the demand necessary to achieve net-zero carbon emissions goals by 2050. According to the NZE projection, battery stationary storage will expand 30-fold between 2020 and 2030, compared to 10-fold in the STEPS scenario. The capacity projection data for each scenario was linearly interpolated between the data provided in the IEA reference. Figure 4.8 shows projections for stationary storage capacity based on IEA's STEPS and NZE scenarios through 2035. Lithium-ion batteries—particularly lithium iron phosphate—currently dominate the stationary storage market and are estimated to make up 76% of the battery stationary storage market, followed by sodium sulfur at 9%, lead acid at 6%, and flow batteries at 3% (Global Market Insights, 2022). The future market for stationary battery storage is expected to be made up primarily of lithium-ion and flow batteries by 2040, with the flow battery market share growing to 10%–15% as the technology matures and asserts its cost competitiveness (Blair et al., 2022).

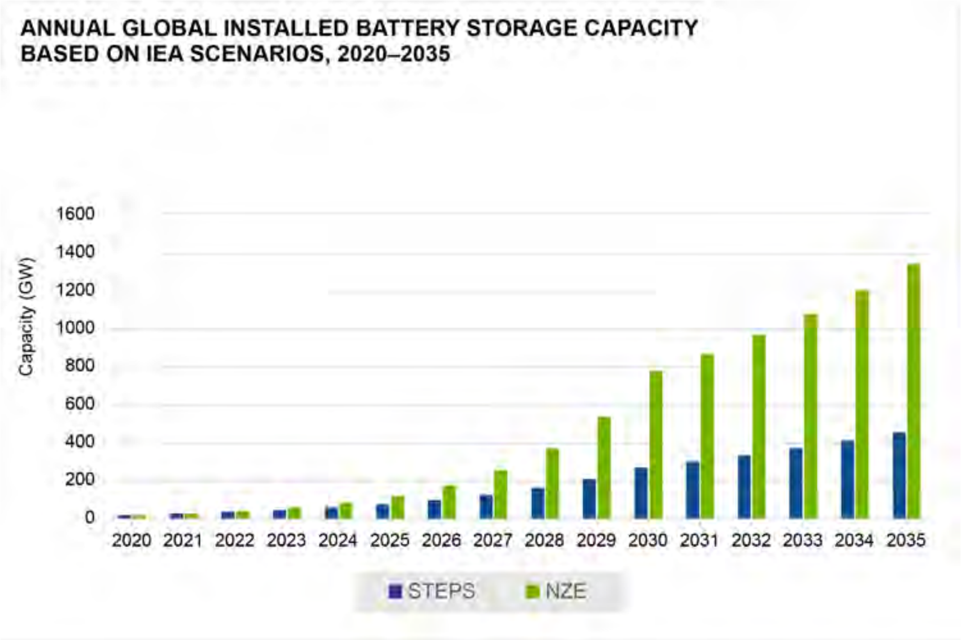


Figure 4.8. Stationary storage installed capacity forecast (IEA, 2023c).

4.2.3 Hydrogen Electrolyzers

For PEM electrolyzers, the low and high penetration scenarios are based on the IEA STEPS and NZE forecasts for growth in hydrogen demand (as shown in Figure 4.9) and the fraction of demand met by electrolysis (as shown in Table 4.2) (IEA, 2022d). The percentages of electrolysis demand met by PEMECs, SOECs, and AECs are informed by the EO 14017 report (Badgett et al., 2022). Lacking published references, the PEMEC and SOEC shares of hydrogen electrolysis demand are assumed to increase over time at the same relative rate in the STEPS and NZE forecasts.

IEA hydrogen demand forecasts (STEPS and NZE projections) through 2035 are shown in Figure 4.9. As this figure shows, hydrogen demand growth in the STEPS scenario is orders of magnitude lower than in the NZE scenario.

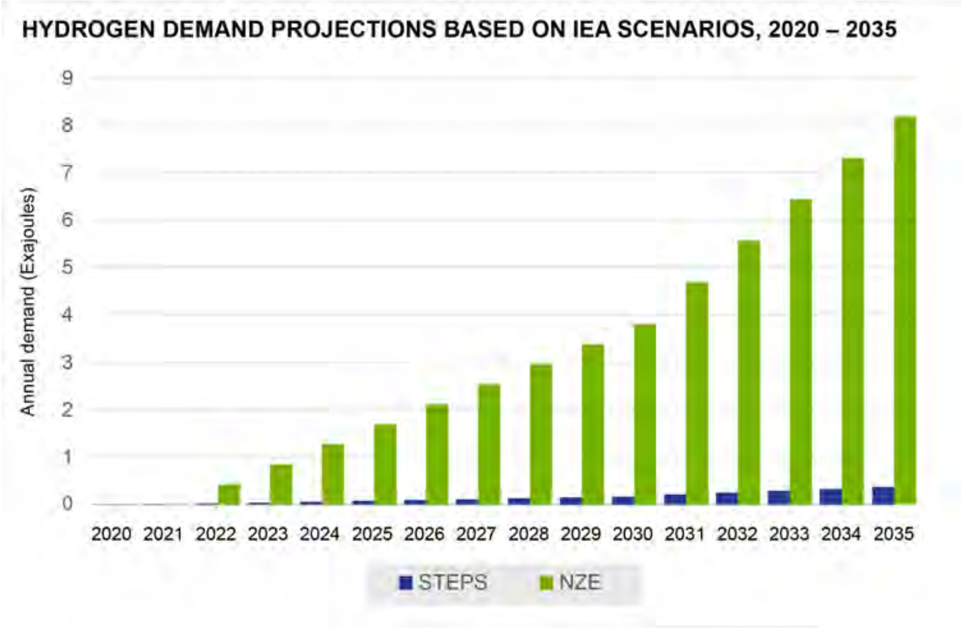


Figure 4.9. Global hydrogen demand – IEA projections.

As shown in Table 4.2, the IEA NZE forecasts that ~62% of hydrogen demand will be supplied by water electrolysis in 2050.

Table 4.2. IEA NZE hydrogen production by electrolysis forecast.

Year	Low Carbon H_2 Production (MT)	Electrolysis H_2 Production (MT)	Electrolysis Share
2020	9	0.5	5%
2030	150	81	54%
2050	520	322.4	62%

Figure 4.10 shows the projection of new hydrogen capacity additions by electrolyzer type in the NZE scenario. Capacity additions for the STEPS scenario never exceed 6 GW through the period 2020–2035.

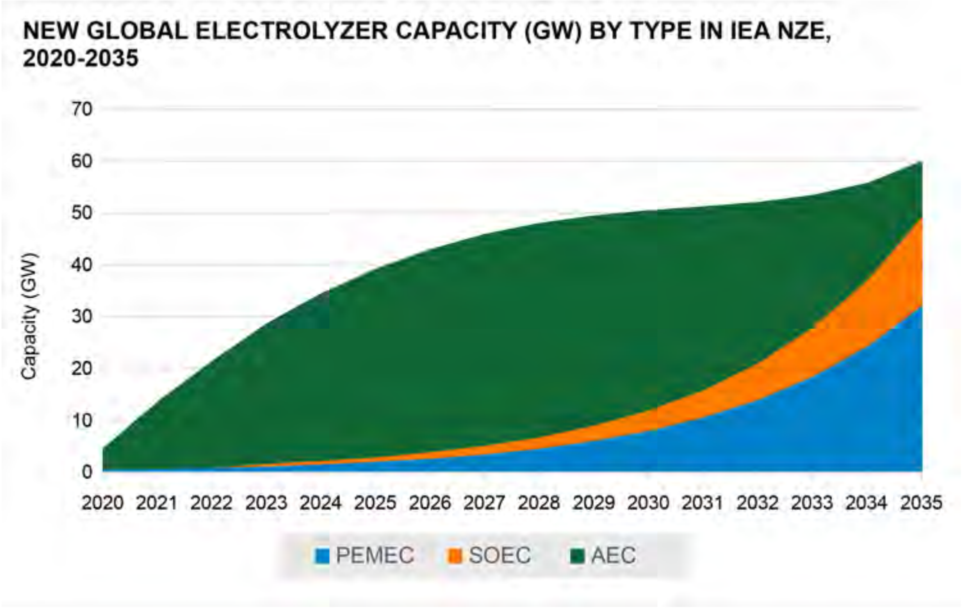


Figure 4.10. Projection of global hydrogen electrolyzer capacity additions by electrolyzer type in the NZE hydrogen demand scenario.

4.2.4 Solar Energy

In order to assess the demand for silicon, indium, tellurium, and gallium in solar applications, solar capacity projections (in GW) from 2021 to 2050 under three different scenarios were obtained from the International Energy Agency (IEA)'s *World Energy Outlook 2022* (IEA, 2022i). The IEA scenario that projects the lowest solar capacity is the Stated Policies Scenario (STEPS) and is based on current policies. The highest projected solar capacity is the Net Zero Emissions by 2050 Scenario (NZE) that considers needed solar capacity to achieve net-zero emissions in electricity generation by 2050. The total projection data for solar capacity for each scenario was provided in years 2021, 2030, 2040, and 2050. The yearly installed capacity of solar PV was interpolated assuming a linear trend based on IEA cumulative capacity data. Additionally, the useful lifetime of newly installed solar capacity is assumed to be 25 years as set by the IEA solar PV projections. New yearly installed capacity projections for each scenario are shown in Figure 4.11.

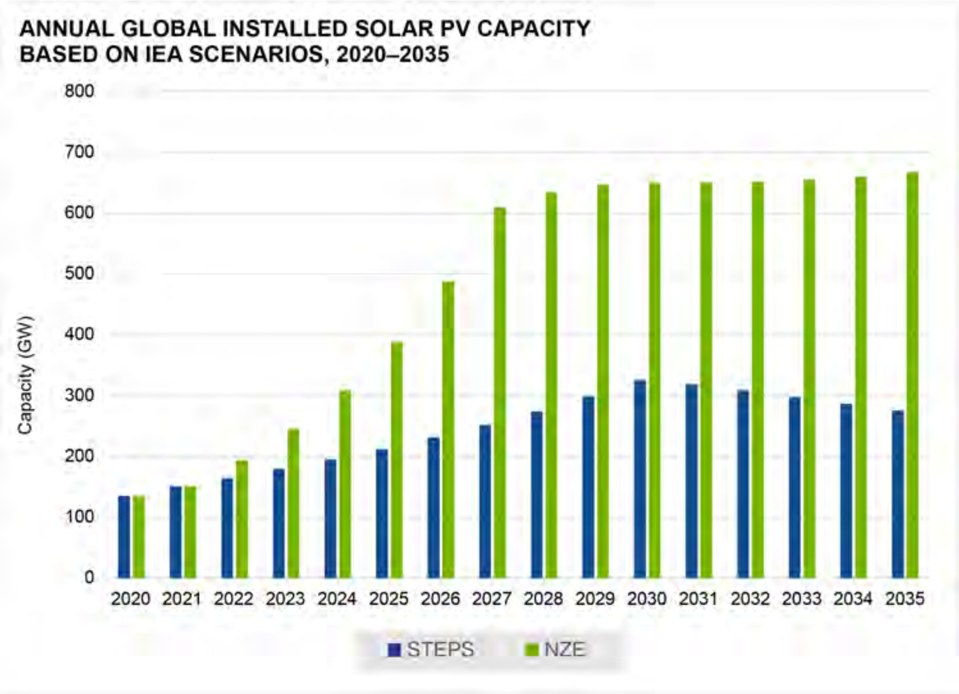


Figure 4.11. Yearly new installed solar PV capacity projections based on the IEA STEPS and NZE scenarios.

The data obtained from the IEA is not technology specific, so additional technology-specific market share projections and material utilization efficiency rates were used to compute projected material demand intensities. Data from the International Renewable Energy Agency (IRENA) was used to estimate CdTe solar technology's baseline market share and thus to project yearly installation capacities (IRENA & IEA-PVPS, 2016). A 2% and 5% market share were maintained out to 2035 (SETO, 2023) to form the low and high penetration rate. A low CIGS demand scenario with 0% market share was used in light of the recent shutdown of the largest CIGS manufacturing plant in the world, which switched to producing silicon PV in 2021 (Bellini, 2021b). A high of 2% market share for CIGS was used in keeping with historical market highs from 2010–2014 (Fraunhofer Institute for Solar Energy Systems ISE, 2022). Silicon's baseline projected market share of 87.7% was obtained from BCC research market reports (BCC Publishing, 2022). High and low cases for silicon deviated from the current market share by an increase of 7% or a decrease of 5%. A high of 7% was chosen because market capture greater than 95% did not seem realistic given current CdTe penetration. A low of 5% was chosen to match the 2009 historic low of silicon market share (Feldman et al., 2021). All market shares for each solar technology were assumed to be constant in their respective demand scenarios. Table 4.3 summarizes the low and high market shares for each technology used in the projections.

Table 4.3. High and low market percent capture for various solar technologies.

Solar PV Technology	Low Market Share	High Market Share
Si	82.7%	94.7%
CIGS	0%	5%
CdTe	2.0%	5.5%

It should be noted that there is significant uncertainty in any projections of future technology adoption rates in the solar PV market. For example, many industry experts in the past decade believed that silicon solar cells would be phased out with new technologies garnering larger market shares. However, silicon solar cells market share has remained high at more than 87% of the market share in 2021 due to its low cost (BCC Publishing, 2022). Additionally, thin-film solar technologies, such as CIGS, were previously thought to be a promising future technology but have yet to capture more than 2.5% of the market share in 2013 (Fraunhofer Institute for Solar Energy Systems ISE, 2022). As of 2022, one of the last remaining CIGS manufacturers halted its production to produce silicon panels instead (Bellini, 2021b; Solar Energy Technologies Office, 2023). Since its peak in 2013 at 2.5%, CIGS has experienced a continuous decline in market share (Fraunhofer Institute for Solar Energy Systems ISE, 2022). CdTe has remained relatively stable at 4%–5% market share, but has also declined from its previous 7% peak market share in 2009 (Feldman et al., 2021). Future adoption rates of solar PV technologies will be highly dependent on multiple factors, including cost, supply, demand, and incumbent technologies.

The range of market shares for each technology was applied to the STEPS and NZE scenarios to determine low and high material demand in conjunction with the material intensity values shown in Table 4.4 and detailed in Appendix B, respectively, for newly installed yearly capacity of each technology. The STEPS scenario combined with the low market share demonstrates the lowest demand case for each technology. The NZE scenario with high market share demonstrates the high demand for that technology.

Table 4.4. Low and high material intensity by solar technology and material.

Solar PV Technology	Material	Low Material Intensity (tonnes/GW)	High Material Intensity (tonnes/GW)
Si	Si	2,933	3,410
CIGS	Ga	2	11
CdTe	Te	20	36

4.2.5 Wind Energy

Two main scenarios used for calculating material demand from wind include STEPS and NZE. These scenarios apply to onshore and offshore wind (Figure 4.12 and Figure 4.13). Because IEA scenarios were developed for cumulative capacity to calculate annual material demand, the annual installation data were derived from the cumulative data. Replacements of retired wind turbines are included based on an assumed 30-year wind turbine lifespan, using historical global capacity data from the EIA (EIA, n.d.). Also, since IEA's NZE scenario did not include a breakdown between onshore and offshore installed capacity, the same breakdown as that in the STEPS scenario is used. As shown in Figure 4.12, onshore wind plays a much larger role compared to offshore wind. Between 2020 and 2025, onshore wind accounts for 90% of the wind portfolio. Starting in 2026, the offshore wind share starts to increase. By 2035, offshore wind could account for between 12% and 23% of the wind portfolio.

Nd, Pr, Dy, Tb, Ga, and Co are all used in the generators of direct drive and hybrid drive wind turbines. Direct-drive turbines are most commonly used in offshore wind turbines and are estimated to make up about 18% of the total wind turbine market, while hybrid drive turbines are estimated to make up another 12% of the market (GWEC, 2022; Serrano-González & Lacal-Arántegui, 2016). The share of hybrid and direct-drive turbines is expected to grow from 30% to 50% by 2025 (GWEC, 2022). Direct-drive turbines contain about 650 kg of

NdFeB permanent magnet per MW, and hybrid drive turbines use about 200 kg of magnet per MW. Detailed assumptions about the amount of each material in these magnets are shown in Appendix B.

Electrical steel demand from wind comes from the generators and transformers of substations. Onshore wind and offshore wind require 1500–5300 kg/MW and 2700–3600 kg/MW of electrical steel, respectively (OpenEI, n.d.). Trajectory A accounts for the low range of electrical steel content in onshore (1500 kg/MW) and offshore wind (2700 kg/MW) associated with the STEPS. Trajectory B is also based on STEPS with high material content of 5300 kg/MW and 3600 kg/MW for onshore and offshore wind, respectively. Trajectories C and D are based on the NZE with low and high material intensities, respectively.

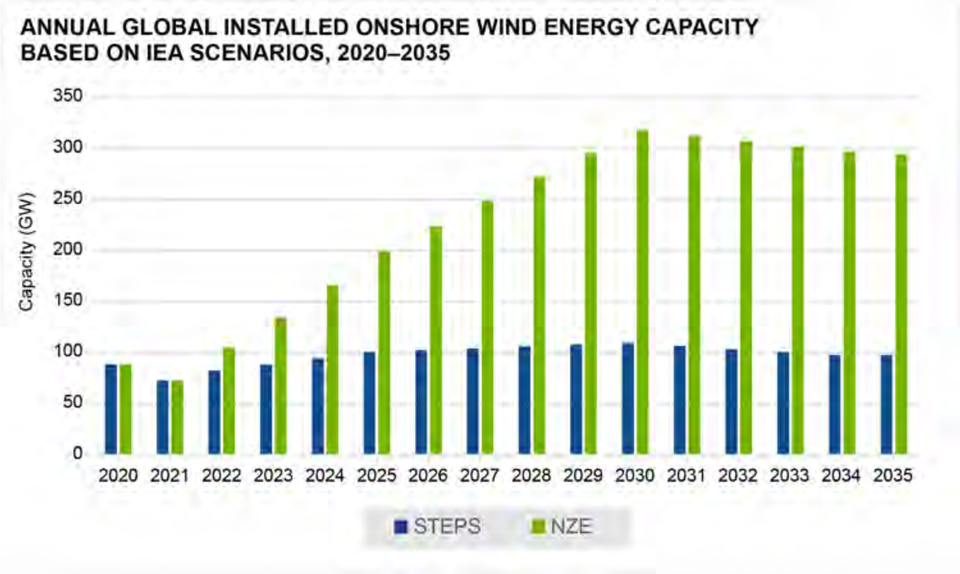


Figure 4.12. Annual installation of onshore wind capacity based on the IEA STEPS and NZE scenarios.

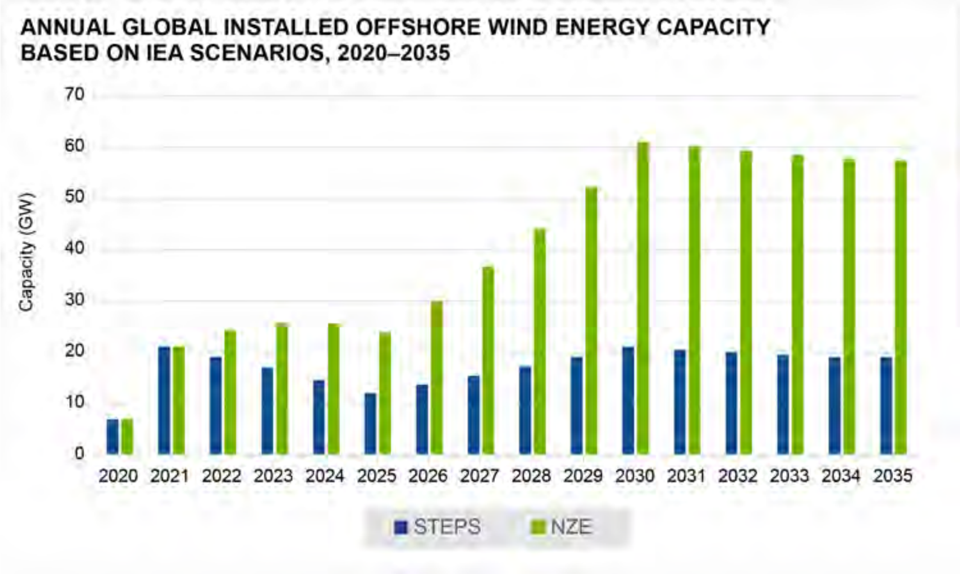


Figure 4.13. Annual installation of offshore wind capacity based on the IEA STEPS and NZE scenarios.

4.2.6 Nuclear Energy

Demand scenarios for the materials utilized for nuclear power were derived from the IEA's Nuclear Fade Case (NFC) (IEA, 2022e) and the NZE scenario (IEA, 2022f). In these two scenarios, nuclear capacity was the identified variable of projection. In the NFC, a nuclear capacity of 373 GWe was projected by 2035; and in the NZE scenario, a nuclear capacity of 623 GWe was projected by 2040. Current nuclear capacity estimations for 2021 range from 394 to 429 GWe (IEA, 2022e, 2022f, 2022i; World Nuclear Association, 2022c). The projected IEA scenarios are shown in Figure 4.14. The NFC scenario assumes that there will be no new investment in nuclear power capacity and no additional investment in nuclear lifetime extensions (IEA, 2019a). The NZE scenario assumes that nuclear capacity nearly doubles from the start of 2022 to 2050. Additionally, the NZE scenario utilizes nuclear technologies that are in advanced stages of development; however, it does not rely on unproven technology breakthroughs (IEA, 2019a). For comparison, the International Atomic Energy Agency (IAEA) projects a slightly higher nuclear capacity in the low case by 2035 at 387 GWe and a smaller nuclear capacity in the high case by 2035 at 578 GWe (IAEA, 2022a). Because the assessed materials were related to nuclear fuels and not in reactor construction, it was possible to assess the annual fuel consumption based on the available nuclear capacity each year. This treatment differs from that used for other materials, which required calculation of the installation capacity due to the one-time usage nature of the material in the application. In conjunction with the annual nuclear capacity derived from IEA scenarios, the material intensities (shown in Table 4.5) were then used to calculate annual material demand. More details on how material intensity was derived can be found in Appendix B.

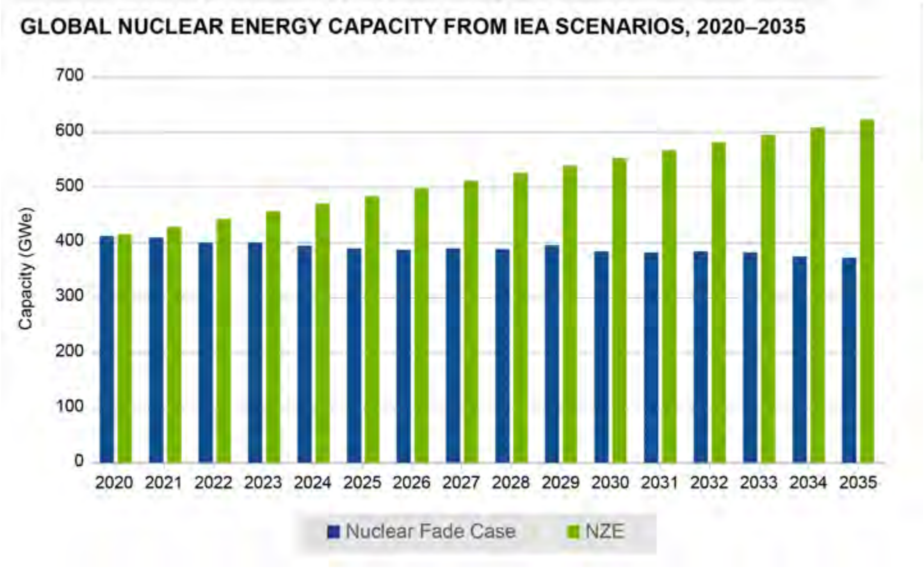


Figure 4.14. Nuclear capacity scenarios developed by the IEA (IEA, 2022e, 2022f).

Table 4.5. Low and high material intensity by material for nuclear capacity.

Material	Low Material Intensity (tonnes/GWe)	High Material Intensity (tonnes/GWe)
U	159	190
Natural Graphite	Startup: 2400 Annual: 800	Startup: 3600 Annual: 1200

4.2.7 Electric Grid

Demand scenarios for the materials utilized for grid networks were derived from the IEA's STEPS, APS, and SDS scenarios (IEA, 2021c). In these scenarios, different materials requirements were identified as a function of grid expansion levels. While STEPS and SDS scenarios were used to estimate Cu needs projection, STEPS and APS were used for ES estimates. Because IEA only constructed two demand scenarios for each material, EIA data were also utilized to obtain four trajectories. First, high and low material intensities were derived from IEA scenarios. Then, these intensities were applied to EIA's scenarios based on economic growth to construct a total of four trajectories.

EIA's High Economic Growth and Low Economic Growth scenarios (EIA, 2021b) reflect the uncertainty in projections of global economic growth, and illustrate the uncertainties in the effects of economic policies. Figure 4.15 shows the projections in global grid capacity following the different growth intensities. The materials intensities projected in the IEA scenarios are applied to these high- and low- estimations of the grid capacity. The needs for Cu for the STEPS scenario range approximately between 21 kt and 40 kt per GW (EIA, 2021b), which is the yearly average of the ratios of mineral quantity requirements to grid capacity, from the year 2020 to 2035. Following the same logic, Cu material intensity in the SDS scenario is about 24 kt to 47 kt per GW, with both scenarios including transformers, distribution, and transmission systems (EIA, 2021b). Using the grid capacity scenarios above, four trajectories were derived.

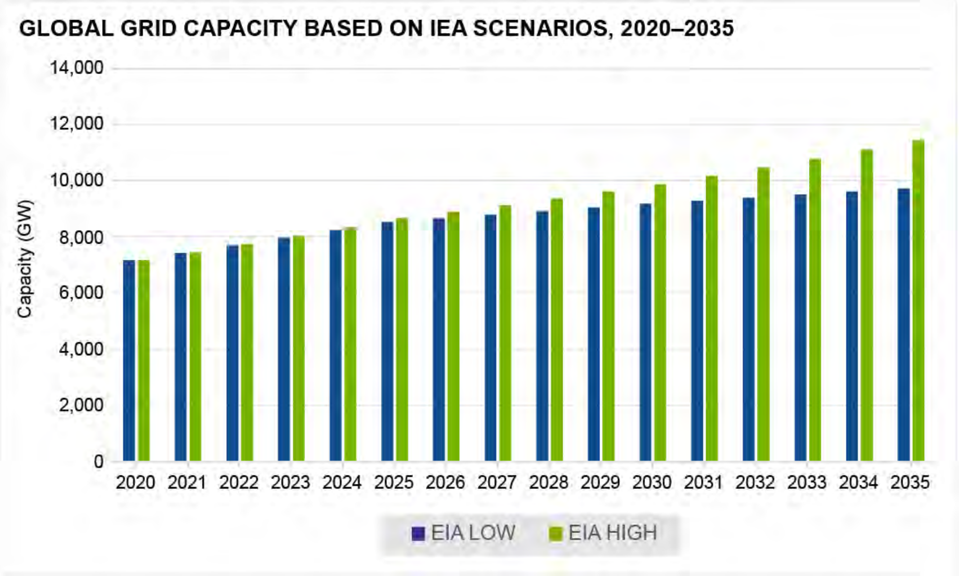


Figure 4.15. Current and planned capacity for the global grid until 2035 (EIA, 2021a).

The need for ES in transformers in the electric grid is also estimated. We compute the material intensity based on the grid expansion forecast, in km. The estimation includes transformers in the distribution and transmission systems, as well as portable ones. For the STEPS scenario, ES intensity varies between approximately 16 mt and 22 mt per km, while in the APS scenario, it stands between 14 mt and 20 mt per km of extension. Figure 4.16 and Figure 4.17 show the grid expansion for those two scenarios.

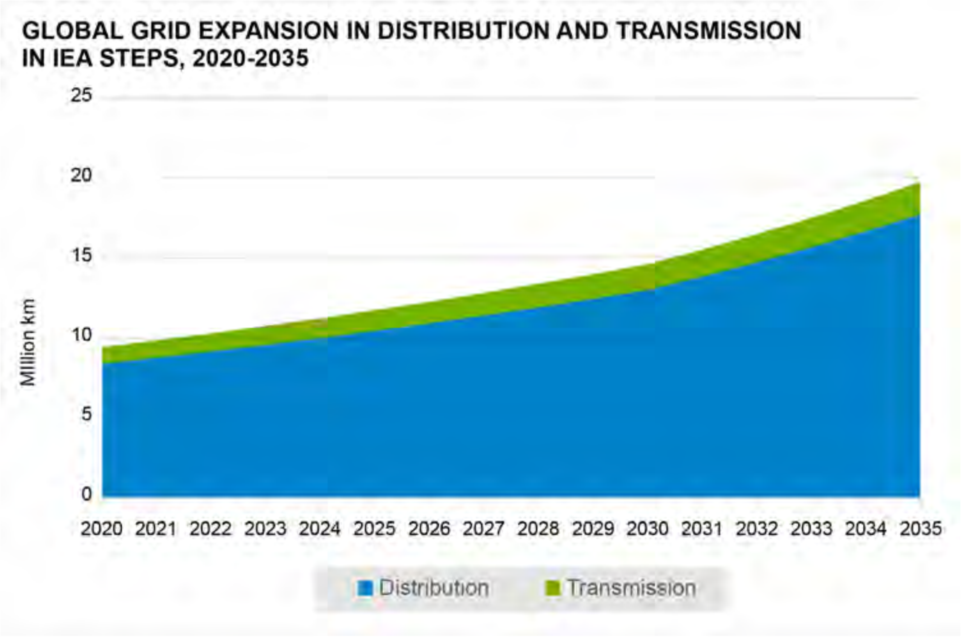


Figure 4.16. Grid expansion in distribution and transmission in the STEPS scenario (IEA, 2020a).

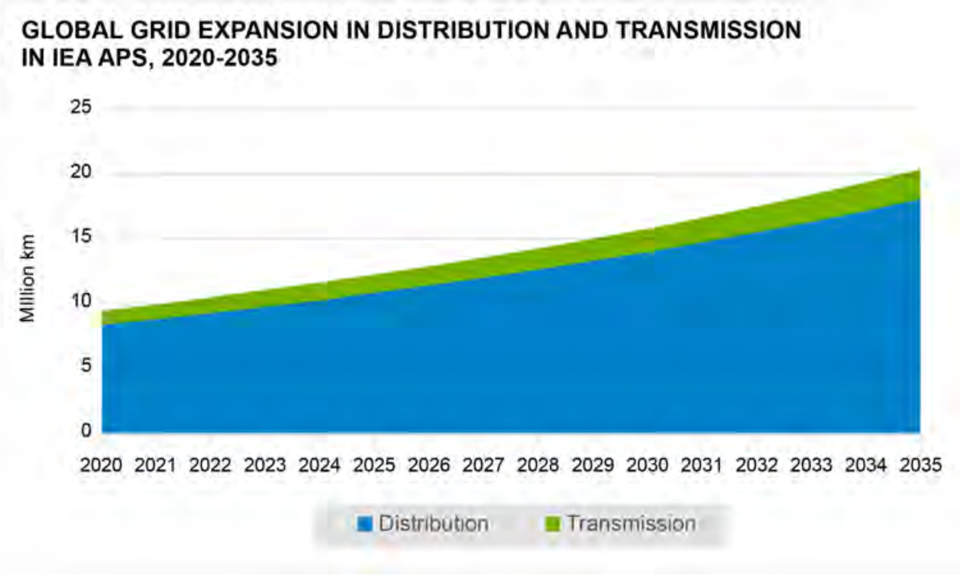


Figure 4.17. Grid expansion in distribution and transmission in the APS scenario (IEA, 2020a).

4.2.8 LED Lighting

Global demand scenarios for LED lighting were developed based on DOE’s 2019 report, “Energy Savings Forecast of Solid State Lighting in General Illumination Applications” (Elliott et al., 2019). Forecasted results for installed LED stocks were reported in number of units (Elliott et al., 2019). By utilizing both a 10% renovation rate (Elliott et al., 2019) and a 20-year lifespan for LED lights (Lighting Electrical, 2023), forecasted LED stocks can be converted into annual sales, a required step in calculating the gallium demand per year. In order to convert to a global annual sales quantity, an assumed value of 20% was used to represent the size of U.S. share in the global market. The results are shown in Figure 4.18. Because only one forecasted scenario could be developed based on the available data, a slightly different approach was used to achieve four demand scenarios for gallium. A combination of low/high material intensities and low/high raw material yields for LED production was used to develop the four scenarios. The material intensities and raw material yields can be found in Table 4.6.

Finally, to complete the development of the four demand trajectories, low/high material intensities and low/high material yields were applied to the global sales of LEDs.

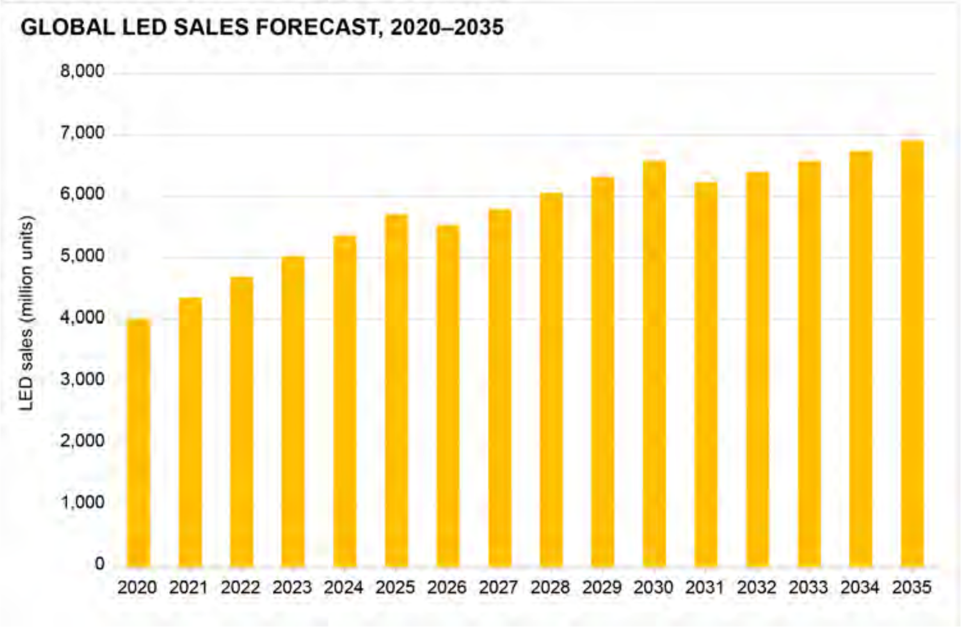


Figure 4.18. Global LED sales extrapolated from DOE's "Energy Savings Forecast of Solid State Lighting in General Illumination Applications" report (Elliott et al., 2019).

Table 4.6. Low/high material intensity and low/high raw material yield for LEDs by material.

Material	Low Material Intensity (grams/LED)	High Material Intensity (grams/LED)	Low Raw Material Yield (%)	High Raw Material Yield (%)
Ga	0.02	0.03	25%	50%

4.2.9 Power Electronics

As discussed in Chapter 2, Si is dominating the power electronics market with more than 90% market share by value in 2022 (Chiu & Dogmus, 2022). It is projected that by 2027, Si will still dominate this market at 80% market share, allowing room for growth in SiC use. GaN market share will grow but at a much slower rate compared to SiC. Within the SiC market, 70% of the drive in demand is the fast-growing EV market, which is projected to reach 80% in 2027 (Chiu & Dogmus, 2022). Regarding the GaN market, dominant applications are in the power supply for consumers, telecom/datacom, and industrial markets with 88% market share by value in 2022 and projected at 80% in 2027. EV application for GaN accounts for only less than 3% of market share currently, but it is expected to grow to 11% in 2027.

Note that although power electronics are components used in various energy technologies, quantifying direct estimates of power electronics consumption from each energy technology is not a straightforward activity. As a result, future demand trajectories were estimated based on recent demand with different CAGRs and market shares of SiC. First, 2021 demand of Si, SiC, and GaN based on wafer size is compiled from three separate reports (Ayari & Chiu, 2022; Chiu & Dogmus, 2022; Rosina & Villamor, 2022). Common sizes include 4-inch, 6-inch, and 8-inch wafers. Among those, the 6-inch wafer is the most common size. As a convention, for reporting purposes, a 6-inch equivalent quantity is derived from a 6-inch quantity combined with conversions of other sizes to the 6-inch wafer. While the 6-inch equivalent is the preferred data, because of data inconsistency among the three reports, only 6-inch wafer data were used to estimate demand. A total of 25 million 6-inch wafers were demanded in 2021. Because the analysis start time is 2020, 2021 data were extrapolated to 2020 using high and low market growth rates of 0.9% and 4.4%, respectively (Rosina & Villamor, 2022). These rates were also used to calculate high and low deployment scenarios. Market shares of SiC by wafer unit are 1.2% and 5.4%, respectively, to derive the low and high penetration rates (Ayari & Chiu, 2022; Chiu & Dogmus, 2022; Rosina & Villamor, 2022). Note that because the main bottleneck in the SiC supply chain is manufacturing, which differs from other materials presented in this report, wafer units instead of mass are used for SiC demand and supply to compare with this industry's capacity. In parallel with GaN, SiC was converted to Si and synthetic graphite quantity (for demand) and aggregated with other applications. However, this quantity is insignificant and does not impact the total Si and graphite demand.

4.3 Demand Trajectories and Production of Materials for Energy Technologies

4.3.1 Aluminum

4.3.1.1 Demand Trajectories

In 2020, aluminum demand in vehicle lightweighting was the biggest contributor toward aluminum demand across the clean energy landscape, consisting of approximately 16% of total aluminum demand. By the end of the short term in 2025, this share increases to 25% given a high material penetration and intensity (Trajectory D). The final year of the demand trajectories, 2035, projects that 30% of aluminum demand is attributable to vehicle lightweighting as compared to 6% for EV batteries and 2% for stationary storage batteries. These trajectories are shown in Figure 4.19.

4.3.1.2 Production

Values for the 2020 production and production capacity of aluminum are sourced from the USGS 2022 commodity summary (USGS, 2022b) and incorporate a low-end 50% recycling rate (Nassar et al., 2015). In 2020, aluminum production and production capacity levels were estimated to be 97.7 million metric tons and 114 million metric tons, respectively. These production levels come mainly from China, accounting for approximately 58% of market share in the production of aluminum. China is followed by India (6%), Russia (5%), Canada (4%), and United Arab Emirates (4%) in the production of aluminum (USGS, 2022b). Production levels in 2020 are able to meet all demand trajectories until 2022, where 2020 production capacity levels must be reached in order to meet projected aluminum demand sufficiently until 2025. By the end of the medium term, all demand trajectories for aluminum greatly outpace production capacity levels. In order to meet these demand levels, replacing aluminum with other lightweight materials will be difficult as aluminum is often an essential alloying component for automobile manufacturing. Additionally, aluminum cannot be substituted easily out of lithium-ion batteries as it is present in all EV battery chemistries analyzed in this report. Global bauxite reserves provide enough aluminum resources to meet those demands, however, but mining production must increase in order to meet projected demand (USGS, 2022b).

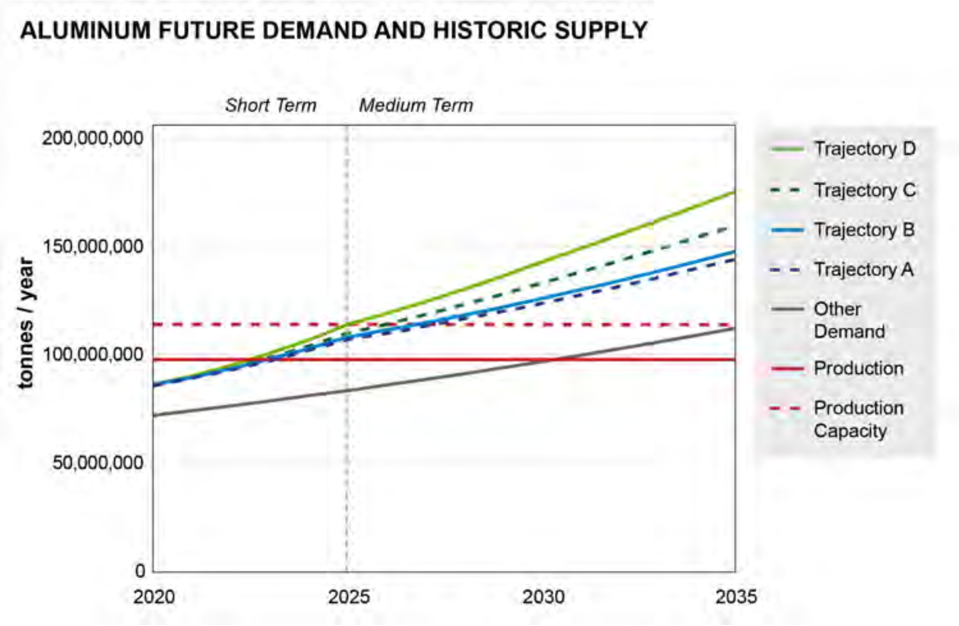


Figure 4.19. Aluminum demand trajectories, current production, and production capacity.

4.3.2 Cobalt

4.3.2.1 Demand Trajectories

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 as shown in Figure 4.20. 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. Calculations for each of these trajectory scenarios were performed for each material's respective clean energy technology.

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's (2022k) *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 (Argonne National Laboratory, n.d.-a; Iloeje et al., 2022; C. Xu et al., 2020). 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 demand 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 GDP growth.

Note that while Trajectory D implies that Co demands will greatly exceed current production capacity, the low material intensity implied by Trajectory C suggests that using battery chemistries with lower or no Co content (such as LFP or nickel-rich chemistries) can help mitigate supply gaps and potentially lower criticality.

4.3.2.2 Production

The production lines are based on 2020 data from the 2022 USGS estimates of global cobalt production. Cobalt recycling rates are not incorporated in production amounts. Production capacity of cobalt was obtained by dividing production by an average capacity utilization rate.

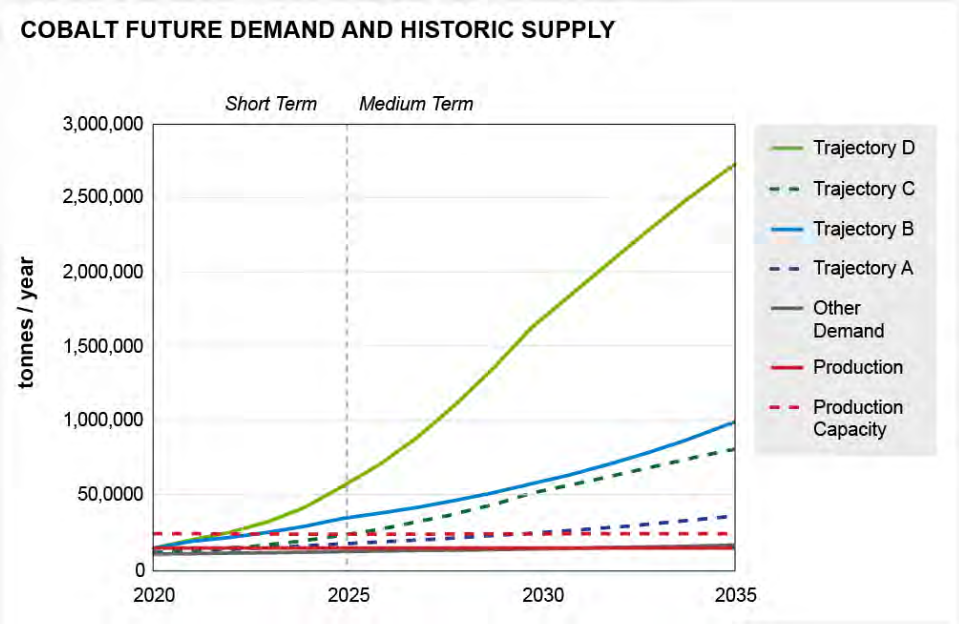


Figure 4.20. Cobalt demand trajectories, current production, and production capacity.

4.3.3 Copper

4.3.3.1 Demand Trajectories

Figure 4.21 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, ICE vehicles, and the electric grid. The STEPS and NZE scenarios are used for low and high projections of wind, EVs, and ICEs. For the electric grid, the STEPS and SDS scenarios are used. Regarding wind turbine demand trajectories, because annual installation decreases after 2030 in both the STEPS and NZE scenarios, Cu demand in all four trajectories reduces from 2030 to 2035. Cu demand for EVs and grid expansion continues to increase from 2020 to 2035 for all trajectories. For ICE vehicles, the demand trend is very different from other applications. In the STEPS scenario, ICE vehicle sales continue to rise until 2035. However, in the NZE scenario, ICE sales start to decline in 2026. The “other demand” curve represents Cu demand for applications such as construction, chemicals, industrial processes, and consumer electronics.

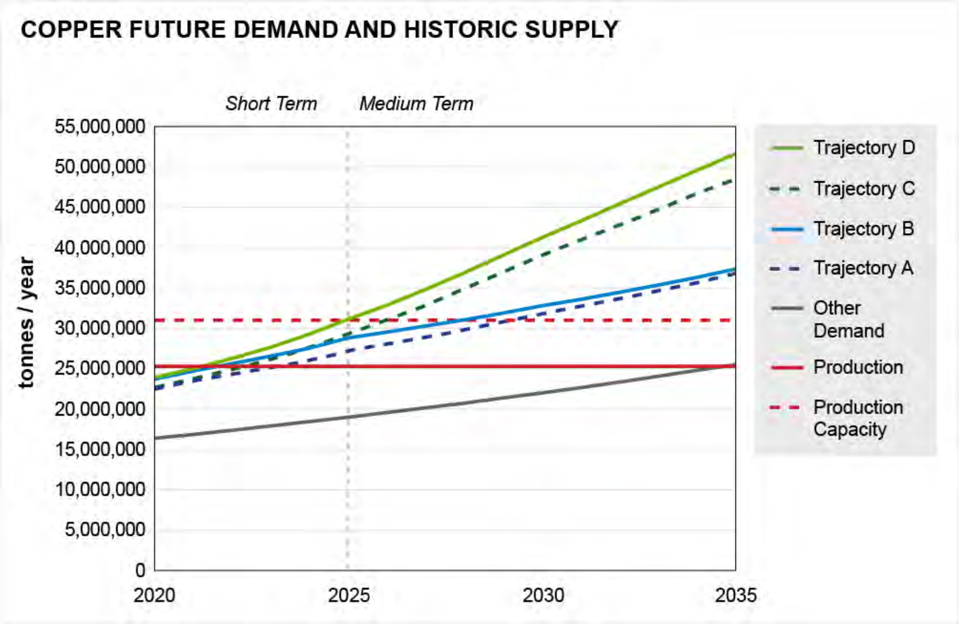


Figure 4.21. Copper demand trajectories, current production, and production capacity.

4.3.3.2 Production

In the United States, production from copper-bearing ores in 2021 was estimated to be 1,200 kt. This amount is a slight decrease from the year 2015 when production was 1,380 kt. Refined Cu production in 2021 was 950 kt, in comparison to 1,090 kt back in 2015. According to the USGS (2022b) report, Arizona was the leading state in Cu production, having an estimated 71% of domestic output. Other mining states include Michigan, Missouri, Montana, Nevada, New Mexico, and Utah. The domestic reserve was estimated at 48,000 kt (USGS, 2022b).

Global Cu mine production, refinery production, and reserve were estimated at 21,000, 26,000, and 880,000 kt, respectively (USGS, 2022b). Chile is the world’s leader in Cu mining production with 5,600 kt (27%) of the global supply in 2021. China dominates the refinery production, with 100,000 kt (38%) in the same year. The largest reserves are in Australia and Chile, with 93,000 kt (11%) and 200,000 kt (23%), respectively (USGS, 2022b).

Cu secondary production comes from the consumer/old scrap and new scrap resulting from the manufacturing process, including metal and alloy production. Unlike other materials, Cu is 100% recyclable and can be recycled perpetually without loss of performance (ICA, 2022a). In 2021, the U.S.’s old (post-consumer) scrap was estimated at 160 kt of Cu, equaling about 8% of apparent consumption of Cu (USGS, 2022b). New (manufacturing) scrap, derived from fabricating operations, yielded approximately 710 kt in 2021 (USGS, 2020). Globally, ~64% of scrap was new (direct melt), and the remainder went through a secondary refinery in 2021 (International Copper Study Group, 2022). Cu scrap constitutes about 28% to 37% of Cu used in the production of new Cu between 2005 and 2021. In 2021, this rate was estimated to be ~34% (International Copper Study Group, 2022).

Because various forms of Cu are used in technologies considered for energy trajectories, refined production data were chosen to compare against demand projections. The refined production includes both primary and secondary production. Refined capacity was estimated to be 31,000 kt in 2022 (International Copper Study Group, 2022).

4.3.4 Dysprosium

4.3.4.1 Demand Trajectories

Figure 4.22 displays the demand for Dy from 2020 to 2035 against current production and production capacity. The clean energy technologies considered for Dy are wind turbines and EV magnets. The STEPS and NZE scenarios from the IEA are used for the low and high deployment scenarios, respectively. The high and low material intensity scenarios depend on magnet sizes and the amount of Dy used per magnet, as detailed in Appendix B. The other demand curve represents Dy demand for other applications such as consumer electronics, air conditioning, industrial machines, Terfenol-D, and other alloys, which are assumed to grow at a 3% rate. 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.

4.3.4.2 Production

Production levels shown in Figure 4.22 were based on 2022 USGS estimates of total rare earth minerals production by country combined with estimates of shares of different rare earths in each country's mines (Li & Yang, 2014; Sanematsu et al., 2016; TMR, 2015; USGS, 2022b). Additional unreported Chinese production is estimated using Adamas (Adamas Intelligence, 2023b). 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 monazite processing capacity in the U.S. in excess of current production was accounted for (Energy Fuels, 2023). Quantities are adjusted to be in terms of Dy content, rather than Dy oxide.

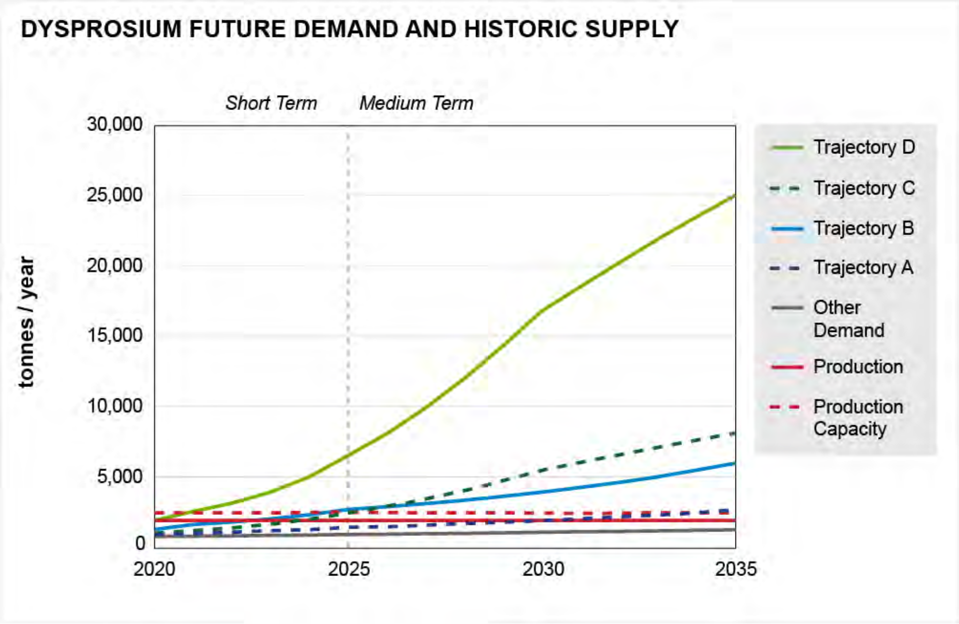


Figure 4.22. Dysprosium demand trajectories, current production, and production capacity.

4.3.5 Electrical Steel

4.3.5.1 Demand Trajectories

Figure 4.23 displays the demand of electrical steel (ES) 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 Trajectories A and B for all technologies. The Announced Pledges Scenarios (APS) from the IEA were used for transformers, and NZE scenarios were used for wind turbines and EVs, to develop Trajectories C and D. The low and high material intensity of electrical steel in each technology can be found in Appendix B. The step change in Trajectories A and C is due to the higher growth of grid expansion, affecting transformer demand in the STEPS scenario compared to the NZE scenario. In the NZE scenario, because of high grid expansion annually between 2021 and 2030, annual expansion after 2030 is at steady growth. However, in the STEPS scenario, because growth in the early years is lower, after 2030, annual grid expansion needs to grow at a higher rate to support renewable energy integration.

4.3.5.2 Production

Production data were obtained from a market report, covering the market forecast, trends analysis, and competition to ES from 2018 to 2033 (Fact.MR, 2023). Information gathered from this report includes production by sectors and applications, that is, automotive, manufacturing, energy, household appliances, and others (construction, fabrication, etc.). Global ES production has been increasing throughout 2022, from about 1 Mt in January to about 1.5 Mt by December, with a global average standing around 1.2 Mt–1.3 Mt per month (Fact.MR, 2023). Global capacity in 2022 was estimated at 25 Mt, of which GOES accounted for 57% of the total capacity.

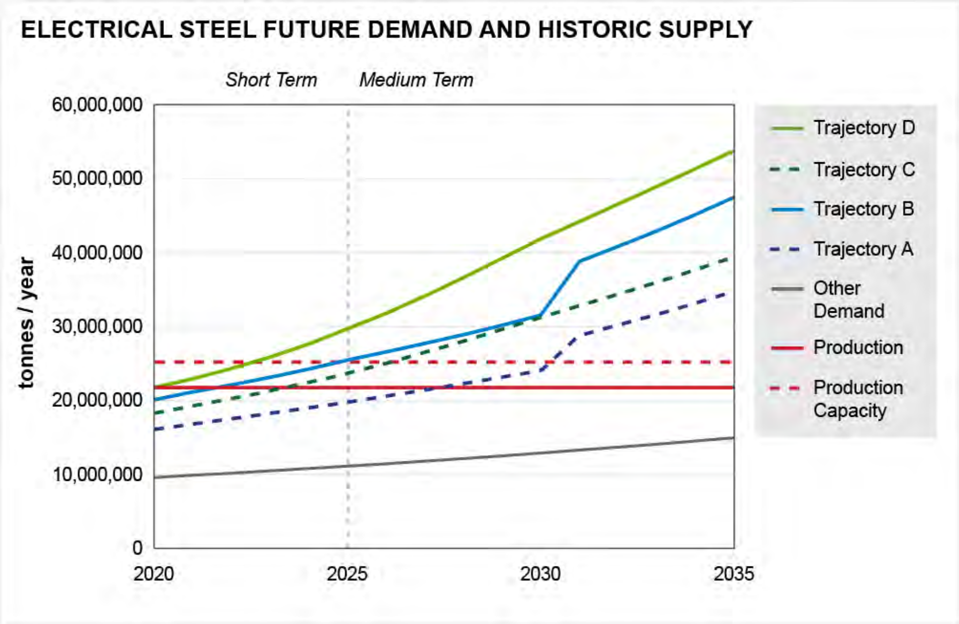


Figure 4.23. Electrical steel demand trajectories, current production, and production capacity.

4.3.6 Fluorine

4.3.6.1 Demand Trajectories

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 as shown in Figure 4.24. 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. Each of these trajectory scenarios were calculated for each material's respective clean energy technology.

For each trajectory, the demand for fluorine was calculated for its use in lithium-ion batteries (LIBs) in electric vehicles and stationary storage. 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 chemistries (Argonne National Laboratory, n.d.-a). A range of the fluorine content in LIBs was further developed based on projected LIB chemistry mixes reported in the literature (C. Xu et al., 2020). This range was then applied to (1) 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 (2) to projections of stationary storage deployment in GW from the IEA's *World Energy Outlook* (IEA, 2022i). 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 of world fluorine demand is assumed to equal 2020 production, which was sourced from the USGS (USGS, 2023).

4.3.6.2 Production

Fluorine production amounts were based solely on primary production, and fluorine production capacity was calculated by dividing 2020 global production by a capacity utilization factor of 86%.

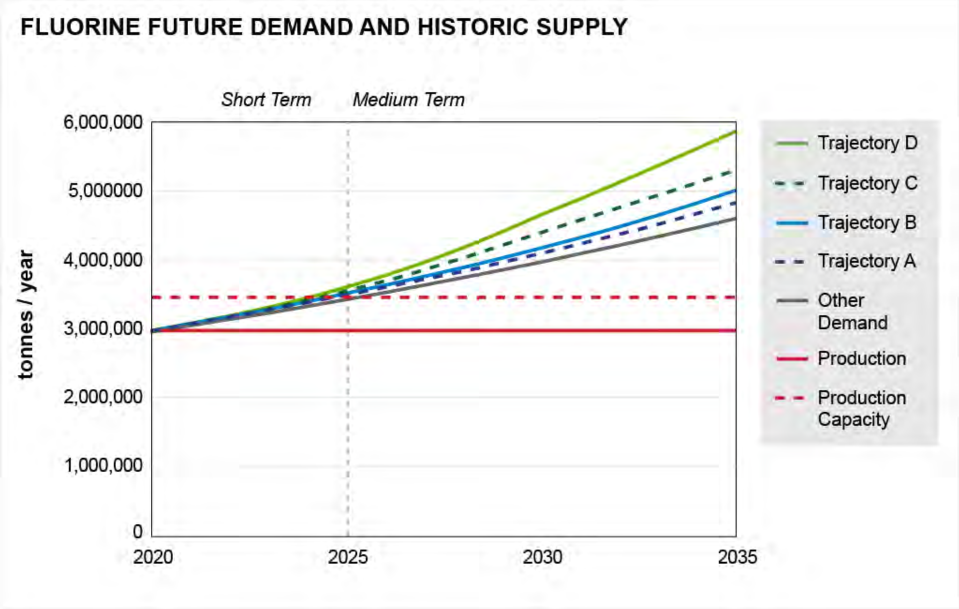


Figure 4.24. Fluorine demand trajectories, current production, and production capacity.

4.3.7 Gallium

4.3.7.1 Demand Trajectories

Figure 4.25 shows four different demand scenarios for gallium from 2020 to 2035 against current gallium production and production capacity. Energy applications considered in this analysis for gallium were 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, different sets of data were utilized to create the demand scenarios. For example, LED lighting relied on DOE's 2019 report, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications" (Elliott et al., 2019); magnets in EVs and wind turbines relied on IEA projection data; solar cells relied on the IEA's STEPS and NZE projection data; and power electronics relied on data from Yole Reports (Ayari & Chiu, 2022). Once these scenarios were developed that established the projected technology prevalence, material intensities and production yields, when applicable, were applied. This resulted in the final trajectory results. Additional information on low and high material intensities used to compute each trajectory may be found in Appendix B (Elliott et al., 2019).

As shown in Figure 4.25, there is a wide gap among the four trajectories due to different technology trends. LED demand is steadily growing for both low and high trajectories. Ga demand for magnets in EVs and wind is highly variable because of the difference between low and high intensities. Trajectories A and C for Ga in magnets are negligible. Ga is sometimes added to magnets to improve coercivity. If Ga prices are high, a different coercivity boosting method would be used. Ga content between 0% and 0.2% has been found in commercial magnets for EVs and wind turbines as shown in Appendix B, respectively. In the case of solar, because CIGS adoption is shrinking, Trajectories A and B assume no CIGS market share between 2020 and 2035, while trajectories C and D assume 5% CIGS market share within the same time frame. Overall, demand for Ga in energy applications is the dominant use of Ga. Other demand not considered in this report includes Ga use in consumer electronics and telecommunications. As Figure 4.25 shows, "other demand" is insignificant.

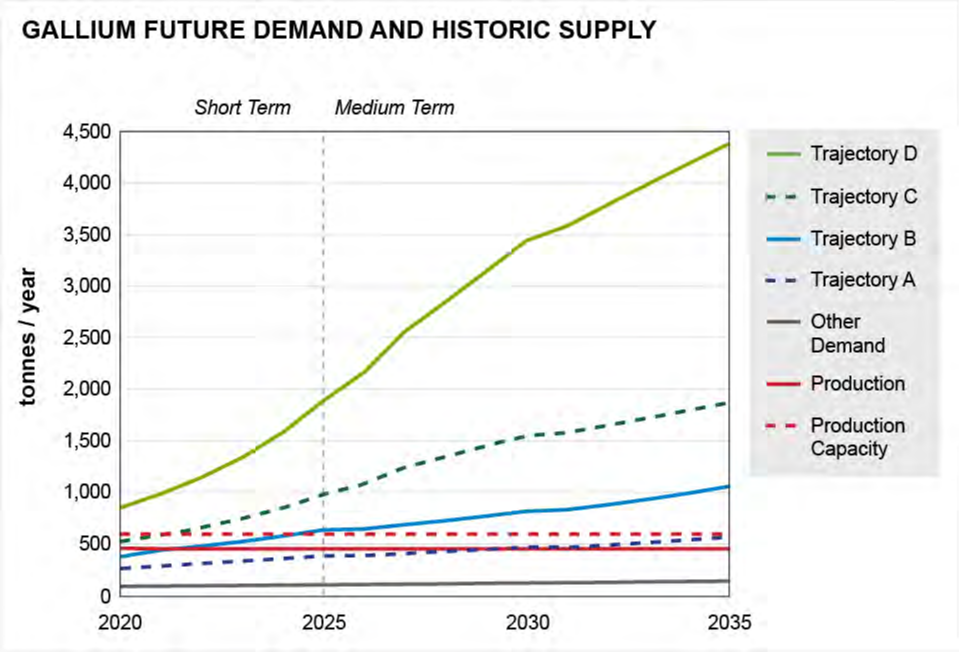


Figure 4.25. Gallium demand trajectories, current production, and production capacity.

4.3.7.2 Production

Production data were obtained from the USGS (USGS, 2022b). Of this data, high-purity refined gallium production was identified as the material form of interest due to the requirement that most semiconductor applications feature 6N purity or higher (IARC, 2006). To compute total high-purity gallium production capacity, the primary high-purity gallium production capacity, 325 mt, was summed with the secondary high-purity gallium production capacity, 273 mt (USGS, 2022b). Regarding current production, because recycling output is not available, an assumed 86% capacity utilization rate was used to derive production from capacity. This number, 232 mt, was then added to primary high-purity gallium production, 220 mt, to compute total supply of high-purity gallium.

4.3.8 Graphite

4.3.8.1 Demand Trajectories

Trajectories for future graphite demand were based on four clean energy technologies: electric vehicle batteries, stationary storage batteries, fuel cell electric vehicles, and nuclear energy. Four different scenarios for each technology type were created and respectively added together to produce the four different trajectories as shown in Figure 4.26. 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. Calculations of each of these trajectory scenarios were performed for each material's respective clean energy technology.

For each trajectory, the demand for graphite was calculated for its use in LIBs in electric vehicles and stationary storage. 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 chemistries (Argonne National Laboratory, n.d.-a). A range of the graphite content in LIBs specific to each technology was further developed based on projected LIB chemistry mixes, silicon contents in anode, and shares of natural vs. synthetic graphite reported in the literature (Eshetu et al., 2021; Pillot, 2021; C. Xu et al., 2020). 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. Similarly, the stationary LIB graphite range was applied to projections of stationary storage deployment in GW from the IEA's *World Energy Outlook* (IEA, 2022i) 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 the 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 a pebble bed reactor and projected nuclear power deployment scenarios. The shares of natural vs. synthetic graphite in fuel cell are assumed to be the same as those in LIBs, while graphite demand for application to nuclear energy is assumed to be 100% natural graphite. Additional information on the 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 demand 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 for world graphite demand is assumed to equal 2020 production.

4.3.8.2 Production

The 2020 production value was sourced from USGS (USGS, 2022b). Graphite production amounts were solely based on primary flake production, and graphite production capacity was assumed to equal the maximum global production from 2017–2021 as reported by USGS (USGS, 2022b).

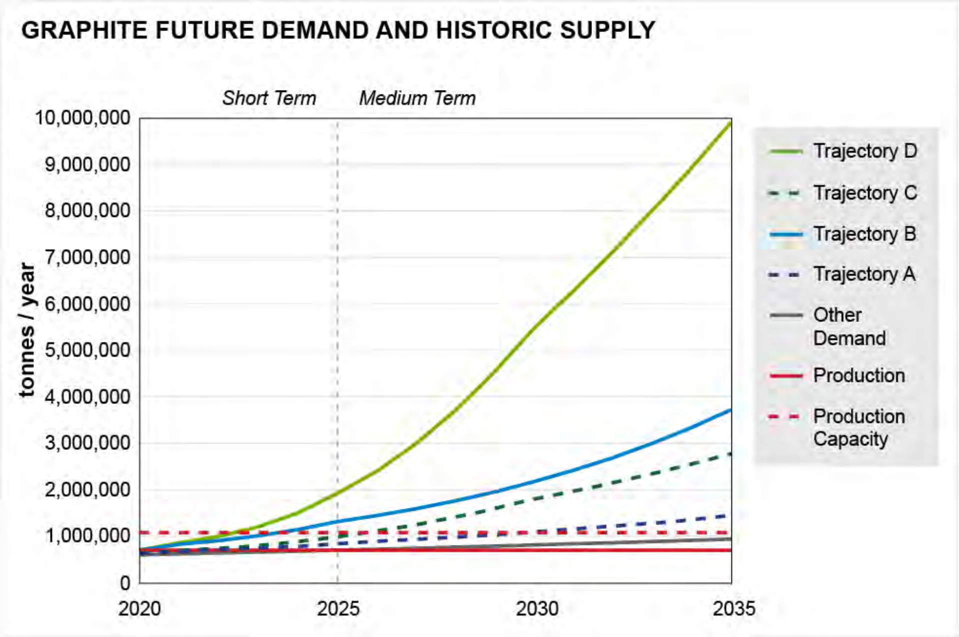


Figure 4.26. Graphite demand trajectories, current production, and production capacity.

4.3.9 Iridium

4.3.9.1 Demand Trajectories

Figure 4.27 displays the demand for iridium (Ir) from 2020 to 2035 against 2020 production and production capacity. The only clean energy technology considered for Ir is proton electrolyte membrane (PEM) electrolyzers. We used the STEPS and NZE scenarios from the IEA for low and high deployment scenarios, respectively. For each of these scenarios, we considered 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.

4.3.9.2 Production

Iridium is a scarce element in the earth’s crust with an estimated content of 0.000003 part per million (Minke et al., 2021). Iridium content in ore concentrates ranges from 0.01–0.22 g/t (USGS, 2022b). Iridium is coproduced with other platinum group metals, where platinum or palladium are the dominant products. It is unlikely that iridium would be produced as a primary product, although some iridium may be recovered from platinum mine overburden, discarded ores, and tailings (Moreira & Laing, 2022). In 2021, 89% of iridium was produced in South Africa, 8% in Zimbabwe, and 3% in Russia (USGS, 2022b). Iridium mine capacity (9.2 tonnes) is estimated from the USGS-reported world mine production in 2021 (7.88 tonnes) and an assumed capacity utilization of 86%.

Iridium is used in chemical manufacturing, refining, and electrochemical catalysts, where significant closed-loop recycling occurs. Other application areas for iridium include electronics (e.g., lithium tantalate mobile phone filters, hardening agents for reed switches, organic light-emitting diodes) and medical devices (e.g., pacemakers, defibrillators) (Hughes et al., 2021). In PEM electrolyzers, iridium serves as the anode catalyst, where hydroxide ions transferred from the cathode are reacted to form oxygen and water. While iridium is not currently the major contributor to PEM electrolysis cost, it is expected to become more significant as production costs decline and electrolysis demand increases.

In the future, a significant fraction of iridium in PEM electrolyzers is expected to be recovered at their end-of-life. This iridium recovery, however, is not considered in the forecasts.

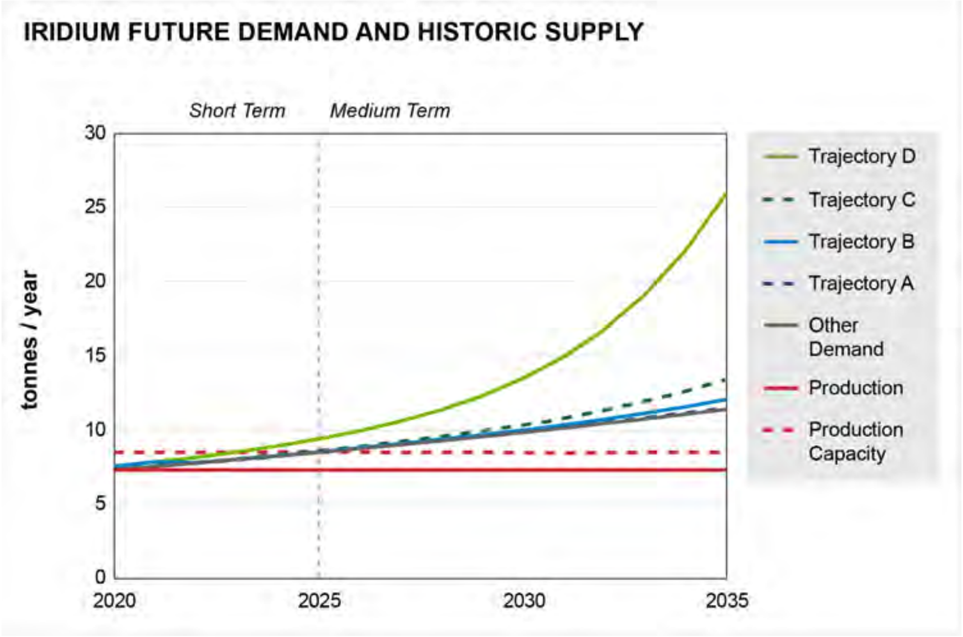


Figure 4.27. Iridium demand trajectories, current production, and production capacity.

4.3.10 Lithium

4.3.10.1 Demand Trajectories

Figure 4.28 shows four different demand scenarios for lithium 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 IEA's NZE 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 (Argonne National Laboratory, 2018; C. Xu et al., 2020), as described in Appendix B. Total primary lithium demand is estimated from the USGS's *2018 Mineral Yearbook* and by applying a 9% growth rate since then, based on historical CAGR that is also from the USGS's *2018 Mineral Yearbook* (USGS, 2022b).

4.3.10.2 Production

Production is based on 2021 USGS estimates from the USGS's *2022 Mineral Commodity Study* of total lithium production (USGS, 2022b). Small amounts of lithium are recycled from lithium-ion batteries, and recycled quantities are likely to grow in the future, but the amount produced from end-of-life batteries in 2020 is estimated to be small enough that it will not substantially affect worldwide lithium supply. Production capacity is estimated using the capacity utilization rate of 86% that the USGS reported for 2018 in its *2018 Minerals Yearbook* (USGS, 2022b).

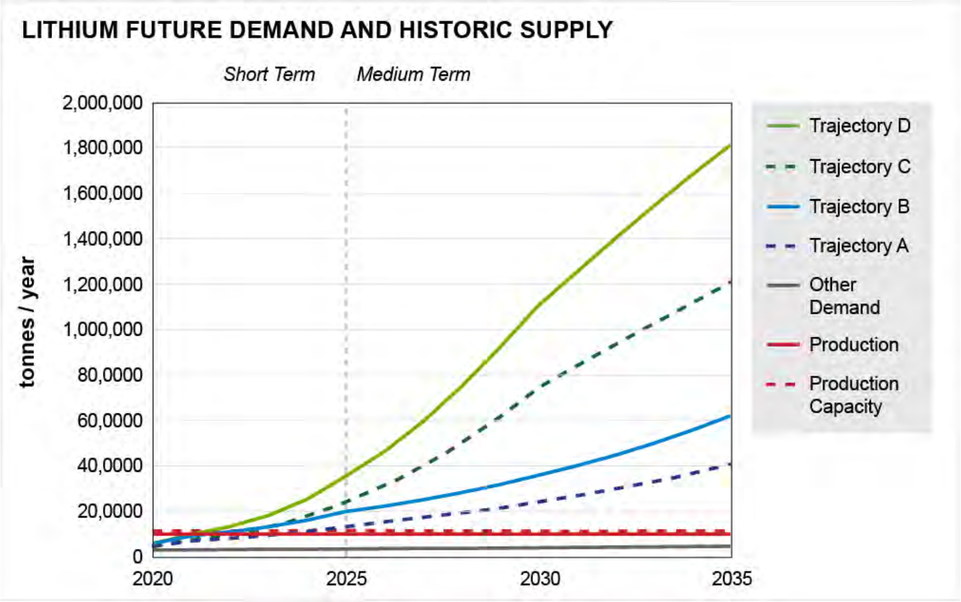


Figure 4.28. Lithium demand trajectories, current production, and production capacity.

4.3.11 Magnesium

4.3.11.1 Demand Trajectories

Magnesium demand trajectories consist of only one of the clean energy technologies: vehicle lightweighting. Across the demand trajectories, magnesium demand in clean energy as a percentage of total magnesium demand ranges from 57% to 59% in 2020. By the end of the short and medium term, magnesium demand in the highest intensity scenario (Trajectory D) consists of 74% and 81% clean energy demand as a percentage of total energy demand. Magnesium demand quickly outpaces 2020 production levels in the highest demand trajectory, and by 2025, all demand trajectories outpace production levels (Figure 4.29). Production capacity levels in 2020 allow for potential supply of magnesium to meet demand trajectories until 2035 for the two lowest intensity scenarios (Trajectories A and B). The higher trajectories (Trajectory C and D) outpace 2020 production capacity levels but only the highest-intensity scenario greatly exceeds this capacity potential. Due to magnesium content having mild substitution limitations in the medium term, production levels must increase to meet demand in the highest-intensity scenario.

4.3.11.2 Production

Magnesium production in 2020 is estimated to be 1.3 million metric tons while production capacity is estimated to be 2.6 million metric tons. The 2020 magnesium production value is sourced from the USGS's *Mineral Commodities 2022 Summary* (USGS, 2022b) and incorporates a low-end recycling rate of 25% (Nassar et al., 2015). Of the total amount of mine production of magnesium in 2020, China represents approximately 88% of market share in the production of magnesium. Other countries such as Russia (5%), Israel (2%), Brazil (2%), and Kazakhstan (2%) have totals that are only a small percentage of what China produces (USGS, 2022b).

Magnesium's availability in natural resources provides large amounts of potential sources if technology improves (USGS, 2022b). Additionally, potential European magnesium projects plan to start producing magnesium as early as 2025 (Onstad, 2022), while in Canada and Australia, there are projects in their start-up phase to boost supply (SMM, 2021). Magnesium supply is projected to reach 1.8 million metric tons by 2030, which, if capacity is expanded at the same utilization rate as current levels (approximately 50% including recycling rates), would sufficiently meet all demand trajectories in that year (SMM, 2021).

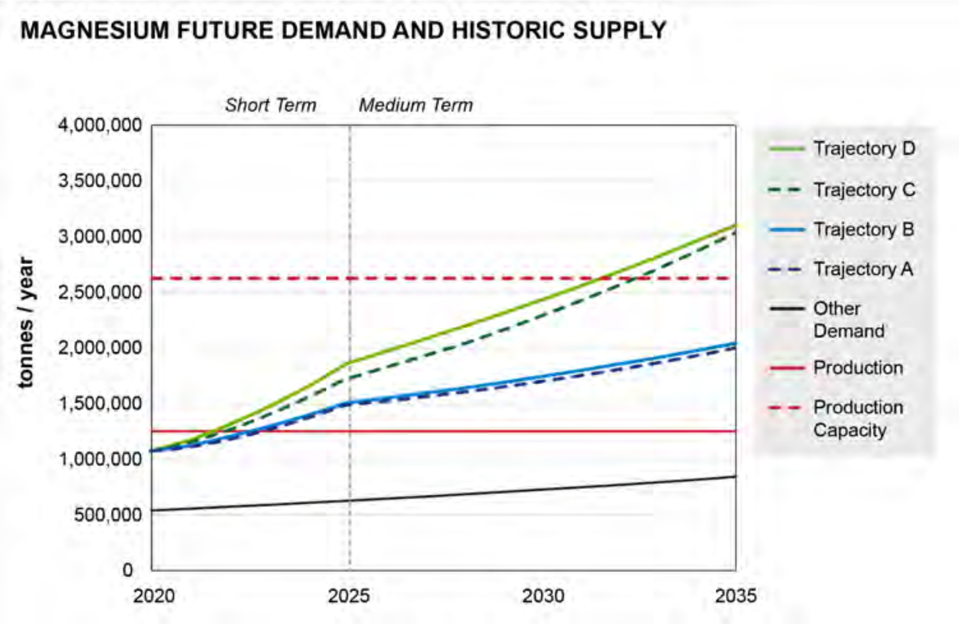


Figure 4.29. Magnesium demand trajectories, current production, and production capacity.

4.3.12 Manganese

4.3.12.1 Demand Trajectories

The majority of the manganese demand in clean energy technologies is driven by lightweighting alloys until after 2025, when high-intensity EV battery demand begins to cut into its share. Through the short term until 2025, manganese in lightweighting remains a large portion of the clean energy demand with 94% demand share in Trajectory A and 80% demand share in Trajectory D. By the end of the medium term, EV batteries in the highest demand trajectory begin to make up a larger share of the manganese demand by constituting approximately 41% of manganese demand while lightweighting consists of approximately 55%. However, in the overall landscape of energy demand, manganese represents a small portion in the short and medium terms. By 2025, manganese demand in all clean energy technologies ranges from 3% to 6% across the demand trajectories. In 2035, this range modestly increases in the highest demand trajectories with a range of from 3% to 10%.

4.3.12.2 Production

Manganese production and production capacity were estimated to be 28.4 million metric tons and 40.5 million metric tons, respectively. Manganese production levels incorporated a 50% recycling rate (Nassar et al., 2015) to 2020 USGS mine production estimates (USGS, 2022b) while production capacity levels utilized a 70% capacity utilization rate from the 2020 production levels (The International Manganese Institute, 2016). This production supply of manganese is relatively diverse, with South Africa accounting for 36% of the production share, followed by Gabon (23%), Australia (17%), China (5%), Ghana (5%), and India (2%) (USGS, 2022b). In the short term, production levels can easily meet demand for manganese across all trajectories and thus it presents no concern for suppliers to require substitution of manganese in favor of less critical materials. The trajectory demand levels remain below supply until 2032, when Trajectory D outpaces supply. It will not be until 2035 that the lowest-intensity trajectory (Trajectory A) exceeds manganese production in 2020 (Figure 4.30). Suppliers, therefore, will need to increase manganese production slightly in the next 15 years to handle increased demand in the medium term. Production levels since 2016 have increased dramatically, and if they continue, these levels will be able to meet projected demand in the medium term. Manganese production by South32, Tshipi é Ntle, United Manganese of Kalahari, and Assmang in South Africa are some examples of producers looking to raise production in order to meet the anticipated demand of manganese (Christianson, n.d.). Additionally, Eramet in Gabon has sent a notice that it intends to expand manganese mine production from 4.3 million tons to 7 million tons by 2023 (Webb, 2019).

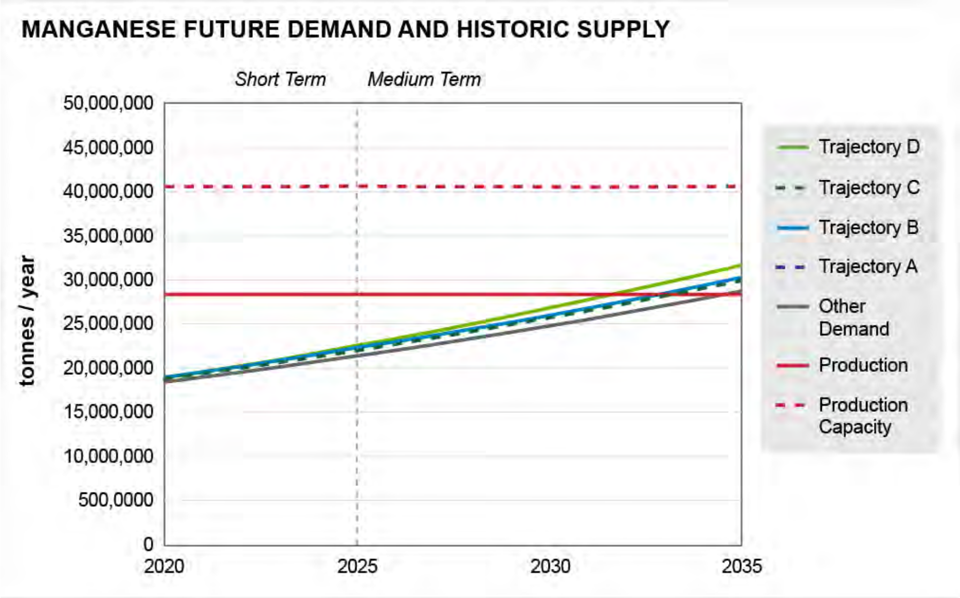


Figure 4.30. Manganese demand trajectories, current production, and production capacity.

4.3.13 Neodymium

4.3.13.1 Demand Trajectories

Figure 4.31 displays the demand for 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, ceramics and glasses, catalysts, and alloys, and are assumed to grow at 3%. Trajectories A and B are based on the 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.

4.3.13.2 Production

Production levels shown in Figure 4.31 were 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 (Li & Yang, 2014; Sanematsu et al., 2016; TMR, 2015; USGS, 2022b). Additional unreported Chinese production is estimated using Adamas (Adamas Intelligence, 2023b). 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 monazite processing capacity in the U.S. in excess of current production was accounted for (Energy Fuels, 2023). Quantities are adjusted to be in terms of Nd content rather than Nd oxide.

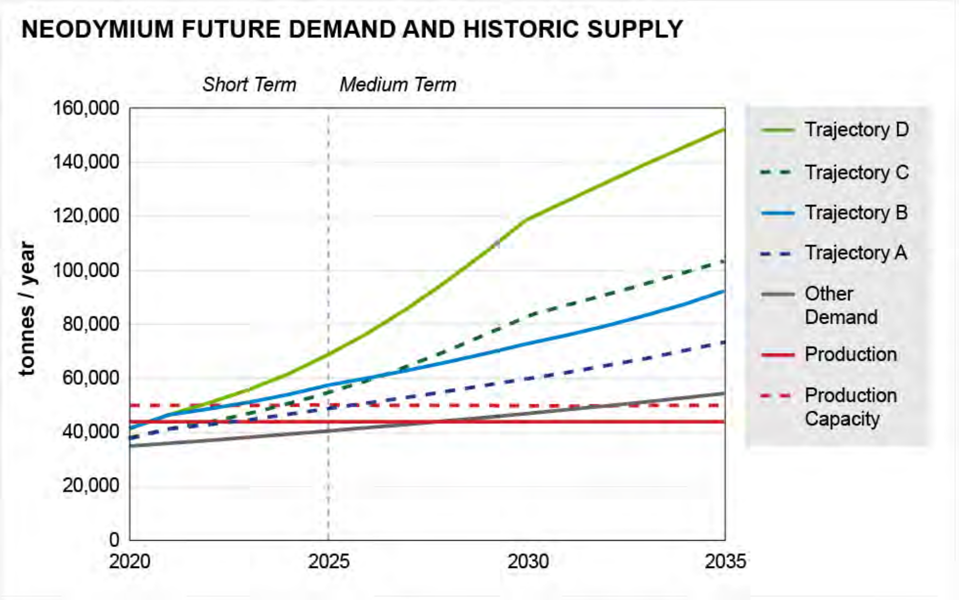


Figure 4.31. Neodymium demand trajectories, current production, and production capacity.

4.3.14 Nickel

4.3.14.1 Demand Trajectories

Figure 4.32 displays the demand of nickel 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 *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 (Argonne National Laboratory, n.d.-a; Iloeje et al., 2022; C. Xu et al., 2020), as described in Appendix B. Total primary nickel demand is estimated from the USGS's *2017 Mineral Yearbook* and by applying a 5% growth rate since then based on historical CAGR from the USGS's *2018 Mineral Yearbook* (USGS, 2020).

4.3.14.2 Production

Production is based on 2020 USGS estimates from the USGS's *2022 Mineral Commodity Study* of total nickel production (USGS, 2022b). Stainless steel is recycled at a high rate, but since 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 that it does not substantially affect worldwide nickel supply.

Production capacity is estimated using the capacity utilization rate of 82% that was calculated for 2014 in the *2019 Critical Materials Strategy*.

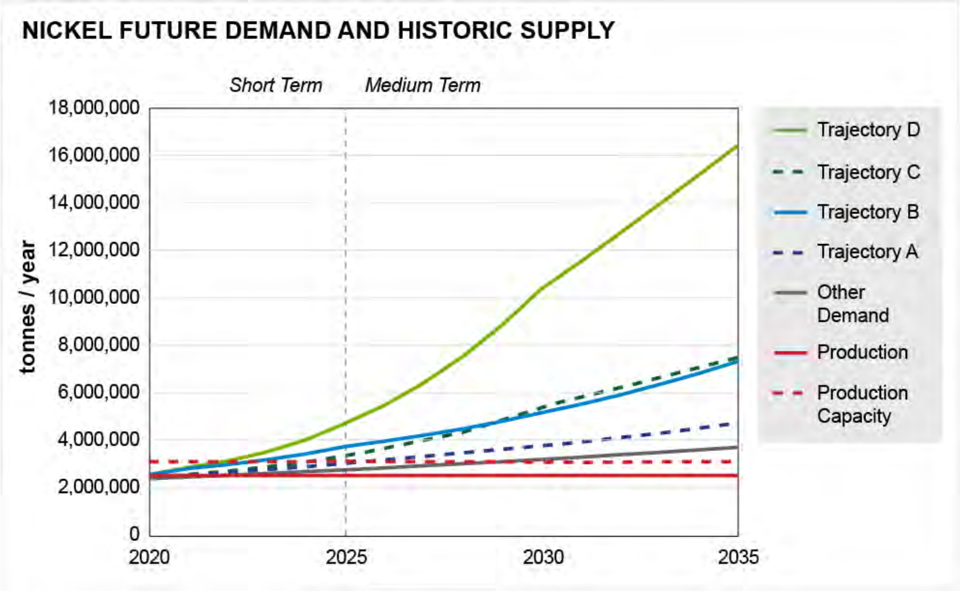


Figure 4.32. Nickel demand trajectories, current production, and production capacity.

4.3.15 Phosphorus

4.3.15.1 Demand Trajectories

Figure 4.33 displays the demand of phosphorus (P) from 2020 to 2035 against current production and production capacity. Phosphorus demand trajectories used the combined trajectories of two clean energy technologies: electric vehicle batteries and stationary storage batteries. Phosphorus is mainly used in agricultural applications, with around 95% of phosphate rock being used in fertilizer and animal feed, with the remainder being used in batteries. Phosphorus is used in lithium-iron-phosphate (LFP) batteries and in the electrolyte of nearly all lithium-ion batteries. LFP batteries have been increasing in popularity in recent years and have the second-highest market share of any battery chemistry (IEA, 2023b).

Demand trajectories for phosphorus were calculated using an assumed global growth rate of 3% based on GDP growth, a 2020 material demand of 29 Mmt, 2021 production of 31 Mmt, and a production capacity of 34 Mmt. All four of the scenarios for future demand projections for phosphorus follow a similar trajectory. Therefore, a comparison between the trajectories is less useful than comparing the shared trajectory to past production capacities. The 2020 production levels can meet all of the demand trajectories until 2022 when 2020 production levels are exceeded. The production capacity is exceeded in 2025 just upon entering the medium term. By the middle of the medium term, the production capacity for all trajectories of phosphorus far exceeds the 2020 production and production capacity levels. Since there are not any clear substitutes for phosphorus in LFP batteries for stationary storage and electric vehicles, either production for phosphorus must increase to meet energy demand or other battery technologies must be implemented to supplement the current market share of LFPs. However, since LFP batteries are currently trending toward a higher market share, an increase in production seems the more likely solution.

4.3.15.2 Production

Phosphorus production is sourced from the USGS's *2021 Mineral Yearbook* assessment of P_2O--$_5$ content of phosphate rock production, converted to be in terms of phosphorus content (USGS, 2022b).

Most of the U.S. supply of phosphorus is produced domestically with only 12% of phosphate rock being imported and with most of these imports coming from Peru (USGS, 2022b). The U.S. is third in mining the most phosphate rock in the world behind Morocco and China. However, the U.S. does not make the top ten in reserves in the world, which could possibly lead to an increased reliance on imports in years to come. Phosphate rock is mined independently of other rocks and is not produced as a by-product of other mining.

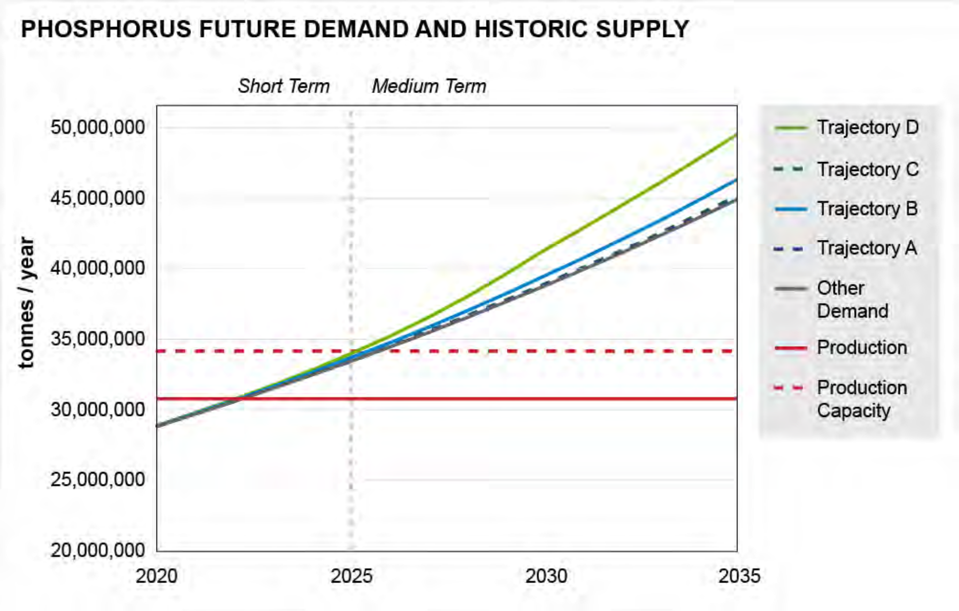


Figure 4.33. Phosphorus demand trajectories, current production, and production capacity.

4.3.16 Platinum

4.3.16.1 Demand Trajectories

Figure 4.34 displays the demand for platinum from 2020 to 2035 against 2020 production and production capacity. Platinum energy demand forecasts for this study explicitly consider PEM electrolyzers, PEM fuel cell electric vehicles (FCEVs), and catalytic converters. Catalytic converters account for about 40% of current platinum demand (Johnson Matthey, 2022). In the NZE forecasts after 2025, the decline in platinum demand for catalytic converters is projected to be greater than the increase in platinum demand for PEM electrolyzers and FCEVs, creating the dips in the Trajectory C and D demands. By 2030, platinum demand for PEM electrolyers and FCEVs overcomes the decrease in catalytic converter demands. This demand behavior does not occur in the STEPs scenario, in which PEM electrolyzer and FCEV demands are significantly lower.

Other platinum demands include both energy and non-energy applications. These energy applications of platinum include catalysts that improve energy and material efficiencies of refining and chemical processes. Major non-energy demands for platinum are in the jewelry and investment sectors. The demand trajectories do not include platinum recovered from chemical and refining catalysts, where recycling rates are 80%–90% (Moreira & Laing, 2022). These industries own or rent their platinum, which consequently does not enter the open market after recovery. Platinum recovered from end-of-life catalytic converters is incorporated in global supply. In the future, significant fractions of platinum in PEM fuel cells and electrolyzers are expected to be recovered at the end-of-life of these technologies as well.

4.3.16.2 Production

Platinum is the most abundant PGM in South Africa, Zimbabwe, and the United States mines, while in Russia and Canada, palladium is the most abundant PGM. In Russia and Canada, PGMs are recovered as by-products of nickel and copper mining (Wilburn, 2012). In 2021, 74% of platinum was mined in South Africa, 11% in Russia, 8% in Zimbabwe, 3% in Canada, and the remainder in seven countries (USGS, 2022b). Platinum mine capacity (224 tonnes) is estimated from the USGS-reported world mine production in 2021 (192 tonnes) and an assumed capacity utilization of 86%.

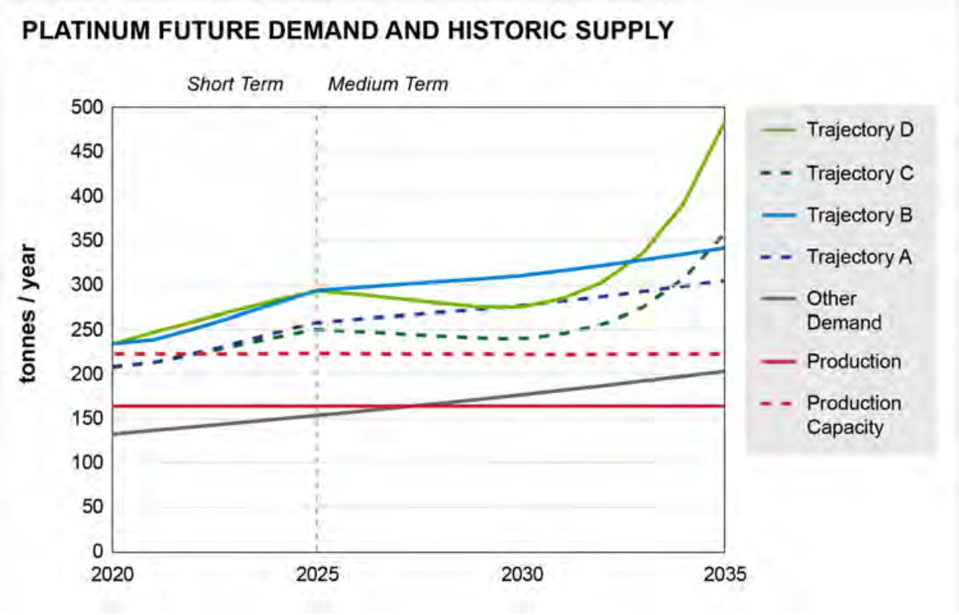


Figure 4.34. Platinum demand trajectories, current production, and production capacity.

4.3.17 Praseodymium

4.3.17.1 Demand Trajectories

Figure 4.35 displays the demand for Pr 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 wind turbine generators. The non-energy demand curve represents Pr demand for other applications, such as consumer electronics, air conditioning, industrial machines, ceramics and glasses, catalysts, and alloys, and are assumed to grow at 3%. Trajectories A and B are based on the 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.

4.3.17.2 Production

Production levels shown in Figure 4.35 were 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 (Li & Yang, 2014; Sanematsu et al., 2016; TMR, 2015; USGS, 2022b). Additional unreported Chinese production is estimated using Adamas (Adamas Intelligence, 2023b). 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 monazite processing capacity in the U.S. in excess of current production was accounted for (Energy Fuels, 2023). Quantities are adjusted to be in terms of Pr content rather than Pr oxide.

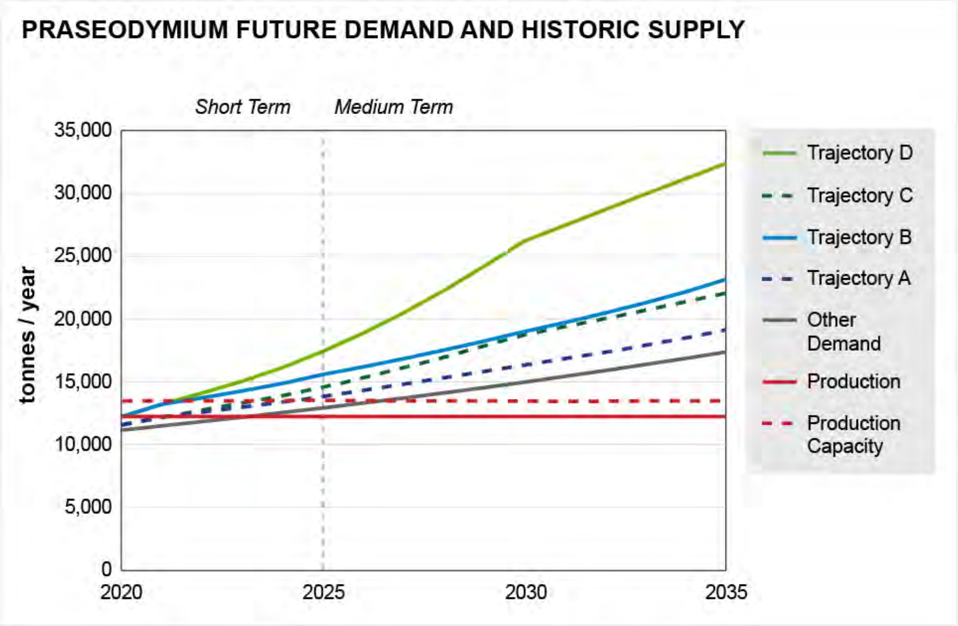


Figure 4.35. Praseodymium demand trajectories, current production, and production capacity.

4.3.18 Silicon

4.3.18.1 Demand Trajectories

Figure 4.36 shows 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. Silicon carbide (SiC) was not considered as its silicon content did not significantly impact projected demand. The four different trajectories consist of the IEA's STEPS and NZE 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 the STEPS scenario with low and high production yield and the NZE scenario with low and 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 the high and low material intensities used to compute each trajectory may be found in Appendix B.

Non-energy demand for silicon in 2020 was estimated based on demand values for silicon metal and ferrosilicon in the *2018 Mineral Yearbook* (USGS, 2021). Silicon metal was presumed to contain 100% silicon while ferrosilicon is assumed to contain 75% silicon (USGS, 2021). The 2018 silicon demand value was projected out to 2020 using a weighted average CAGR of industries that use silicon metal (silicones, polysilicon, and aluminum) and a CAGR of ferrosilicon (USGS, 2021). From 2020 onward, 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 of global production amounts sourced through the USGS *Minerals Commodity Summaries 2022* (USGS, 2022b). Because recycling of silicon was deemed insignificant by the USGS, silicon recycling rates are not incorporated into production amounts (USGS, 2022b). Production capacity of silicon is an average capacity utilization rate in 2020 for China and the rest of the world applied to 2020 production (SMM, 2023).

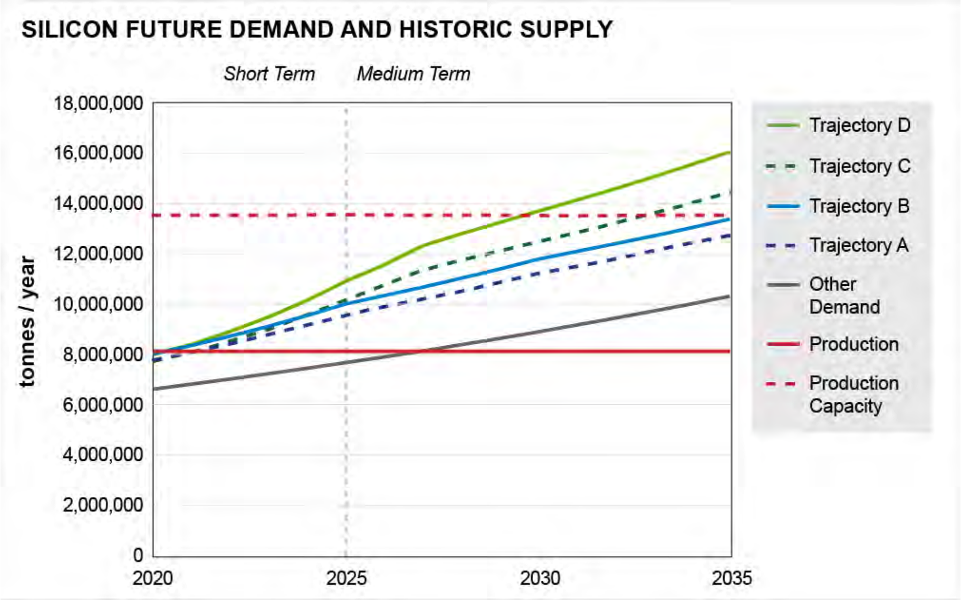


Figure 4.36. Silicon demand trajectories, current production, and production capacity.

4.3.18.2 Production

China was the largest producer by an order of magnitude compared to other countries and consistently produced more than 70% of the world's silicon supply in 2021 (USGS, 2022b). Interestingly, in 2021 the United States relied primarily on Brazil (30%), Canada (21%), and Norway (13%) for its silicon (metal grade) supply. The dip in global production during 2017 was attributed to oversupply and decreased demand in the steel and aluminum alloy industries (USGS, 2021). Increased U.S. demand corresponded to silicon-related product production plants reopening in 2021 after COVID-19 shutdowns. These reopenings also corresponded to a 50% price increase for raw silicon (USGS, 2022b). Silicon solar cells account for about 5% of the overall demand on raw silicon materials (calculated from USGS supply and total material intensity).

4.3.19 Silicon Carbide

4.3.19.1 Demand Trajectories

Figure 4.37 displays the demand of silicon carbide (SiC) from 2020 to 2035 for 6-inch wafers against current production and production capacity in a 6-inch equivalent. As mentioned before, data inconsistent from various reports prevented the authors from having a common unit. However, based on Yole's report for the 2022 market, 6-inch n-type wafer units accounted for 71% of total n-type wafers including 4-inch, 6-inch, and 8-inch wafers. The four trajectories are derived from high and low CAGRs of 1.2% and 5.4%, and high and low SiC market penetration rates of 0.9% and 4.4% (Chiu & Dogmus, 2022; Rosina & Villamor, 2022).

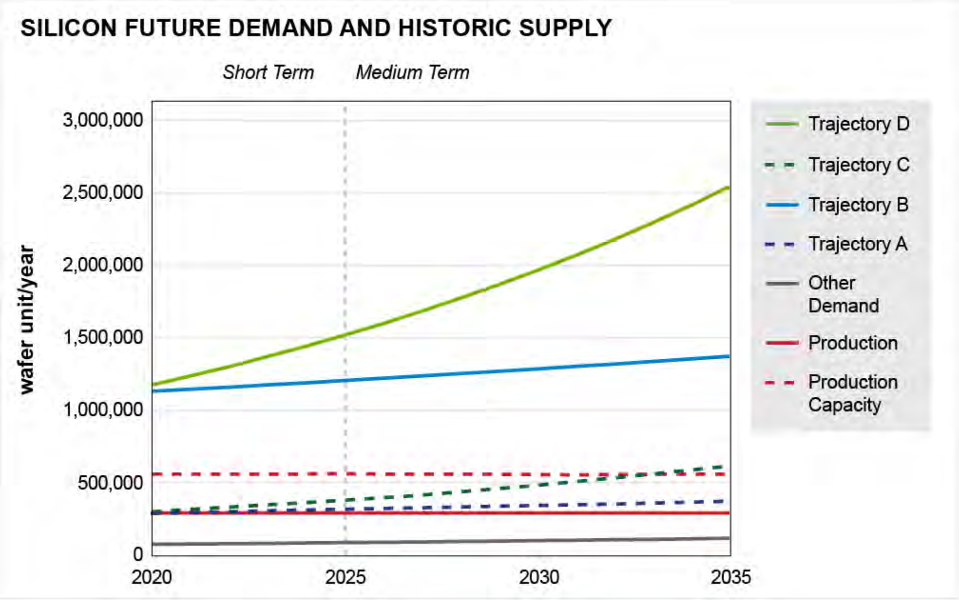


Figure 4.37. Silicon carbide demand trajectories, current production, and production capacity.

4.3.19.2 Production

SiC capacity was compiled from Yole's report by summing the capacity in 2022 in 6-inch equivalent of nine companies (Chiu & Dogmus, 2022). The list of companies includes Wolfspeed, II-IV (or Coherent Corp), SiCrystal, SK Siltron CSS, TankeBlue, Showa Denko, GT Advanced, STMicroelectronics, and SICC. The total capacity in 2022 was 560,000 wafer units, the 6-inch equivalent.

4.3.20 Tellurium

4.3.20.1 Demand Trajectories

Tellurium's primary energy technology application is in CdTe thin-film solar PVs, but it is also utilized in thermoelectric devices, metallurgical applications, as a rubber volcanizing agent, and as catalyst (USGS, 2022b). Of the applications of tellurium, 40% of global tellurium production goes toward CdTe thin-film solar PVs, and the remainder is utilized in technologies not considered as energy technologies in this study. Of these other technologies, 30% of Te is utilized in thermoelectric devices that are growing at an 8% CAGR (MMR, 2019), 15% is utilized in metallurgical applications with Te use estimated to have a 3% CAGR (Technavio, 2023), and applications as a rubber volcanizing agent and catalyst make up the remaining 15%—also with a 3% CAGR (Fortune Business Insights, 2021b).

Material intensity for Te has fallen sharply over time in CdTe thin-film solar PV cells due to decreases in active layer thickness and improvements in the module design of CdTe panels. Older CdTe solar PV cells had Te material intensities ranging from 60–100 tonnes/GW (McNulty & Jowitt, 2022; Redlinger et al., 2015). The current material intensity of Te, approximately 36 tonnes/GW and used herein as the high materiality intensity scenarios (Trajectories B and D), has been demonstrated by the U.S. producer, First Solar (First Solar, 2022). It is expected to continue to trend downward to 20 tonnes/GW by 2040 (Alves Dias et al., 2020) and is used herein as the low material intensity scenarios (Trajectories A and C). A further discussion on Te intensity in CdTe thin-film solar PV cells can be found in Appendix B.

Using these material intensities, the IEA STEPS and NZE scenarios, and the expected range of global CdTe solar PV market share ranging between 2% to 5.5% through 2035, Figure 4.38 shows the high and low demand trajectories, competing technology demands, as well as supplies of Te. The demand for Te is expected to range from between 450 and 1,150 tonnes per year in the short term in 2025 and increasing to between 685 to 1,910 tonnes per year in the medium term by 2035. As Figure 4.38 shows, there is a wide range of potential demand for Te depending on future solar PV installation and CdTe market share. Current production levels of Te are just shy of 580 tonnes per year with an estimated production capacity of 650 tonnes per year. Without significant expansion of the tellurium supply capacity, shortages of Te could occur in the short term and are likely in the medium term.

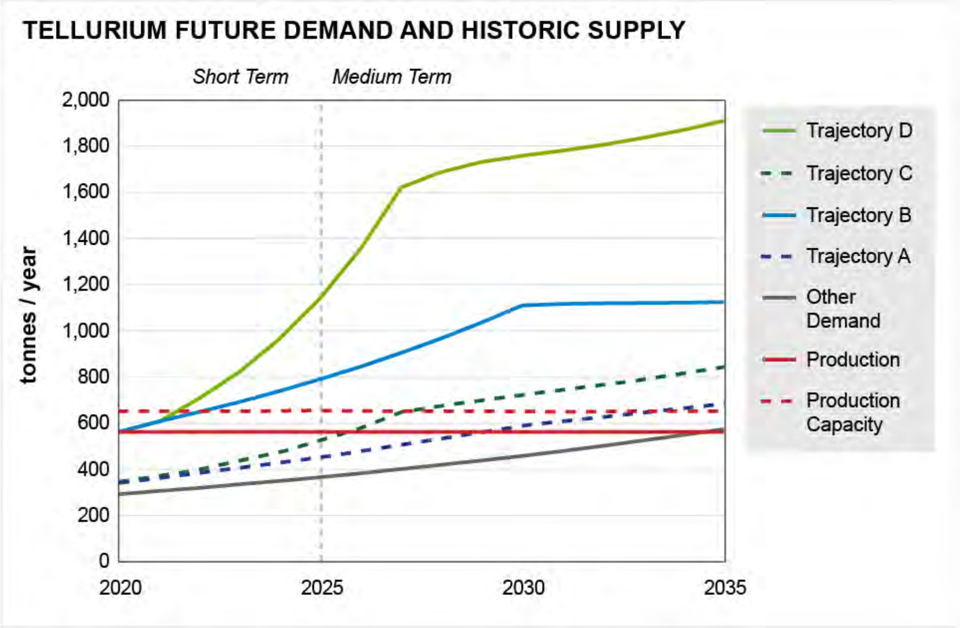


Figure 4.38. Tellurium demand trajectories, current production, and production capacity.

4.3.20.2 Production

Tellurium is primarily produced as a by-product from copper mining and processing facilities, where approximately 90% of global Te supply is refined from copper anode slimes. To a much lesser extent, Te is produced from the skimming at lead refineries; is captured from the flue dusts and smelting of bismuth, copper, nickel, lead-zinc ores, and other precious metals; and can also be coproduced from bismuth telluride and gold telluride ores (USGS, 2022b). The production of Te and its global supply is 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 & Jowitt, 2022).

Globally, 580 tons of refined Te were produced in 2021 and global Te production levels have generally increased since 2015. China is the world’s leader in Te production, producing an estimated 340 tons (58%) of the global supply in 2021. Japan and Russia are interchangeably the second-largest producers of Te, producing 75 tons (13%) and 70 tons (12%), respectively, in 2021 (USGS, 2022b). Canada and Sweden are the next-largest producers at 45 tons (8%) and 40 tons (7%), respectively. Bulgaria, South Africa, and The Philippines are also Te producers, combining for less than 2% of global production (USGS, 2022b).

In the U.S. for the first time in recent history, primary production of Te was recovered from copper slimes in Utah in late 2021 at a facility with the capacity to produce 20 tons per year (USGS, 2022b). Te is indirectly produced from a copper mine in Texas where the copper anode slimes are sent to Mexico to recover commercial-grade tellurium (USGS, 2022b).

Due to the lack of Te refining in the United States despite having an estimated 3,500 tons of reserves, more than 95% of Te is currently imported from other countries (USGS, 2022b). Between 2017 and 2020, the U.S. sourced 57% of Te from Canada, 19% from Germany, 17% from China, 4% from the Philippines, and 3% from other countries (USGS, 2021). However, the imports from both Canada and Germany fell sharply in 2020 when only 0.025 tons were imported from these countries down from 2 tons in 2019 and 99 tons in 2018. In 2020, 1 ton was imported from Germany (USGS, 2021, 2022b). In 2021, the imports of Te significantly increased, with 82% from the Philippines at 9.5 tons, and a 161% increase in Te imports occurred from Japan in the same year (USGS, 2022b).

Secondary production of Te is limited globally and domestically because there is little or no scrap from which to obtain secondary Te, and its uses are highly dispersive and dissipative. In Europe, Te was recovered in 2021 from scrapped selenium-tellurium photoreceptors in old plain-paper copiers (USGS, 2022b). In the U.S., a plant recycled CdTe solar cells; however, the amount recycled was limited because most of these solar cells are relatively new and have not yet reached the end of their useful life to warrant recycling (USGS, 2022b).

4.3.21 Terbium

4.3.21.1 Demand Trajectories

Figure 4.39 displays the demand for Tb 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 Tb demand for other applications such as consumer electronics, air conditioning, industrial machines, phosphors for fluorescent lighting and LCD displays, terfenol-D, and other alloys, and are assumed to grow at 3%. Trajectories A and B are based on the IEA’s STEPS scenarios for growth in electric vehicle and wind turbine sales, while Trajectories C and D are based the IEA’s NZE 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.

4.3.21.2 Production

Production levels shown in Figure 4.39 were 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 (Li & Yang, 2014; Sanematsu et al., 2016; TMR, 2015; USGS, 2022b). Additional unreported Chinese production is estimated using Adamas (Adamas Intelligence, 2023b). 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 monazite processing capacity in the U.S. in excess of current production was accounted for (Energy Fuels, 2023). Quantities are adjusted to be in terms of Tb content rather than as Tb oxide.

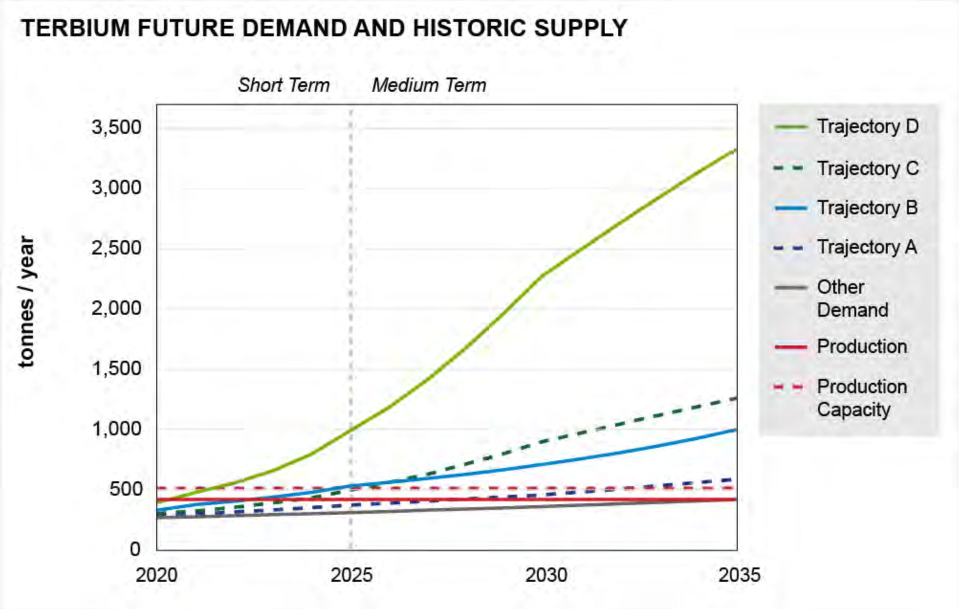


Figure 4.39. Terbium demand trajectories, current production, and production capacity.

4.3.22 Titanium

4.3.22.1 Demand Trajectories

Figure 4.40 displays the demand of titanium from 2020 to 2035 for the four trajectories evaluated compared to 2020 production and production capacity. An estimated 60%–75% of titanium alloys are used for energy applications, which include gas turbine blades; lightweighting aircraft, spacecraft, rail, marine, and land vehicles; and corrosion resistance in refineries and power plants (Feng et al., 2023). This study's focus is on PEM electrolyzers and road vehicle lightweighting.

In PEM electrolyzers, titanium metal is used in the gas diffusion layer and bipolar plate at the anode (Steen et al., 2017). Titanium in the gas diffusion layer is typically in the form of a thin and porous metal foam, pressed directly to the iridium catalyst. The gas diffusion layer performs two functions: (1) establishing electro-conductivity between the bipolar plate and the catalyst layer; and (2) uniformly distributing the reactant (water) and product (oxygen) in and out of the anode during operation. Titanium is chosen for this application because of its corrosion resistance in the acidic environment experienced at the anode. The acid-resistant titanium bipolar plate is a solid plate engraved with a serpentine flow field. Its functions include feeding the incoming water to the anode catalyst layer and removing the oxygen produced during the electrolysis (Zhu et al., 2022).

The titanium components contribute significantly to the capital cost of PEM electrolyzers, which include raw material cost and the machining of complex, intricate flow patterns (Lettenmeier et al., 2017). Research focused on reducing these costs includes titanium coated on austenitic stainless steel; protective gold and niobium coatings; different titanium forms such as foams, meshes, and felts; and manufacturing methods (Daudt et al., 2019; Lettenmeier et al., 2017; Sánchez-Molina et al., 2021; Stiber et al., 2022; Yang et al., 2018; Young et al., 2021).

Titanium is also used for lightweighting vehicles. This study considers titanium use in aluminum castings for road vehicle applications. While titanium use in road vehicles is limited by cost, aluminum-titanium alloys are being explored for this application, particularly with the aim of meeting increasingly stringent fuel economy goals (Blanco et al., 2022). Titanium demand for road vehicles assumed in this study are based on an aluminum 356 cast containing 0.25% titanium (The Aluminum Association, 2015).

4.3.22.2 Production

The major sources of titanium are ilmenite (94%) and rutile (6%) ore concentrates (USGS, 2022b). Mine production in 2022 totaled 9,500 kt. China accounted for 36% of titanium mine production, Mozambique for 12%, South Africa for 10%, and Australia for 6%, with the remaining production spread across more than 15 countries (USGS, 2022b). China dominated titanium sponge production as well, accounting for 58%. Other significant titanium sponge producers include Japan (20%), Russia (11%), and Khazakhstan (6%). The assumed global titanium mining capacity is 350,000 tonnes as reported by the USGS.

More than 95% of titanium ore concentrates are consumed for titanium oxide production, relegating titanium sponge to minor product status. 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. The primary technology for producing titanium sponge is the Kroll process (Perks & Mudd, 2019). Because this process is inefficient, as well as being energy-, labor-, capital-, and operating cost-intensive, alternative technologies are being researched (El Khalloufi et al., 2021).

Titanium scrap is an important source of the metal, although some applications, particularly defense applications, require virgin titanium sponge (U.S. Department of Commerce, 2019). Historically, titanium sponge prices have experienced volatility; examples include increasing prices in response to defense demand in years 2003 to 2006 (Seong et al., 2009) and, in 2018, decreasing prices in response to capacity growth, particularly in China.

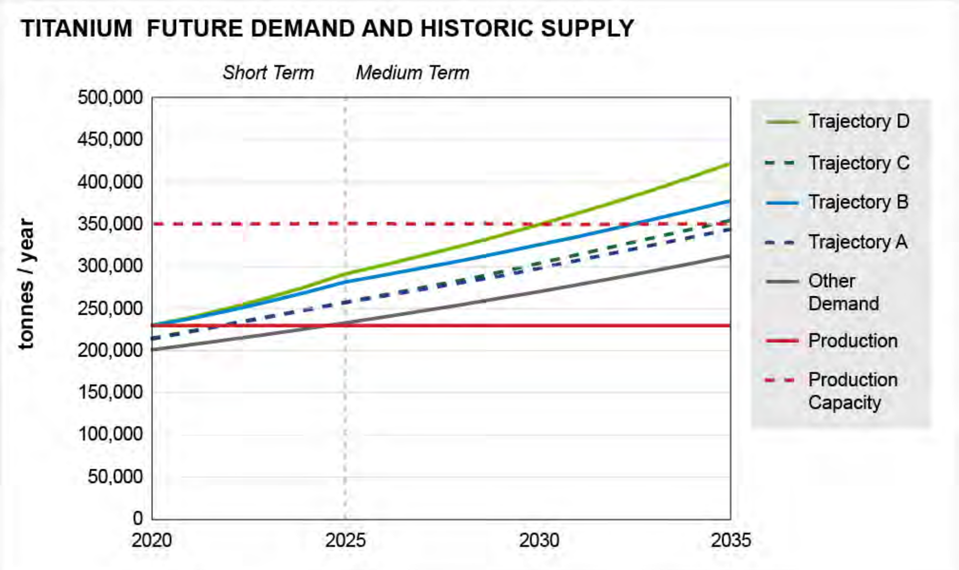


Figure 4.40. Titanium demand trajectories, current production, and production capacity.

4.3.23 Uranium

4.3.23.1 Demand Trajectories

Figure 4.41 shows four different demand scenarios for uranium from 2020 to 2035. The only energy application considered for uranium was terrestrial, electricity-generating nuclear reactors (IEA, 2022h). Two IEA scenarios were utilized to determine projected nuclear capacity until 2035, including the nuclear fade case

(NFC) for low trajectories and the NZE scenario for high trajectories. This capacity data was used in conjunction with material intensity data to produce the four separate demand scenarios. Additional information on how low and high material intensities were developed to be used to compute each trajectory may be found in Appendix B.

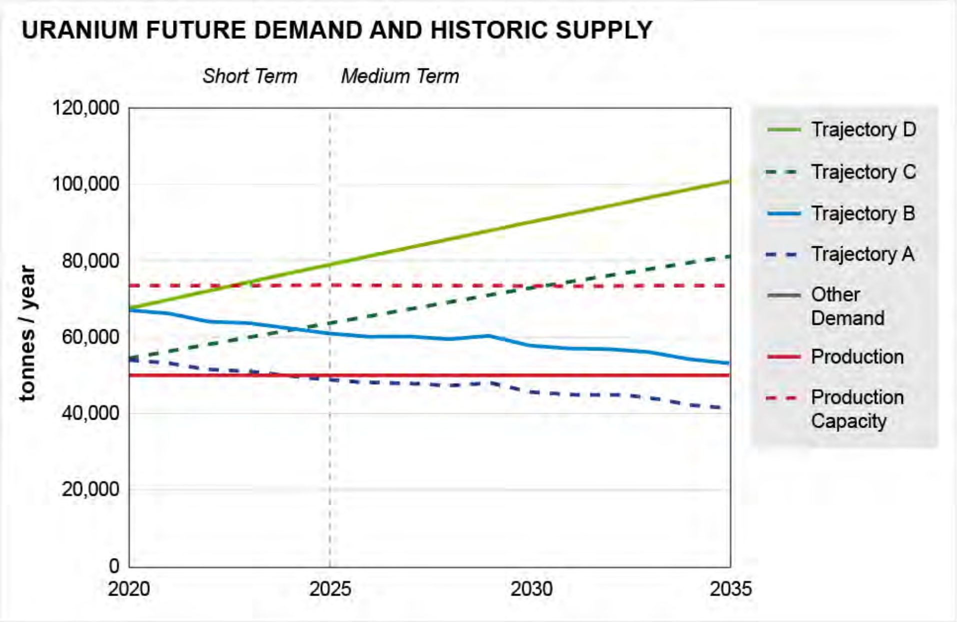


Figure 4.41. Uranium demand trajectories, current production, and production capacity.

4.3.23.2 Production

Production data were obtained through the Nuclear Energy Agency, World Nuclear Association, and the International Atomic Energy Agency (IAEA, 2016; NEA, 2023; World Nuclear Association, 2022e). Primary production, ~50 kt (World Nuclear Association, 2022c), and secondary production, ~2 kt (World Nuclear Association, 2020), were summed to produce the total global supply of natural uranium. Primary production capacity, ~73 kt (World Nuclear Association, 2021), and secondary production capacity, ~4 kt (World Nuclear Association, 2020), were summed to create the total global production capacity of natural uranium (IAEA, 2016; NEA, 2023; World Nuclear Association, 2022e). Primary production, ~50 kt (World Nuclear Association, 2022e, 2022f), and secondary production, ~2 kt (World Nuclear Association, 2020), were summed to produce the total global supply of natural uranium. Primary production capacity, ~73 kt (World Nuclear Association, 2021c), and secondary production capacity, ~4 kt (World Nuclear Association, 2020), were summed to create the total global production capacity of natural uranium.

It should be noted that the figure shows total uranium production as less than all of the demand trajectories. The reason for this discrepancy has to do with civil stockpiles of uranium (World Nuclear Association, 2022f). Due to the challenges in quantifying the total civil stockpiles, it is difficult to determine the annual supply of uranium due to these stockpiles (World Nuclear Association, 2022f). However, estimates provided by the World Nuclear Association at the end of 2020 yielded an estimation of 282 kt of uranium in civil stockpiles globally (World Nuclear Association, 2022f).

5 Criticality Assessment

This chapter details the criticality assessment methodology and presents criticality results for both the short and medium terms. 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.

5.1 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 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.

5.1.1 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, 2022i; The World Bank, 2022a).

  - 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 & 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.

5.1.2 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 taken into account as well 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 Chapter 4. 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 demand from non-energy sectors 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 factor 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) (The World Bank, 2022b) and Yale University's Environmental Performance Index (Wolf et al., 2022). 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.

5.1.3 Scoring Rubric

As with previous CMS reports, this report is based on qualitative assessments informed by quantitative analyses. 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 5.1. The thresholds applied to some metrics (such as "energy demand") are defined using an iterative process in order to achieve a relatively uniform distribution of scores across 23 key materials. Using this approach, it is possible that the thresholds for some metrics could change in future assessments depending on the materials considered in the assessment.

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 5.1. 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

5.1.4 Data on Material Form

Three of the metrics, "basic availability," "producer diversity," and "political, regulatory, and social factors," use data on different material forms due to inconsistencies in data availability. Additionally, different purities or stages of the supply chain were considered depending on the characteristics of a specific material. When data for multiple supply chain stages are available, calculations were conducted for all stages; however, the final score was attributed based on the stage with the highest risk. For example, both mining and enrichment stages were considered for uranium. Because the enrichment stage led to a higher risk score for producer diversity, this value chain step was used to determine both producer diversity and political factors to evaluate supply risk. Table 5.2 lists data of material form used for estimating the three metrics by material.

Table 5.2. Data on material form used for estimating three metrics: basic availability; producer diversity; and political, regulatory, and social factors.

Material	Basic Availability	Political, Regulatory, and Social Factors	Producer Diversity
Aluminum	Mined and recycled aluminum	Mining	Mining
Cobalt	All mined cobalt	Mining	Mining
Copper	Refined copper, including recycling	Mining and refining	Mining and refining
Dysprosium	Dysprosium in mined rare earths	Mining, separation, metal refining	Mining, separation, metal refining
Electrical steel	GOES & NOES production	GOES & NOES production	GOES & NOES production
Fluorine	Fluorspar mining	Fluorspar mining	Fluorspar mining
Gallium	Refined, high purity (99.99999%), including recycling	Refined, high purity (99.99999%)	Refined, high purity (99.99999%)
Graphite	Flake graphite	Flake graphite mining	Flake graphite mining
Iridium	Refined iridium, including recycling	Mining	Mining
Lithium	All mined lithium	Mining and refining	Mining and refining
Magnesium	Mined and recycled magnesium	Mining	Mining
Manganese	Mined manganese	Mining	Mining
Neodymium	Neodymium in mined rare earths	Mining, separation, metal refining	Mining, separation, metal refining
Nickel	All mined nickel	Mining, refining, class I nickel mining, class I nickel refining	Mining, refining, class I nickel mining, class I nickel refining
Phosphorous	Phosphate rock	Phosphate rock mining	Phosphate rock mining

Material	Basic Availability	Political, Regulatory, and Social Factors	Producer Diversity
Platinum	Refined platinum, including recycling	Mining	Mining
Praseodymium	Praseodymium in mined rare earths	Mining, separation, metal refining	Mining, separation, metal refining
Silicon	Ferrosilicon and silicon metal converted to silicon content production	Ferrosilicon and silicon metal converted to silicon content production	Ferrosilicon and silicon metal converted to silicon content production
Silicon carbide	6-inch wafer manufacturing	Market share based on revenue estimates of SiC power device manufacturers	Market share based on revenue estimates of SiC power device manufacturers
Tellurium	Refined tellurium, including recycling	Refined tellurium	Refined tellurium
Terbium	Terbium in mined rare earths	Mining, separation, metal refining	Mining, separation, metal refining
Titanium	Titanium metal	Titanium metal production	Titanium metal production
Uranium	Mining	Mining and enrichment	Mining and enrichment

5.2 Identification of Critical Materials

Figure 5.1 and Figure 5.2 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 5.1 and Figure 5.2 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.

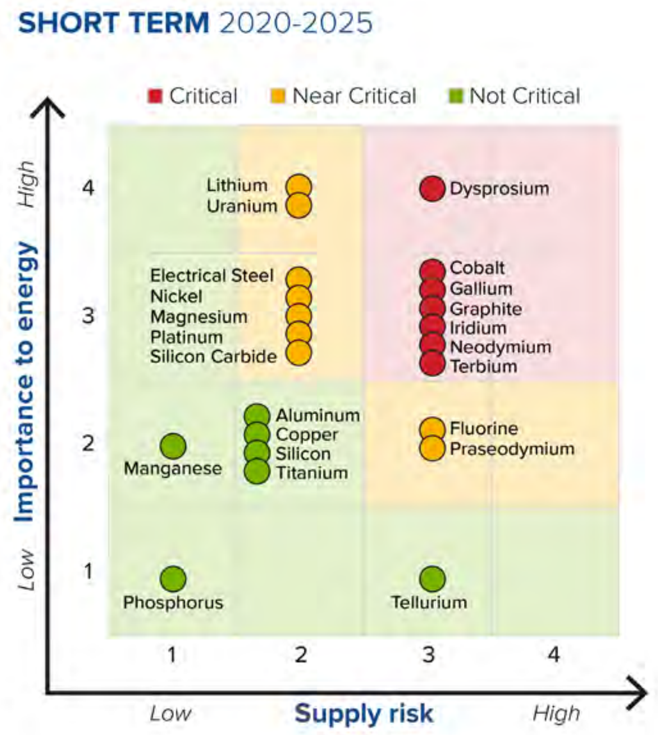


Figure 5.1. Short-term (2020–2025) criticality matrix.

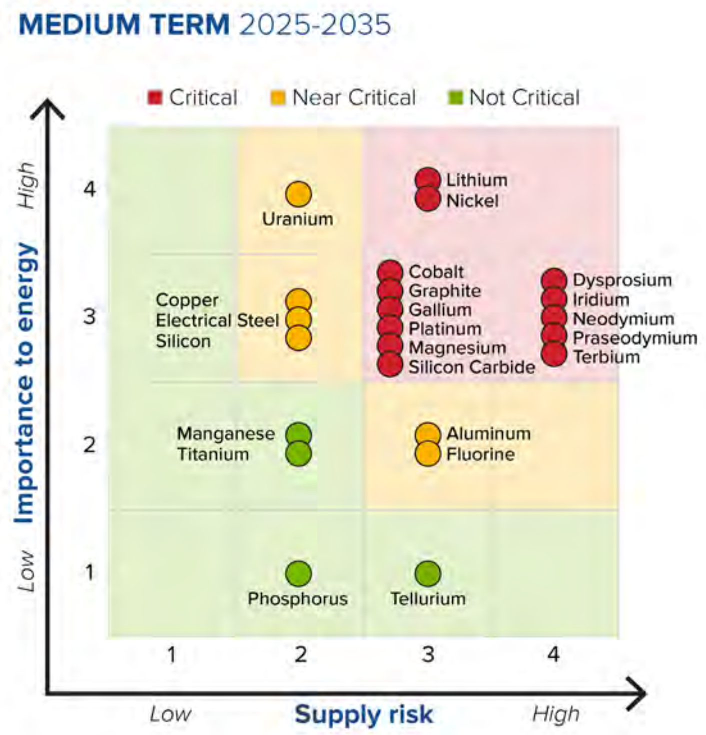


Figure 5.2. Medium-term (2025–2035) criticality matrix.

According to the analysis, there are seven critical materials in the short term, which include cobalt, dysprosium, gallium, natural graphite, iridium, neodymium, and terbium. 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 13 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, SiC, and terbium 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, 38 candidate materials were considered, and 23 were evaluated for criticality after the screening process. The 2019 assessment considered 16 materials.

5.3 Methodological Challenges, Uncertainties, and Limitations

There are several challenges and uncertainties that impact the “importance to energy” and “supply risk” scores that could affect the criticality of certain materials in this analysis. These challenges include issues with data quality and availability, methodological challenges, and other general limitations with how these findings should be used. These issues have been addressed to varying degrees in this assessment.

Data quality is among the most deciding factors affecting the criticality results. Although some aspects of this assessment are qualitative, data on market growth rates, market shares, types of applications, production capacity, manufacturing yield, recycling rates, material intensities, prices, and deployment trajectories are quantitative. While data on major materials and applications are available publicly, data on minor materials are much more scarce and require subscriptions to market reports. The main challenge is that different market reports on the same material convey conflicting data that are difficult to resolve.

Similarly, data on material intensity for most materials and technologies is difficult to obtain, mostly due to proprietary information, which can pose a degree of uncertainty in the analysis. In some cases, the high intensities reflect current technologies and low intensities reflect future goals. In most cases, the gap is due to an array of proprietary technologies that different companies are using. For example, offshore wind turbines could use 1.5 mt to 5.3 mt of electrical steel per MW of wind due to different turbine designs. However, the use of high and low scenarios for material intensity helps address this uncertainty and provides some insight into the possible impact that improvements in material intensity could have on material criticality overall.

Information on substitution is also often not straightforward, which could affect the demand trajectories for materials and estimates of energy importance. For example, for graphite, the substitution between synthetic graphite and natural graphite is vague for various applications such as batteries and nuclear energy. Therefore, natural graphite demand might have been lower if better data on substitution were available. Lacking better information on material substitution could cause the energy importance of some materials to be overstated.

There are also challenges with data consistency across technologies and materials. Some trajectories depend on CAGRs or market share data from market reports to estimate material demand. In most cases, CAGRs and market shares based on market values are different from those based on material mass. For example, CAGRs from 2021 to 2027 of SiC for wind applications is 163% and 135% based on market value and wafer unit, respectively (Chiu & Dogmus, 2022). Unfortunately, most market reports provide CAGRs based on market values and not on material quantity. To overcome data scarcity in those situations, CAGRs for market value were used to derive material demand. Because CAGRs based on market value are often higher than those of material quantity, Trajectories C and D could potentially inflate material demand. This approach may overestimate the impacts of energy demand within “importance to energy” and basic availability within “supply risk.” As a result, the criticality for some materials could be overstated.

Data frequency can also be a challenge. For example, the political, regulatory, and social factors (PRS) metric relies on WGI indicators from 2021, which was released prior to the Russian invasion of Ukraine. To account for lower political scores of PRS factors, a worst-case scenario was conducted by taking the lowest scores of all producing countries from 1996 (the first year for which the data are available) to 2021 with respect to government effectiveness, regulatory quality, and rule of law. Using the same methodology outlined in Section 5.1, a new set of PRS scores for the worst case were derived. PRS scores for Cu, electrical steel, and silicon changed from 2 to 3 under the worst-case analysis. However, because PRS accounts for only 20% of the supply risk score, the change in PRS score only increases supply risk scores of these material by 0.2 and did not change their overall criticality.

There are certain aspects of measuring criticality that are difficult to capture perfectly, particularly when quantifying the overall importance of a material to clean energy (broadly defined). Although efforts to evaluate the importance of each material have been emphasized, there is no simple method to weigh the relative magnitude to which the various technologies included in this assessment contribute to decarbonization. For energy generation technologies, estimating their ability to reduce carbon emissions is relatively straightforward based on the contribution of each technology in the IEA global energy scenarios. However, it is much more challenging to compare generation technologies against transmission and some end-use applications. Especially with transmission, it is difficult to estimate carbon footprint savings when generation technologies are unknown. Furthermore, certain materials are used in multiple technologies while others are used in only one technology. For example, silicon can be used in solar PVs, wind, HVDC converters, EV inverters, electrical steel, and lightweighting alloys, while dysprosium is used only in magnets in EVs and wind. In such a case, it is difficult to determine whether silicon is more or less important than Dy.

Another important consideration is that scores for energy demand and basic availability were assigned based on the high market penetration scenarios reflected in Trajectories C and D. Because some materials and technologies are substitutes for others, the “high” scenarios would not both be true at the same time. For example, in a world where LFP is the predominant chemistry for Li-ion battery chemistries in EVs, nickel and cobalt become relatively less critical, yet their scores are based on a world in which NMC811 is the predominant chemistry. Thus, the criticality for materials in such instances may be overstated. However, as pointed out in previous sections, material criticality is dynamic because the future is unknown, and capturing this uncertainty furthers the overall goals of the criticality assessment. That is, it is more likely to capture something that *could* be critical in the future. Increasing the frequency of material criticality assessments is one potential strategy to capturing the dynamic nature of criticality.

The specific form of each material is also an important consideration, especially for engineered materials as even a single type of engineered material may be available in many different grades and specifications. For example, electrical steel can be defined in multiple ways depending upon the desired properties and its underlying material composition specific to an individual grade type. The exact properties and composition depend on the specific end use. Because engineered materials are intermediate forms of materials before they are integrated into components and systems, criticality metrics can be evaluated for all forms of the material all the way down to its constituent natural raw materials. This flexibility could cause criticality in multiple segments. The distinction between raw material availability and manufacturing constraint is important to address supply chain bottlenecks. A similar point can be made for evaluating different forms of a raw material from its production at the mining stage through refining into specific purities and compounds.

As stated in Chapter 1, this assessment takes a global view of material demand and puts less emphasis on U.S. demand. While this approach ensures that policies impacting global material demand in major economic regions like Asia and Europe are taken into account, it does not reflect how important certain materials are to the U.S. energy sector or economy. The U.S. Critical Minerals List issued by the USGS focuses on the U.S. economy (Nassar & Fortier, 2021) and complements this analysis well. For example, CdTe has a much larger market share in the United States than globally. While this analysis shows that Te is not critical in the short and medium terms, Te is listed on the USGS critical minerals list. Note that the USGS analysis focusses on importance to the U.S. economy, while this assessment focuses on importance to global clean energy technologies.

Finally, material criticality is identified in this report by deriving four demand trajectories based on technology penetration and material content. The main goal of this report is to guide R&D decisions to promote change in technology penetration based on improved features or reducing material intensities. In addition to changing R&D strategies, multiple countries employ strategic stockpiling to reduce material criticality. However, because this analysis was not developed with stockpiling in mind, it should not be used to make decisions about whether or not to stockpile specific materials.

6 Conclusions and Next Steps

This 2023 CMA serves as the fourth update to DOE's long-standing CMS reports, first released in 2010. It aims to serve as a guide to the department in prioritizing RD&D strategies by providing an analysis of the materials most critical to securing a decarbonized, clean energy future. This version incorporates a number of notable changes from the previous CMS reports. Leveraging findings from DOE's 2022 supply chain deep dive reports, this assessment evaluates a much longer initial list of materials, including a number of engineered materials in addition to natural materials. It also introduces a screening methodology to develop a list of key materials to be evaluated for criticality and a formal scoring rubric for the criticality assessment with defined thresholds and logic.

In total, the assessment evaluates an initial list of 38 materials essential to clean energy technologies, 23 of which are evaluated for their criticality after passing the initial screening described in Chapter 3. Of those, seven are found to be critical for clean energy in the short term, while 13 are found to be critical in the medium term. As the energy sector continues to decarbonize, the list of potential materials essential to clean energy technologies will only increase.

The dynamic nature of material criticality necessitates that DOE revisit this assessment at regular intervals, especially as the energy transition is occurring at a rapid pace. As such, DOE plans to update the assessment in approximately three years to account for changes in market conditions, technology advancement, technology adoption trends, production capacity, and the global policy landscape. The update will also help evaluate the effectiveness of DOE's existing RD&D strategy and potential focus areas for future strategy. Updates to the assessment also allow for the opportunity to revisit certain methodological and data challenges and considerations, including a number of suggestions raised by the public during the Request for Information (RFI) process.

Future assessments may take into account a number of potential areas for improvement, such as consideration of materials used in the manufacturing process that do not make up the final composition of a final product, or better information and data on recycling. In particular, developing a keen understanding of recycling markets will be important to future assessments as the stock of materials embedded in energy technologies becomes a prevalent resource, especially for materials with geopolitical sensitivities. From a methodological perspective, improvements in understanding and reflecting possible material and system substitutions is key, as are enhancements that allow for the assessment of multiple supply chain stages. It is also challenging to define the risk associated with materials produced as co- and by-products and the methodology could potentially be enhanced to address these issues more carefully. It will also be important to explicitly define the grades and specifications of engineered materials as well as the actual forms of raw materials being evaluated.

It is important to note that while some materials might not be deemed critical in this assessment, certain value chain steps might have bottlenecks that were not examined closely in this report. This limitation is because the scope of this assessment is meant to be broad rather than deep when evaluating criticality among diverse materials using a common framework. DOE will continue to perform "deep dive" supply chain studies to provide insights on vulnerabilities across specific supply chains and will use these to inform future assessments.

In addition to informing DOE's RD&D agenda, this assessment will provide a basis for DOE's secretarial determination of critical materials and related policy initiatives. By taking a global perspective and forward-looking approach, this study outlines four possible trajectories for material demand based on high and low deployment scenarios and material intensities. The criticality of most materials in this analysis is due to high deployment trajectories and high material intensities. As clean energy continues to be deployed globally, future RD&D efforts will focus on reducing material intensity, increasing manufacturing efficiency, improving recycling rates and efficiency, finding better substitutes, and enhancing primary production efficiency. DOE's strategic framework will continue to focus on five pillars: (1) diversify and expand supply from primary sources; (2) develop alternative materials and systems; (3) enhance material and manufacturing efficiency; (4) promote the circular economy through recycling, reuse, and remanufacturing; and (5) use analyses to enable and speed up science discoveries. For each of the critical materials identified in this report, DOE will proceed with an integrated strategy to address material-specific risks. Ultimately, addressing material criticality in the present will ensure that a clean energy future is possible for decades to come.

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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		**0.70**	**0.30**		**0.40**	**0.10**	**0.20**	**0.10**	**0.20**
Factor	**Importance to Energy**	Energy Demand	Substitutability Limitations	**Supply Risk**	Basic Availability	Competing Technology Demand	Political, Regulatory, and Social Factors	Codependence on Other Markets	Producer Diversity
Short term									
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	**2.8**	2	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	**2.8**	2	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
Terbium	**2.7**	3	2	**3.2**	3	3	3	3	4

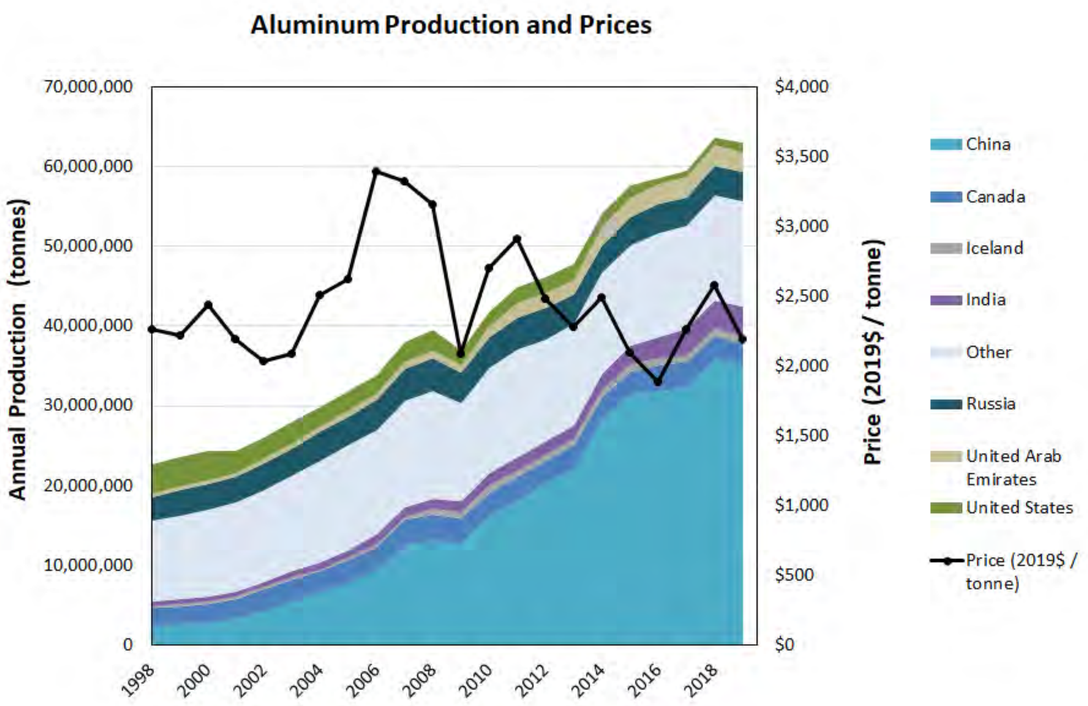
Weight		**0.70**	**0.30**		**0.40**	**0.10**	**0.20**	**0.10**	**0.20**
Factor	**Importance to Energy**	Energy Demand	Substitutability Limitations	**Supply Risk**	Basic Availability	Competing Technology Demand	Political, Regulatory, and Social Factors	Codependence on Other Markets	Producer Diversity
Titanium	**2.0**	2	2	**1.6**	1	1	2	1	3
Uranium	**4.0**	4	4	**1.9**	2	2	2	1	2
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
Terbium	**3.1**	4	1	**3.6**	4	3	3	3	4
Titanium	**2.0**	2	2	**2.0**	2	1	2	1	3
Uranium	**4.0**	4	4	**2.0**	3	1	2	1	1

<table>
<tr><th>Aluminum (Al)</th><th>Atomic number: 13</th></tr>
<tr><td colspan="2">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.</td></tr>
<tr><td colspan="2">Importance to Energy: <i>Short term: 2, medium term: 2</i></td></tr>
<tr><td colspan="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.</td></tr>
<tr><td>Energy Demand
Short term: 2
Medium term: 2</td><td>• 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 subtechnology 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.</td></tr>
<tr><td>Substitutability Limitations
Short term: 3
Medium term: 3</td><td>• 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 it 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 (Li-ion batteries or LIBs), 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 that is not a big concern for energy storage system (ESS) batteries.</td></tr>
<tr><td colspan="2">Supply Risk: <i>Short term: 2, medium term: 3</i></td></tr>
<tr><td colspan="2">The supply risk for 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.</td></tr>
<tr><td>Basic Availability
Short term: 2
Medium term: 3</td><td>• 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 the 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</td></tr>
</table>

	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 production is moved to carbon-priced areas. Research is being conducted that will decarbonize the aluminum production process through alternative anodes in aluminum smelting; carbon capture, utilization, and storage (CCUS); hydrogen; or mechanical vapor recompression. Use of these technologies is still not widespread, and most electricity that is used in aluminum manufacturing is from 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 put 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 about 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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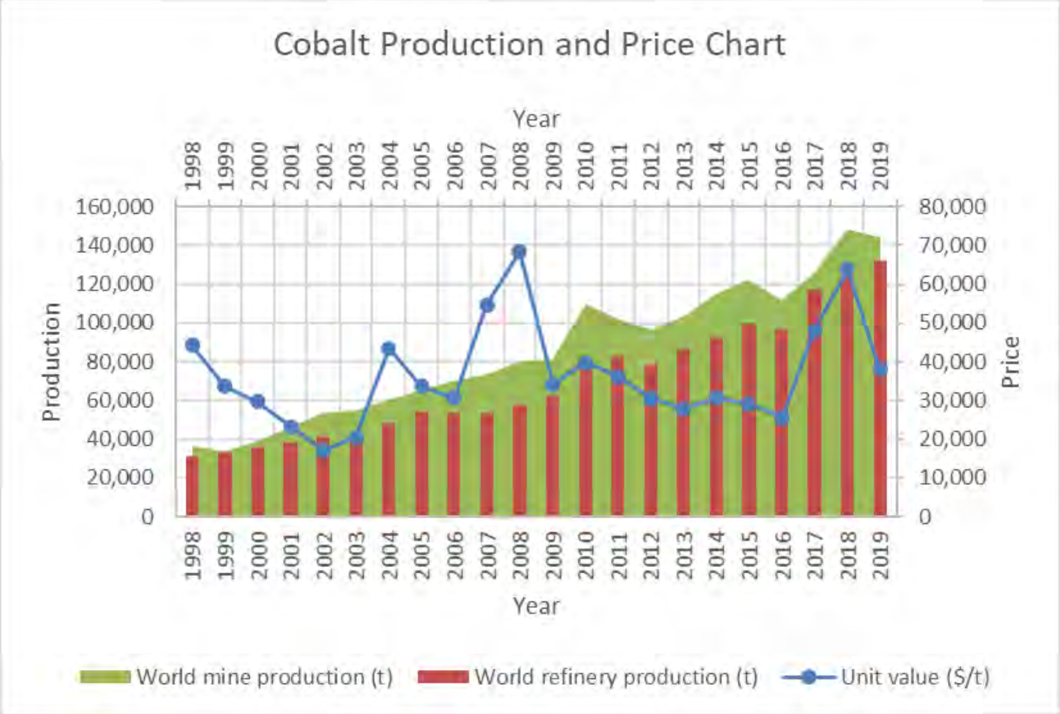
Cobalt (Co)	Atomic number: 27
Cobalt is a transition metal that is widely used in various industrial and technological applications, such as rechargeable battery electrodes, and in superalloys for gas turbine engine blades and other critical components, as catalysts in chemical and petrochemical processes, and in Samarium Cobalt high-strength permanent magnets.	
Importance to Energy: *Short term: 3, medium term: 3*	
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.	
Energy Demand Short term: 4 Medium term: 4	• 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.
Substitutability Limitations Short term: 2 Medium term: 2	• 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-nickel (Ni) low-Co chemistries, primarily driven by ethical, environmental, and supply security concerns.
Supply Risk: *Short term:3, medium term: 3*	
The supply risk for cobalt is considered moderate to high in the short and long terms. The Democratic Republic of Congo (DRC) and Australia account for more than 65% of global cobalt reserves, and 60% of global production is concentrated in the 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.	
Basic Availability Short term: 3 Medium term: 3	• 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.
Competing Technology Demand Short term: 2 Medium term: 1	• 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.
Political, Regulatory, and Social Factors Short term: 4 Medium term: 4	• 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.
Codependence on Other Markets Short term: 3 Medium term: 3	• Roughly 90% of cobalt is produced in conjunction with copper and/or nickel.
Producer Diversity Short term: 4 Medium term: 4	• Most of the cobalt (about 70%) comes from Congo, which contributes to the Herfindahl-Hirschman Index (HHI) producer diversity score of 5280 for all cobalt mining. Indonesia and Russia each account for about 5%.

Historical Price and Production



Source: USGS Cobalt historical statistics

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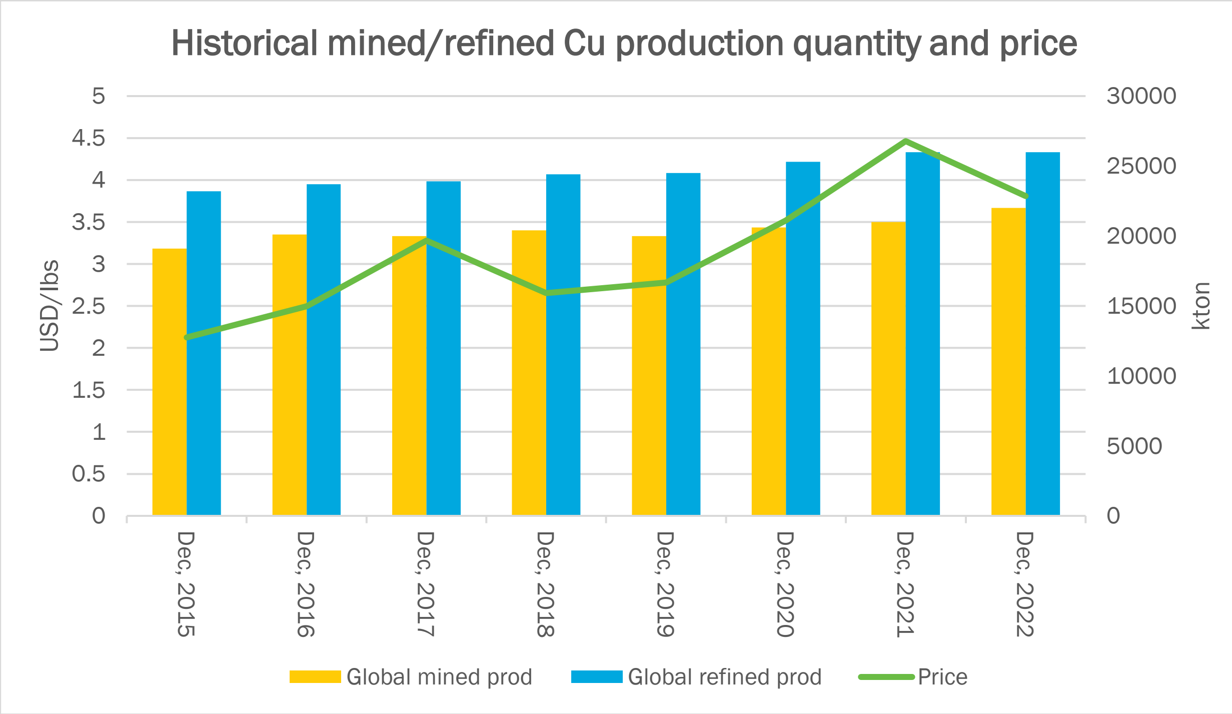
<table>
<tr><th colspan="2">Copper (Cu) Atomic number: 29</th></tr>
<tr><td colspan="2">Cu is generally found in nature in association with sulfur and is extracted as copper sulfides from large open pit mines in porphyry copper deposits (Craig and Leonard, 2019). Copper is the third most-used metal in industry after iron and aluminum due to its high ductility, malleability, thermal and electrical conductivity, and corrosion resistance.</td></tr>
<tr><th colspan="2">Importance to Energy: <i>Short term: 2, medium term: 3</i></th></tr>
<tr><td colspan="2">Cu needs vary widely across technologies. The demand for clean energy technologies is growing, and Cu is essential to them, such as in 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.). 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, 2022c,d]) and high-voltage direct current (HVDC) deployment (~39 GW [Baig, 2019]) 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><th colspan="2">Supply Risk: <i>Short term: 2, medium term: 2</i></th></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). In the long term, however, the portion of recycled copper may fall given the rapidly rising copper demand to meet electrification needs. Technology maturation for expanded uses will take years for the level of recycle currently seen to return.
• 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 sources have predicted copper shortages of 10 Mt in 2035 and 14 Mt in 2040 (Mills, 2023).</td></tr>
</table>

	• Based on projected demand trajectories in Chapter 4, 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 both the short term and medium term.
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 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). China is the largest Cu refining country, with around 40% market share (IEA, 2021), • 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 the 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 (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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Dysprosium (Dy) Atomic number: 66

Dysprosium is a rare earth metal that is used in the production of powerful neodymium iron boron (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.

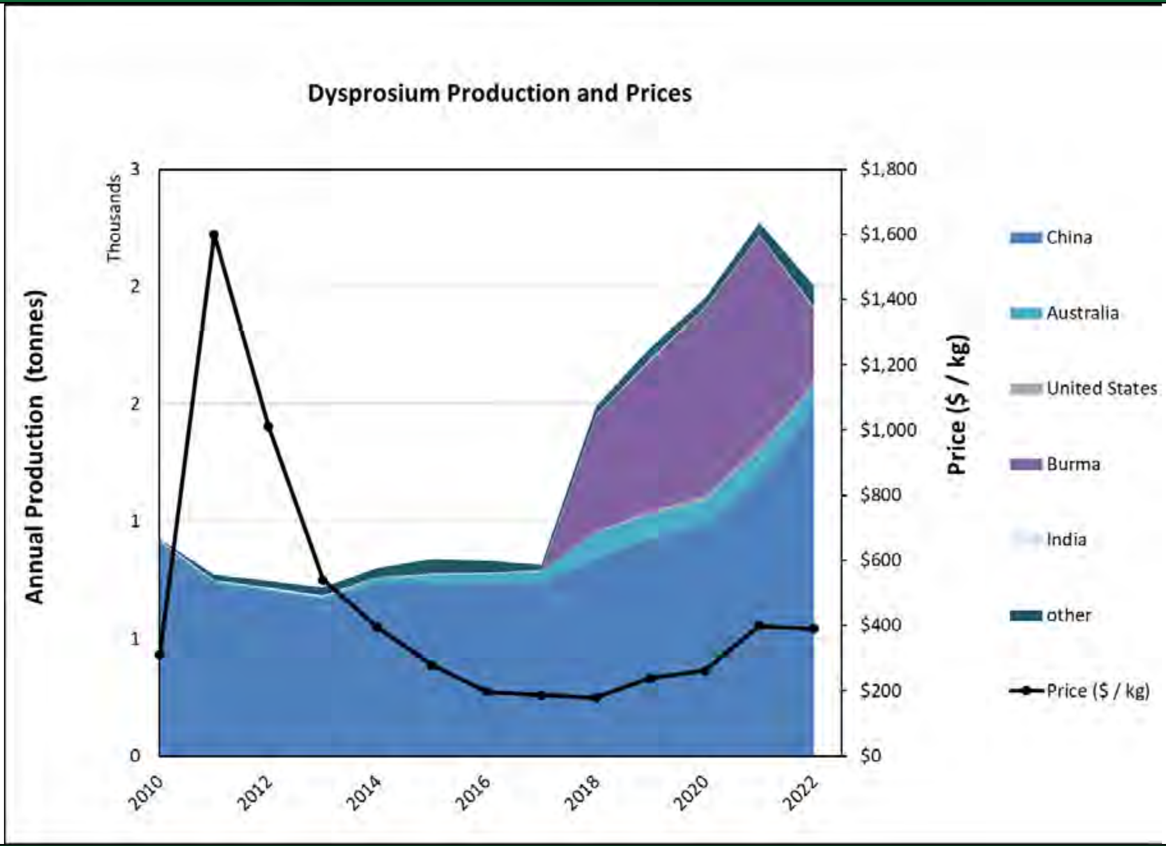
Supply Risk: *Short term: 3, medium term: 4*

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 two of the four trajectories, including by 155% in the highest scenario. • Demand for Dy is projected to exceed current capacity by 2035 in all four trajectories, including by 878% in the highest scenario. • 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 (2023) 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	• 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.

Short term: 3 Medium term: 3	• 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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Electrical Steel — Atomic number: N/A

Electrical steel is an iron-silicon (Fe-Si) alloy having varying amounts of 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.

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

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% of the market share in 2021 (Fact.MR, 2022; The Business Research Company, 2023b). Amorphous steel is mostly used in distribution transformers due to its lower no-load energy losses (Najafi & Iskender, 2018). It can lower core losses by 60%–70% when compared to GOES (Dabbs, 2023). Amorphous steel is not suitable for large power transformers (LPTs) because of its lower saturation magnetization, which, when required to operate at constant full load, leads to lower efficiencies (Hirzel, 2014).

Energy Demand Short term: 3 Medium term: 3	• 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 the short and medium term.
Substitutability Limitations Short term: 3 Medium term: 2	• Alternatives to electrical steel exist at the material level but do not seem to play a major role. Because amorphous steel is considered a new electrical steel for the purpose of this report, there is no substitute for electrical steel in distribution transformers, commercial and industrial transformers, and current transformers. However, for large power transformers, conventional electrical steel is the only material of choice (Totemeier, 2004). For relays, inductors and high-frequency transformers, nickel iron alloys are being used (Totemeier, 2004). Iron-cobalt alloys are used in certain motors and generators. This alloy is 25% lighter in weight than the thin-gauge electrical steel and utilized for aerospace and lightweighting for motor vehicles (Eckard, 2020).In the medium term, with nickel iron alloys 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.

Supply Risk: *Short term: 2, medium term: 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 risk due to usage of GOES in charging infrastructure (Vittori et al., 2021).

Basic Availability Short term: 2 Medium term: 3	• 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 manufacturers' (OEMs') requirements (Vittori et al., 2021). There are only five 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 Chapter 4, 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) of 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 start and thus further disrupt supply. The score for PRS factors is 50th percentile, so a score of 2 was given for both the 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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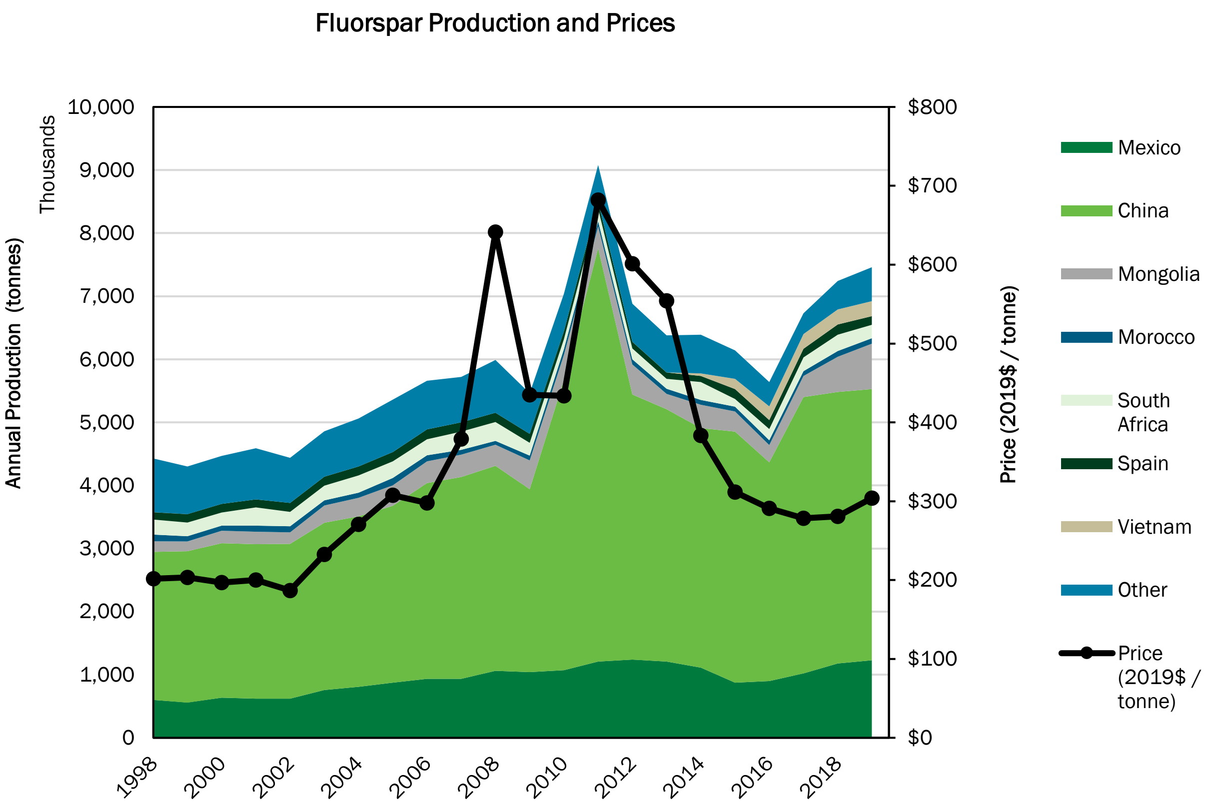
<table>
<tr><th>Fluorine (F)</th><th>Atomic number: 9</th></tr>
<tr><td colspan="2">Fluorine is mainly used for hydrogen fluoride (HF) production, steel making, and aluminum smelting. Among the in-scope energy applications, fluorine is used in the cathode binder material and electrolyte salt of lithium-ion 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. While fluorine-free cathode binder materials and electrolyte salts exist, 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 industrial waste streams. However, the volume is small (<10%) compared with imports for consumption.</td></tr>
</table>

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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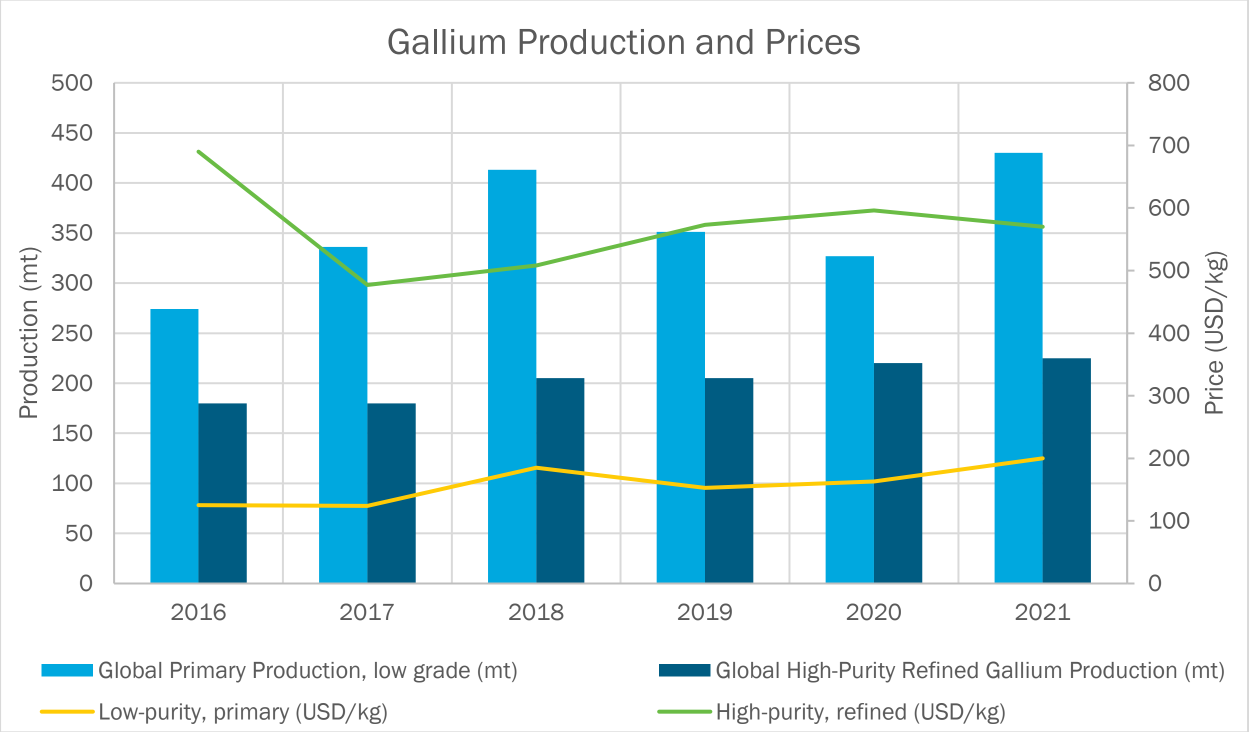
Gallium (Ga)	Atomic number: 31
Gallium is a soft, silvery metal that is liquid at room temperature and used in applications such as integrated circuits, laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells.	
Importance to Energy: *Short term: 3, medium term: 3*	
Gallium is utilized 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.	
Energy Demand Short term: 4 Medium term: 4	• 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%.
Substitutability Limitations Short term: 2 Medium term: 2	• 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 gallium nitride (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.
Supply Risk: *Short term: 3, medium term: 3*	
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.	
Basic Availability Short term: 2 Medium term: 3	• 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).
Competing Technology Demand Short term: 3 Medium term: 3	• 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).
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• 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%.
Codependence on Other Markets Short term: 4 Medium term: 4	• 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).
Producer Diversity Short term: 4 Medium term: 4	• 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 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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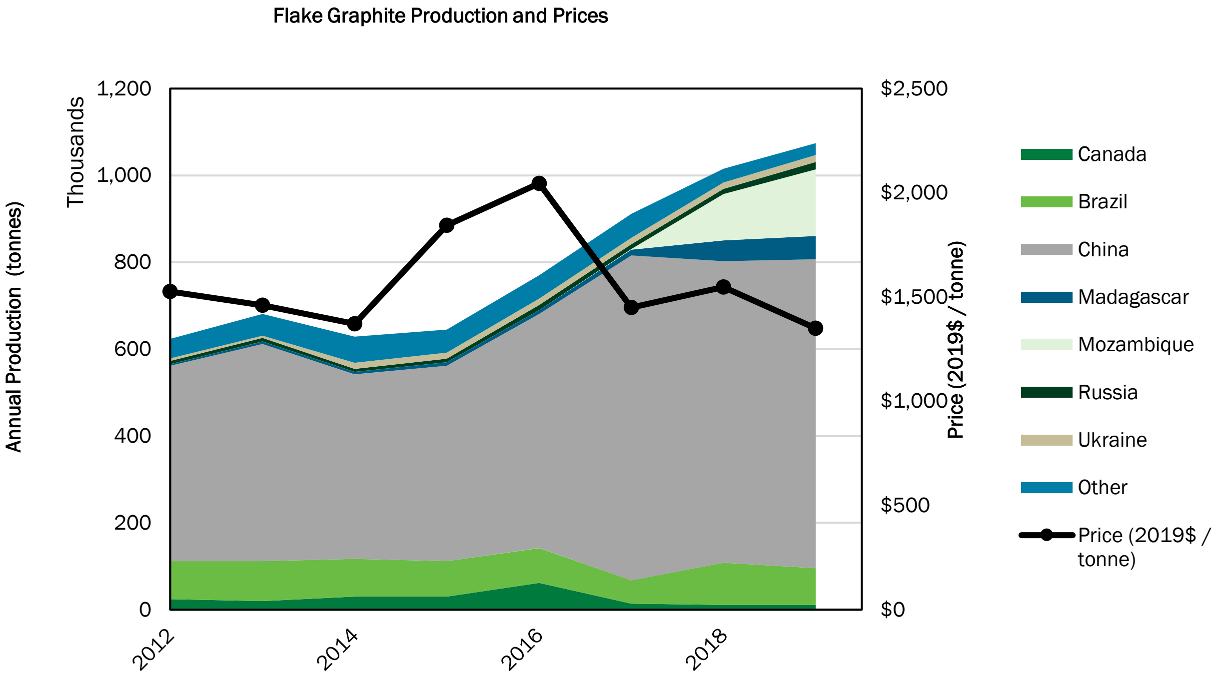
Graphite (C)	Atomic number: 6
Graphite is a form of carbon that has a layered structure. It is used in batteries, fuel cells, and nuclear reactors. Beyond energy applications, major uses of graphite include in refractories, foundries, and lubricants. Among the three types of natural graphite, only flake graphite is suitable for battery and fuel cell applications.	
Importance to Energy: *Short term: 3, medium term: 3*	
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.	
Energy Demand Short term: 3 Medium term: 4	• In 2025, flake graphite demand for energy applications will account for 64% of the total demand. EV batteries represent the most dominant subtechnology 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%.
Substitutability Limitations Short term: 2 Medium term: 2	• 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.
Supply Risk: *Short term: 3, medium term: 3*	
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.	
Basic Availability Short term: 3 Medium term: 3	• 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.
Competing Technology Demand Short term: 2 Medium term: 2	• 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 could 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%.

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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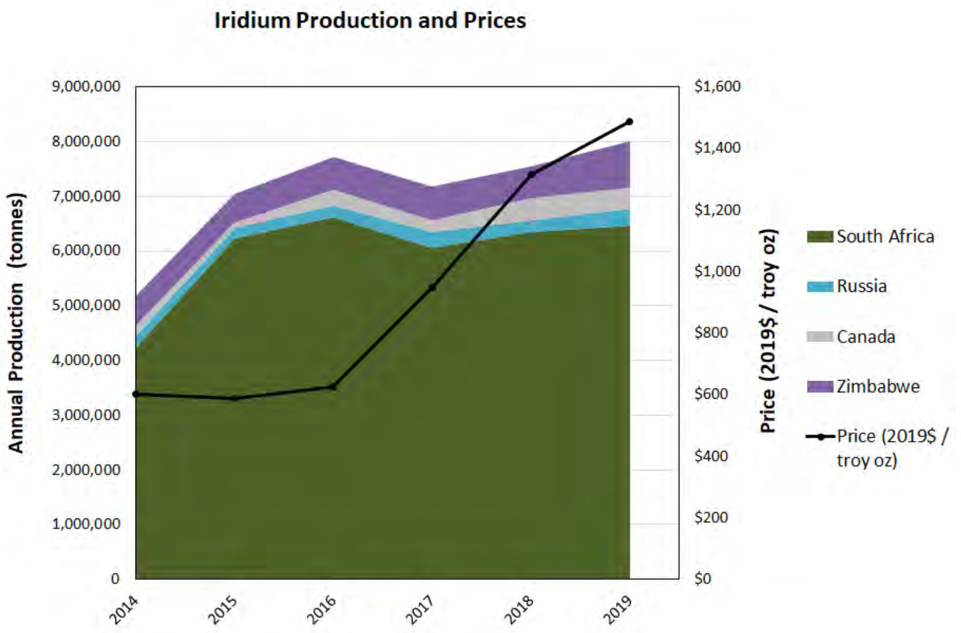
Iridium (Ir)	Atomic number: 77
Iridium is the least-abundant platinum group metal, accounting for <2% of mined content. The chemical, electrochemical, and electronics industries currently account for the majority of iridium demand.	
Importance to Energy: *Short term: 2, medium term 3*	
Supporting the 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) reaching, 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 cells (PEMECs). However, this substitution has been found to have reduced catalyst stability in laboratory testing. • For hydrogen production, substitutes for PEM electrolyzers include alkaline electrolyzers (commercialized) and solid oxide electrolyzers (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. o Trajectory A: 2025; percent of 2020 Ir capacity = 102% o Trajectory B: 2025, percent of 2020 Ir capacity = 103% o Trajectory C: 2025, percent of 2020 Ir capacity = 104% o Trajectory D: 2025, percent of 2020 Ir capacity = 113% o Trajectory A: 2035, percent of 2020 Ir capacity = 138% o Trajectory B: 2035, percent of 2020 Ir capacity = 145% o Trajectory C: 2035, percent of 2020 Ir capacity = 161% o 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 gross domestic product (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 platinum group metal (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 demand for 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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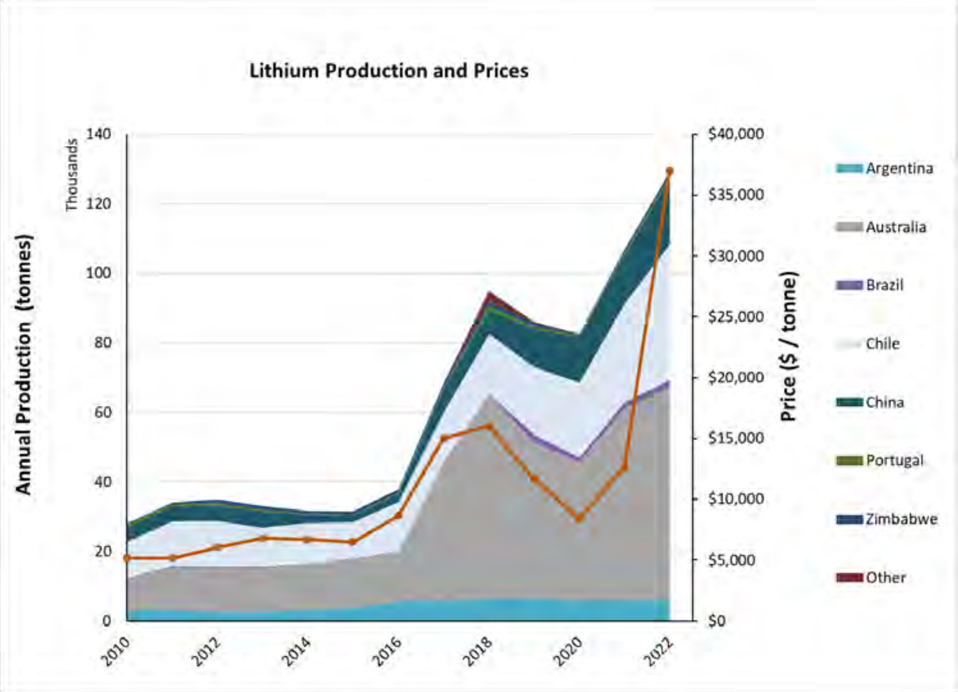
Lithium (Li)	Atomic number: 3
Lithium is used in the Li-ion batteries in EVs, consumer electronics and stationary storage, metallurgy and coatings, ceramics and glass, lubricant grease, air treatment, pharmaceuticals, and polymers.	
Importance to Energy: *Short term: 4, medium term: 4*	
Lithium used 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 nickel metal hydride (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 of 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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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.

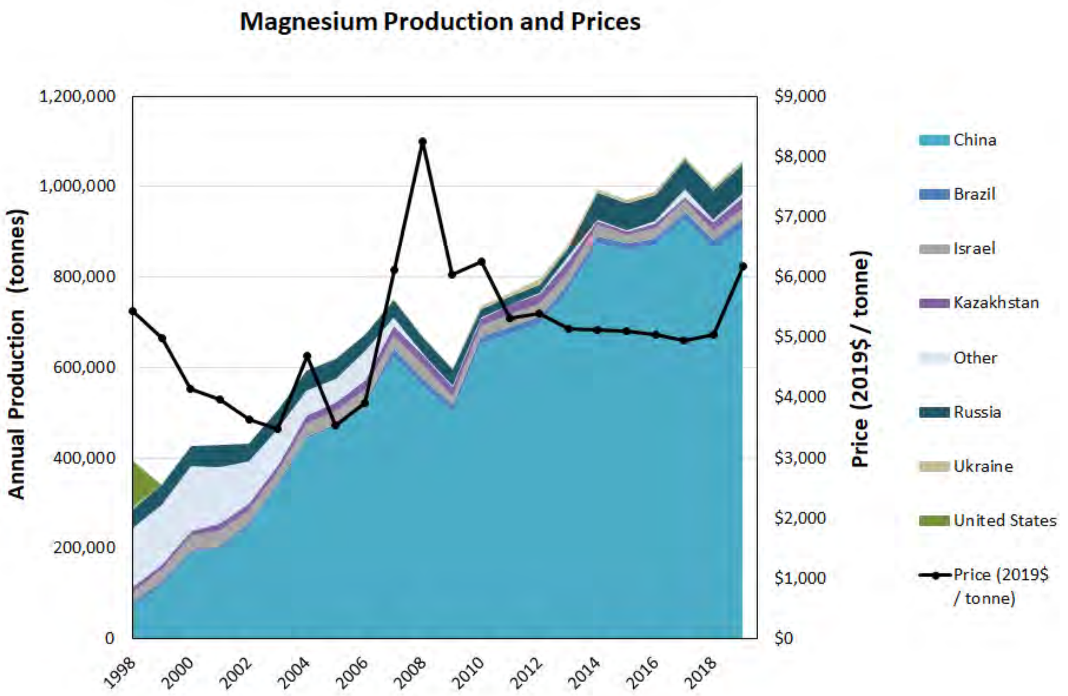
Supply Risk: *Short term: 2, medium term: 3*

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 carbon dioxide (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 plans to start producing magnesium as early as 2025. Other European projects have projected 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 it has 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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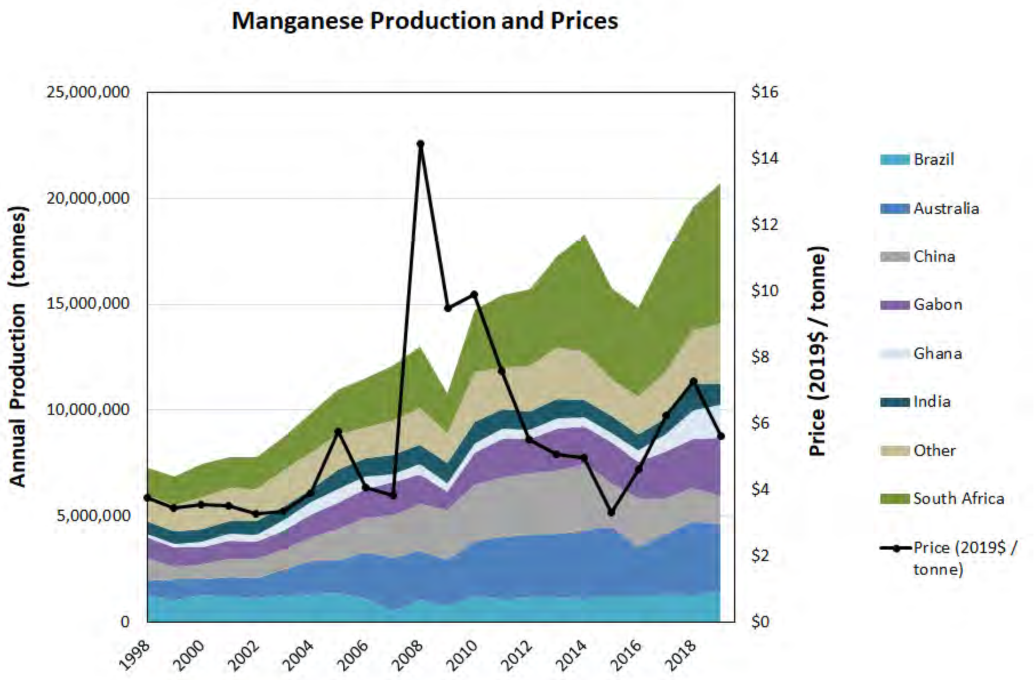
Manganese (Mn)	Atomic number: 25
Manganese is a transition metal that is primarily used for its alloying properties in steel. Manganese is also used in aluminum alloys and batteries.	
Importance to Energy: *Short term: 2, medium term: 2*	
Use of manganese in energy applications, including in the lightweighting 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 subtechnology 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 subtechnology 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% of manganese consumption. • In the short term, manganese could be fully substituted out of Li-ion batteries by replacing NMC and lithium-ion manganese oxide (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 lithium nickel manganese oxide [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 given that 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 about the basic availability of 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. However, full-scale mining of marine ferromanganese deposits is not yet viable. • 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, although identified global resources are enough to meet future manganese demand, 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; however, 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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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 41% of Nd demand is expected to be from magnets in EVs and wind turbines. • In 2035, 64% 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, and it is not likely that more than 25% of the Nd/Pr content of the magnet will be Pr. • Substitution of Ce for some Nd in magnets may also be possible.

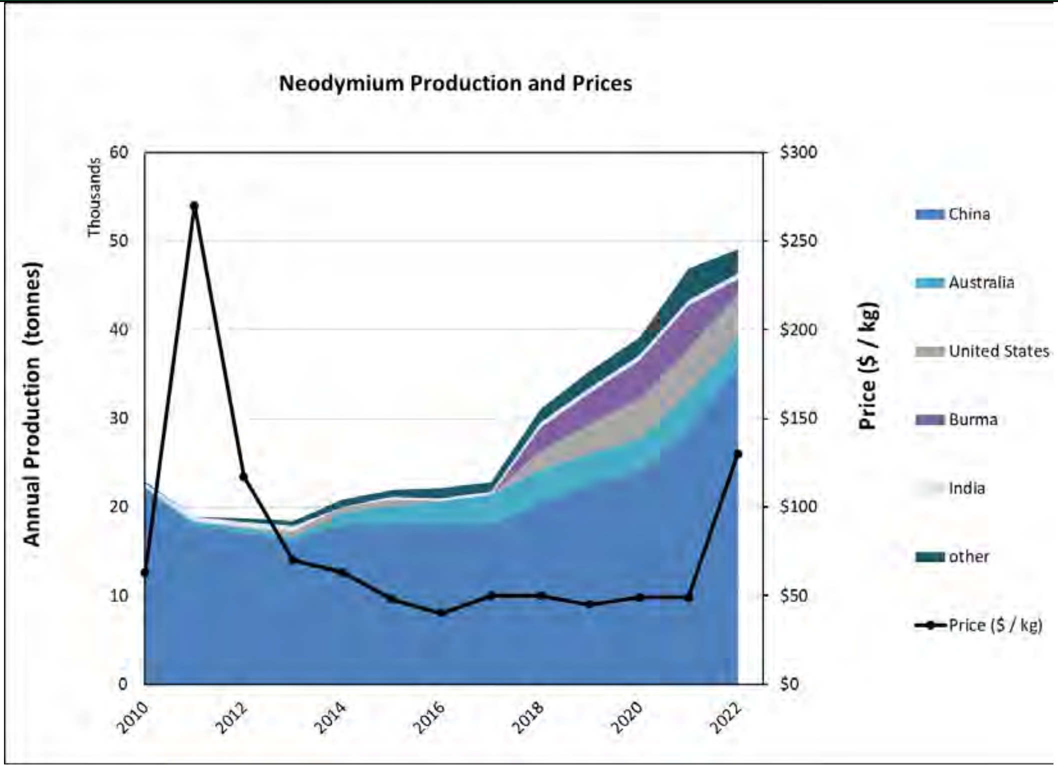
Supply Risk: *Short term: 3, medium term: 4*

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: 2 Medium term: 4	• Demand for Nd is projected to exceed current capacity by 2025 in two of the four trajectories, by about 37% in Trajectory D, and is very close to exceeding capacity in a third trajectory. • 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 (2023) 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	• 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. • The current rating for Nd oxide and NdPr oxide separation is 43.0; and for mining, it is 47.4.

Medium term: 3	• 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 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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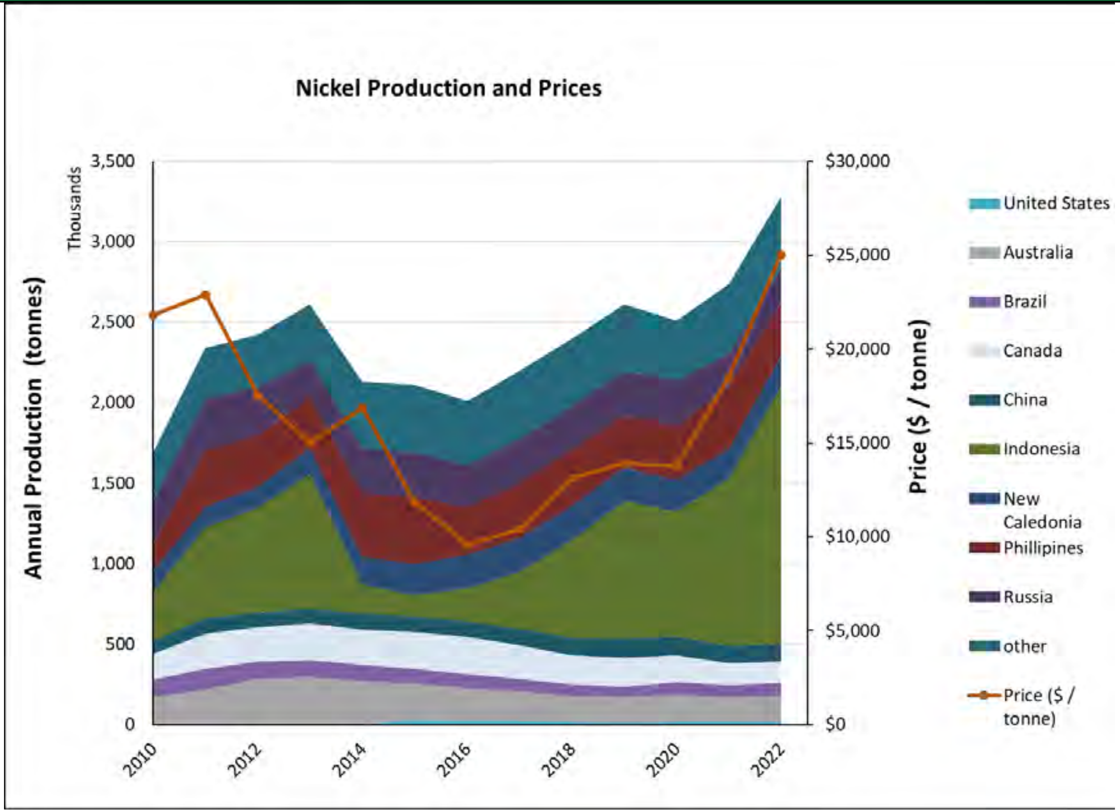
Nickel (Ni)	Atomic number: 28
Nickel is used in the cathodes of Li-ion batteries in electric vehicles, consumer electronics and stationary storage, stainless steel, metallurgy and coatings, electroplating, and other alloys.	
Importance to Energy: *Short term: 3, medium term: 4*	
Nickel used in Li-ion 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. Rapid growth is also expected for solid oxide electrolyzers and fuel cells, but it 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.	
Energy Demand Short term: 3 Medium term: 4	• 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.
Substitutability Limitations Short term: 2 Medium term: 3	• 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.
Supply Risk: *Short term: 2, medium term: 3*	
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 of 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.	
Basic Availability Short term: 2 Medium term: 3	• Three of four trajectories exceed current production capacity by 2025—the highest by about 54%. • All trajectories significantly exceed current production capacity 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.
Competing Technology Demand Short term: 1 Medium term: 1	• 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%.
Political, Regulatory, and Social Factors Short term: 3 Medium term: 3	• 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.

Codependence on Other Markets Short term: 2 Medium term: 2	• While nickel is often produced in conjunction with copper and/or cobalt, it is usually the primary product of the mines where it is produced.
Producer Diversity Short term: 2 Medium term: 2	• Almost half —49%—of mined nickel comes from Indonesia, which contributes to an HHI score of 2795 for all nickel mining. • 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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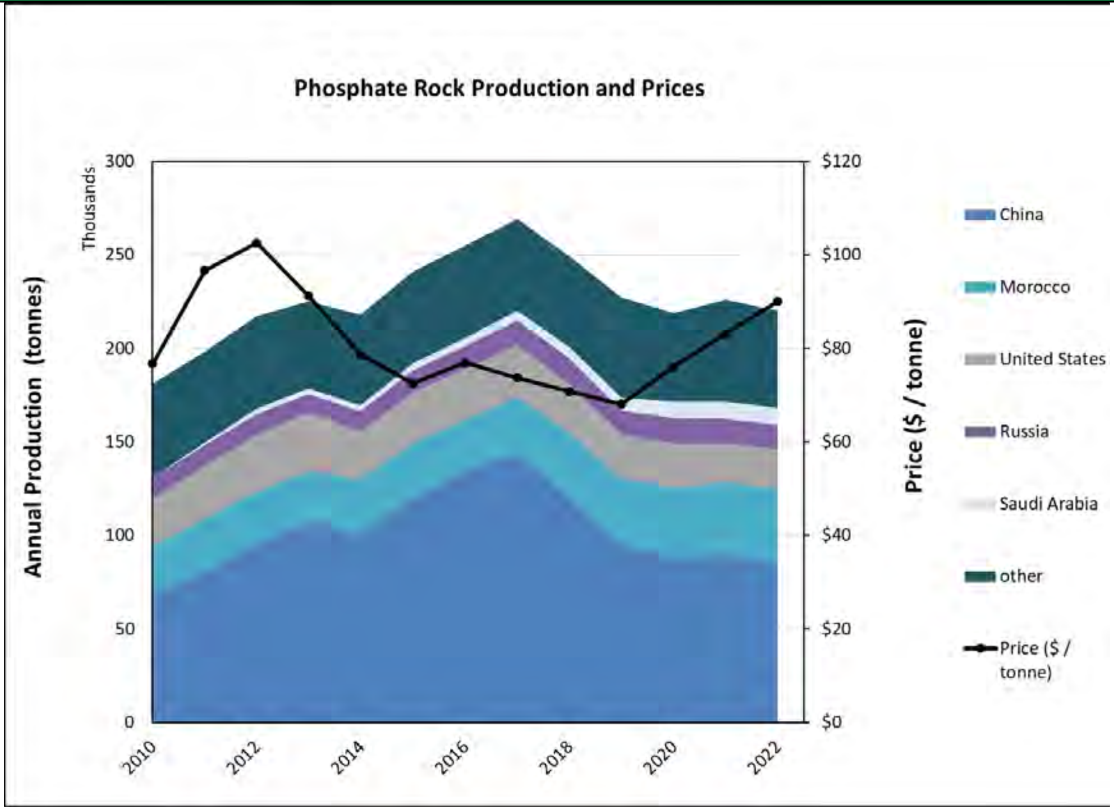
Phosphorus (P)	Atomic number: 15
Phosphorus is most abundant within the agricultural sector; however, it does have some applications in energy storage technologies. These uses include in EV batteries and stationary storage batteries.	
Importance to Energy: *Short term: 1, medium term: 1*	
Using the IEA's 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	• LFP batteries, which use significant amounts of P, could be the energy source for up to 60% of the EVs in the market, and all Li ion batteries use small amounts of P in the electrolyte. • However, the share of phosphorus that is used for energy applications never exceeds 10% in the four trajectories modeled. • In Trajectory D, 5% of P is used for energy applications in 2025, and 9% in Trajectory D in 2035.
Substitutability Limitations Short term: 2 Medium term: 2	• NMC and NCA Li-ion batteries, which use no P in the cathode, 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 production and imports may be necessary. Most P consumed in the U.S. 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 consumed in the U.S. 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, in all four trajectories, demand would exceed the estimated future phosphorus capacity, as projected, driven largely by the growth in other demand matching that of the GDP growth rate (3%). • In Trajectory D, P use in LFP batteries becomes a notable additional driver of demand. • This is not a major concern in the short or medium term, though, because of the world's ability to expand production and the ability of the U.S. to expand its phosphorus imports. • There are concerns about the depletion of P supplies in the long term given its importance for food production; however, USGS estimates that world reserves of phosphate rock are sufficient to last more than 300 years at current rates of production, and world resources are sufficient to last more than 1000 years.
Competing Technology Demand Short term: 1 Medium term: 3	• Currently, an overwhelming majority of phosphorus is used in agriculture (more than 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, the 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 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 2036. • 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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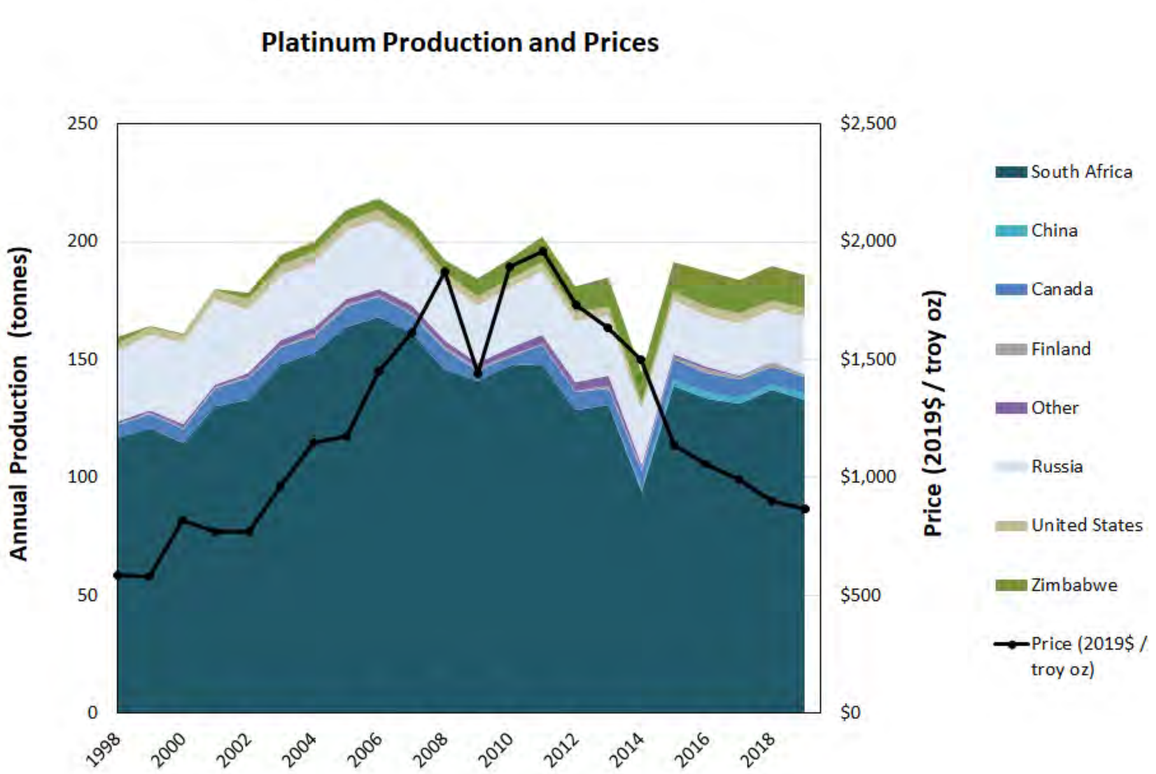
Platinum (Pt)	Atomic number: 78
Platinum is a transition metal used in energy applications, including vehicle catalytic converters and chemical and petroleum refining catalysts (where catalysts contribute to energy and material efficiencies). Other demands include in jewelry, electronics, and investment. 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 is 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). o Trajectory A – 2025: catalytic converters 47% o Trajectory B – 2025: catalytic converters 54% o Trajectory C – 2025: catalytic converters 45% o 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). o Trajectory A – 2035: catalytic converters 38% o Trajectory B – 2035: catalytic converters 44% o Trajectory C – 2035: FCEVs 44% o 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 within the scope of 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 electrolyzers (commercialized) and solid oxide electrolyzers (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 terms. 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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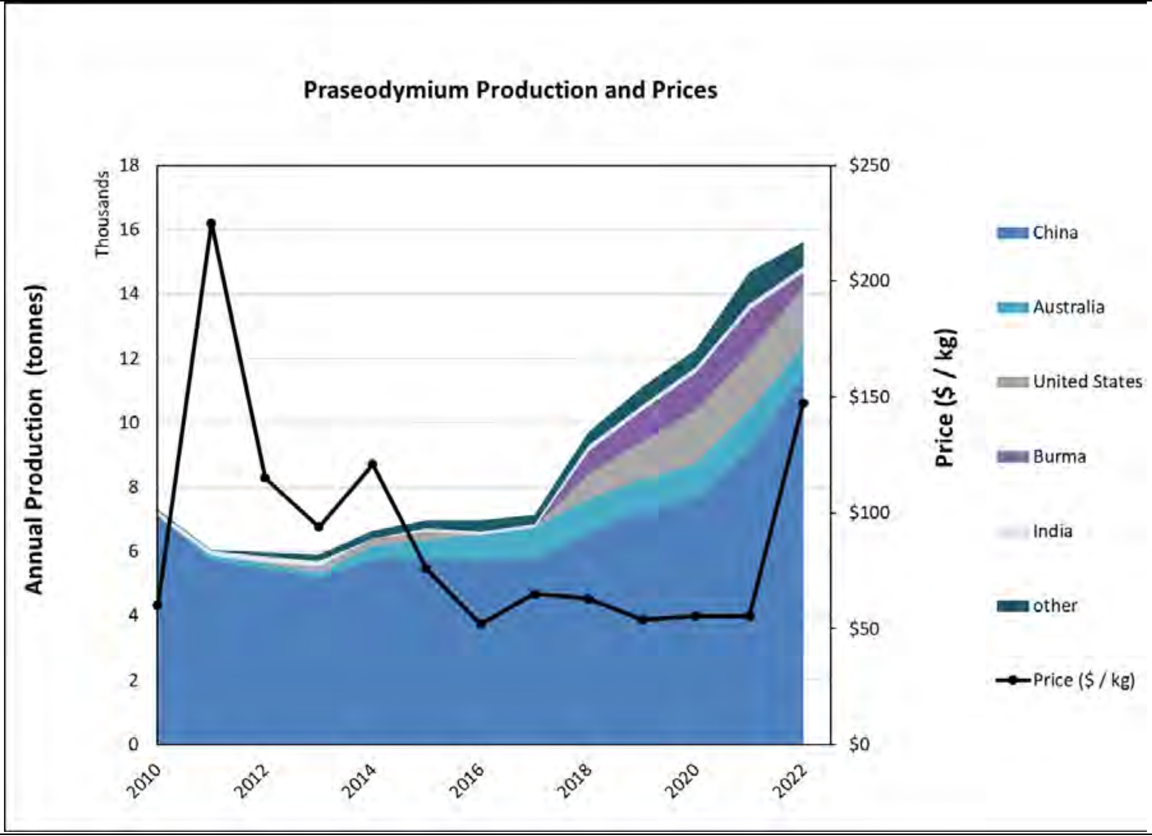
Praseodymium (Pr)	Atomic number: 59
Praseodymium is a rare-earth metal that is used in the production of powerful NdFeB magnets, which are used in applications such as electric vehicle motors, wind turbine generators, consumer electronics, industrial motors, and non-drivetrain uses in vehicles. In addition, Nd oxide is used in ceramics and glasses, catalysts, and some alloys.	
Importance to Energy: *Short term: 2, medium term: 3*	
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.	
Energy Demand Short term: 2 Medium term: 3	• In 2025, about 25% of Pr demand is expected to be from magnets in EVs and wind turbines. • In 2035, about 45% of Pr demand is expected to be from EVs and wind turbines. • The 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: 2 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 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 and 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.
Supply Risk: *Short term: 3, medium term: 4*	
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.	
Basic Availability Short term: 2 Medium term: 4	• Demand for Nd is projected to exceed current capacity by 2025 in two of the four trajectories and is very close to exceeding capacity in a third trajectory. • 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.
Competing Technology Demand Short term: 3 Medium term: 3	• 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 (2023) projects that magnet use in industrial applications and consumer electronics will grow between 5% and 10% per year.
Political, Regulatory, and Social Factors	• 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.

Short term: 3 Medium term: 3	- The current rating for Pr oxide and NdPr oxide separation is 42.9; and for mining, it 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.
Codependence on Other Markets Short term: 3 Medium term: 3	- Pr is an important source of revenues, along with Nd, for most rare-earth deposits, although significant 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 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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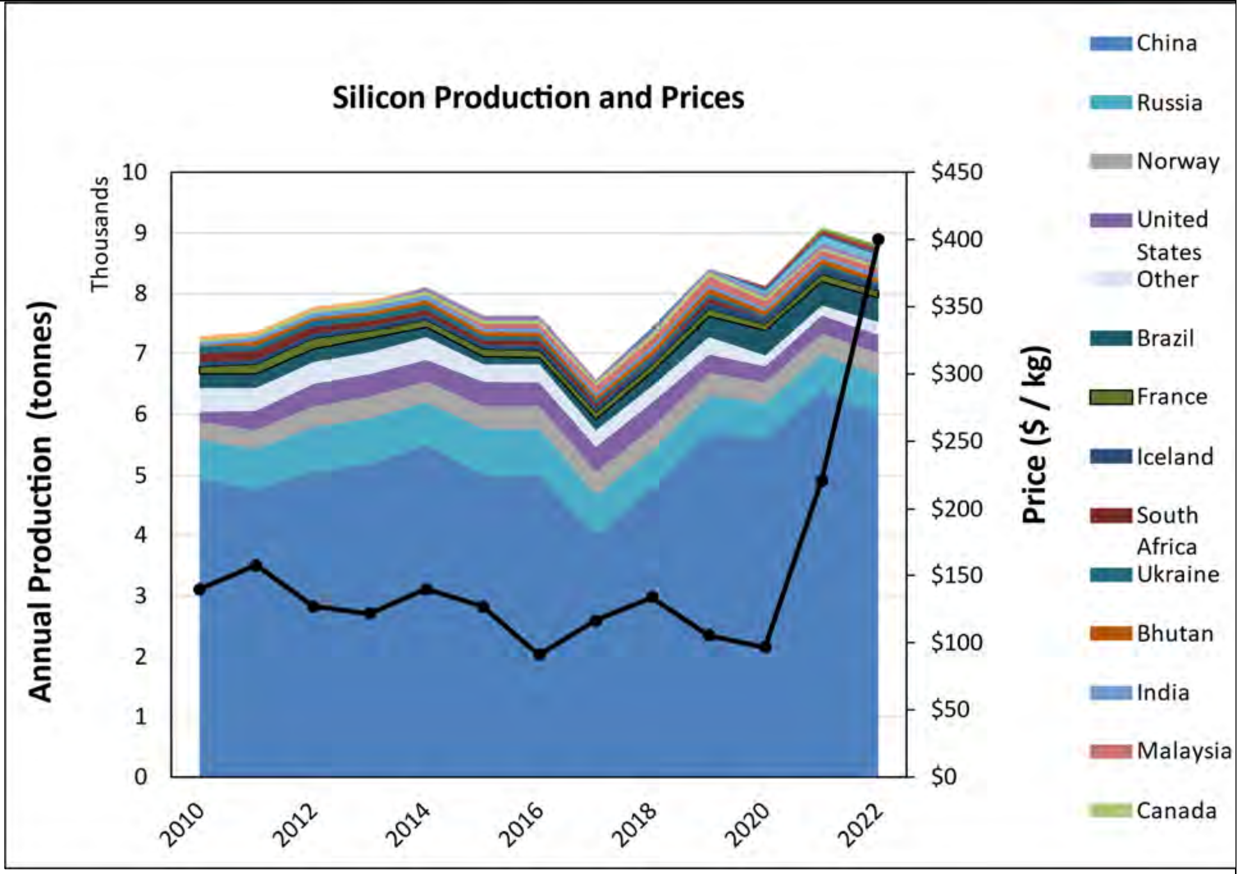
Silicon (Si)	Atomic number: 14
Silicon is the second most abundant material on earth and is a popular semiconductor used to manufacture a variety of chemicals (e.g., silanes, silicones, oils, elastomers, surfactants), metal alloys (e.g., aluminum and steel), solar cells, and computer chips.	
Importance to Energy: *Short term: 2, medium term: 3*	
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 [GOES] and non-grain oriented electrical steel [NOES]).	
Energy Demand Short term: 2 Medium term: 3	• 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).
Substitutability Limitations Short term: 3 Medium term: 3	• 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 cadmium-tellurium (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). The fabrication complexity of CIGS solar cells and their 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.
Supply Risk: *Short term: 2, medium term: 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 easily be 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.	
Basic Availability Short term: 1 Medium term: 2	• 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 mines (i.e.,

	usually quartz that is processed into silicon), current raw material supply can meet demand (U.S. Geological Survey, 2022b). As of 2020, current reserves are expected to meet demand for 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). 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, while China also reduced 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 from 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 are 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 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 Research, 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, respectively (Chiu and Dogmus, 2022; Rosina and Villamor, 2022). 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.

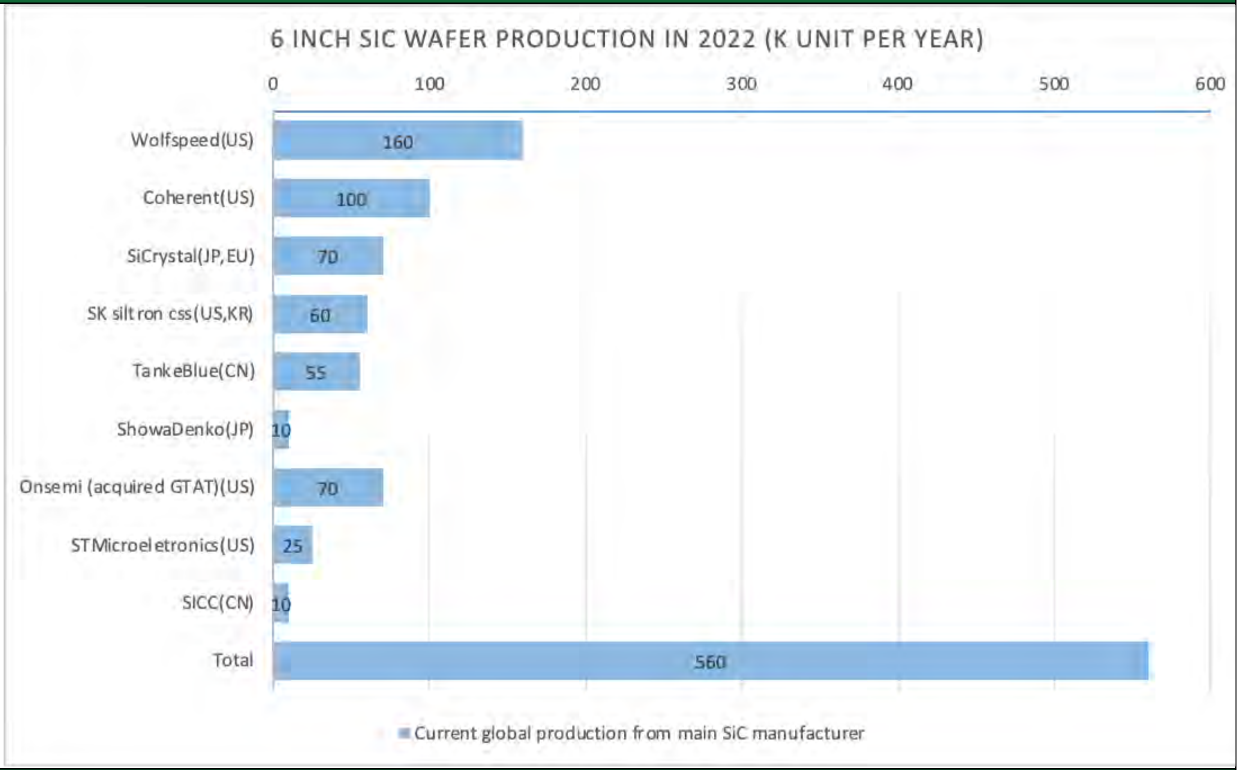
Supply Risk: *Short term: 2, medium term: 3*

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 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), the 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 shares based on discrete modules in 2020 indicated that 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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Tellurium (Te)	Atomic number: 52

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).

Importance to Energy: *Short term: 1, medium term: 1*

The primary application (40% of Te demand) 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).

Energy Demand Short term: 1 Medium term: 1	• 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.
Substitutability Limitations Short term: 1 Medium term: 1	• There are numerous other solar PV technologies available, including Si-based solar PV, that could easily substitute for CdTe solar PV installations.

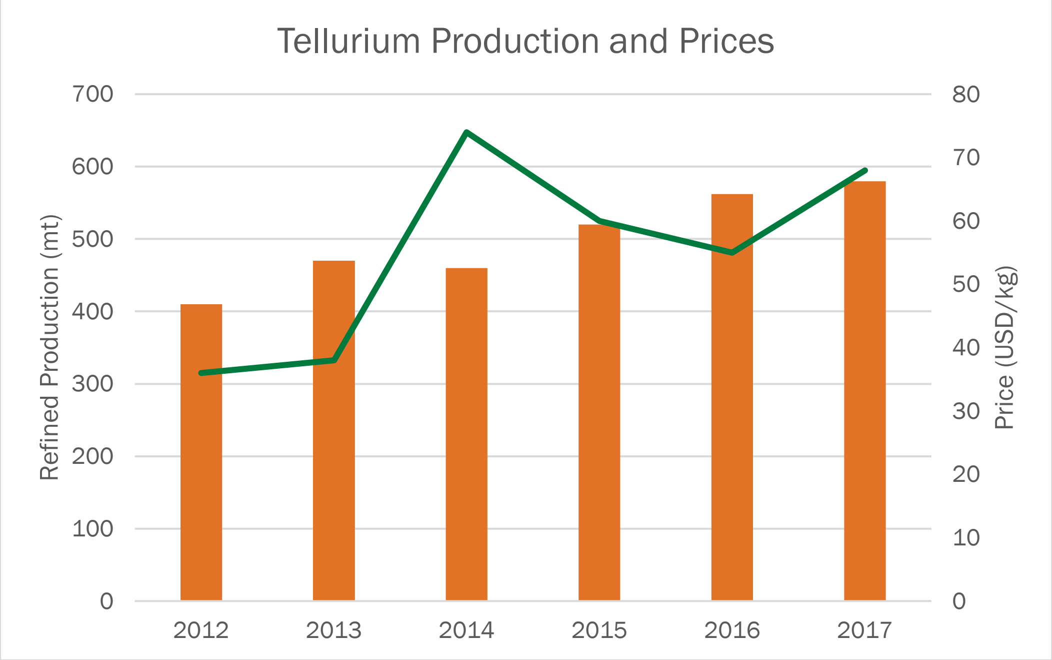
Supply Risk: *Short term: 3, medium term: 3*

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 the potential for demand to exceed supply unless tellurium production increases.

Basic Availability Short term: 3 Medium term:4	• 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 Chapter 4, by 2025, three out of four 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 four 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.
Competing Technology Demand Short term: 3 Medium term: 3	• 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 growth rates of the non-energy applications are no greater than 5% (USGS, 2022c).
Political, Regulatory, and Social Factors Short term: 2 Medium term: 2	• 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).

Codependence on Other Markets Short term: 4 Medium term:4	- 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 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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Terbium (Tb)	Atomic number: 65

Terbium 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, Tb oxide is used in phosphors for fluorescent lamps and color televisions, terfenol-D, and other alloys.

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

Electric vehicles and wind turbines are both key drivers of terbium demand, with vehicles being the more important source of growth, especially in the medium term and beyond. Terbium is very important to clean energy in the short term, where its high share of use is driven by key clean energy applications; however, in the medium term, the potential for more substitution away from terbium reduces its importance slightly.

Energy Demand Short term: 3 Medium term: 4	• In 2025, about 65% of Tb demand is expected to be from magnets in EVs and wind turbines. • In 2035, 85% of Tb demand is expected to be from EVs and wind turbines. • The 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: 2 Medium term: 1	• 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. • The use of Tb and Dy 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. • Tb use in magnets can be eliminated by replacing it with Dy.

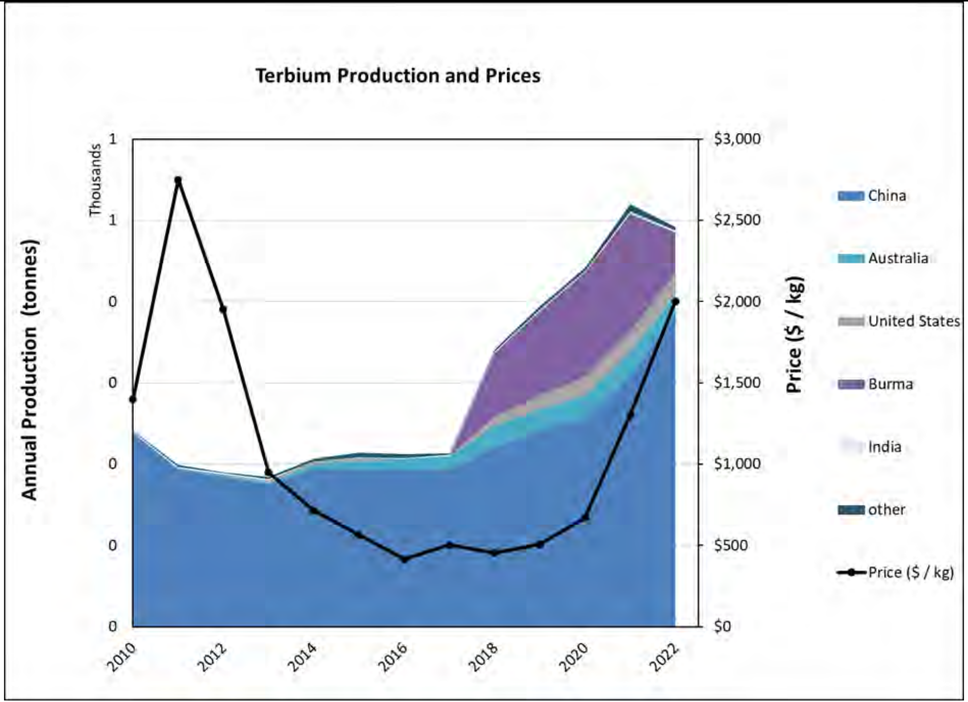
Supply Risk: *Short term: 3, medium term: 4*

Supply risk for terbium is high in the short term and especially in the medium term. Tb 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 Tb is projected to exceed current capacity by 2025 in two of the four trajectories, including by 94% in Trajectory D. • Demand for Tb is projected to exceed current supply by 2035 in all four trajectories, with more than six times as much in the highest trajectory. • 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 Tb, 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 Tb include its use in magnets in consumer electronics, industrial motors, non-drivetrain automotive motors, in phosphors for fluorescent lamps and color televisions, and in terfenol-D and other alloys. • Adamas Intelligence (2023) 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. The second-largest producer, Burma, brings it down, while the U.S. and Australia bring it up, leading to a weighted average rating of 42.5 for Tb mining.

	• The score for separation is very slightly higher due to the smaller role played by Burma, which is partly offset by the smaller roles played by the U.S. and Australia.
Codependence on Other Markets Short term: 3 Medium term: 3	• While Tb is an important source of revenues for heavy rare-earth deposits such as ionic clays, it is not the largest source due to the small quantities of Tb in these deposits. • Some Tb 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 94% of Tb separation happens in China, leading to an HHI score of 8860 for Tb separation by country. • The current HHI score for metal refining is estimated to be 8125; and for mining, it is 6314. • 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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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 biofeedstocks 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.

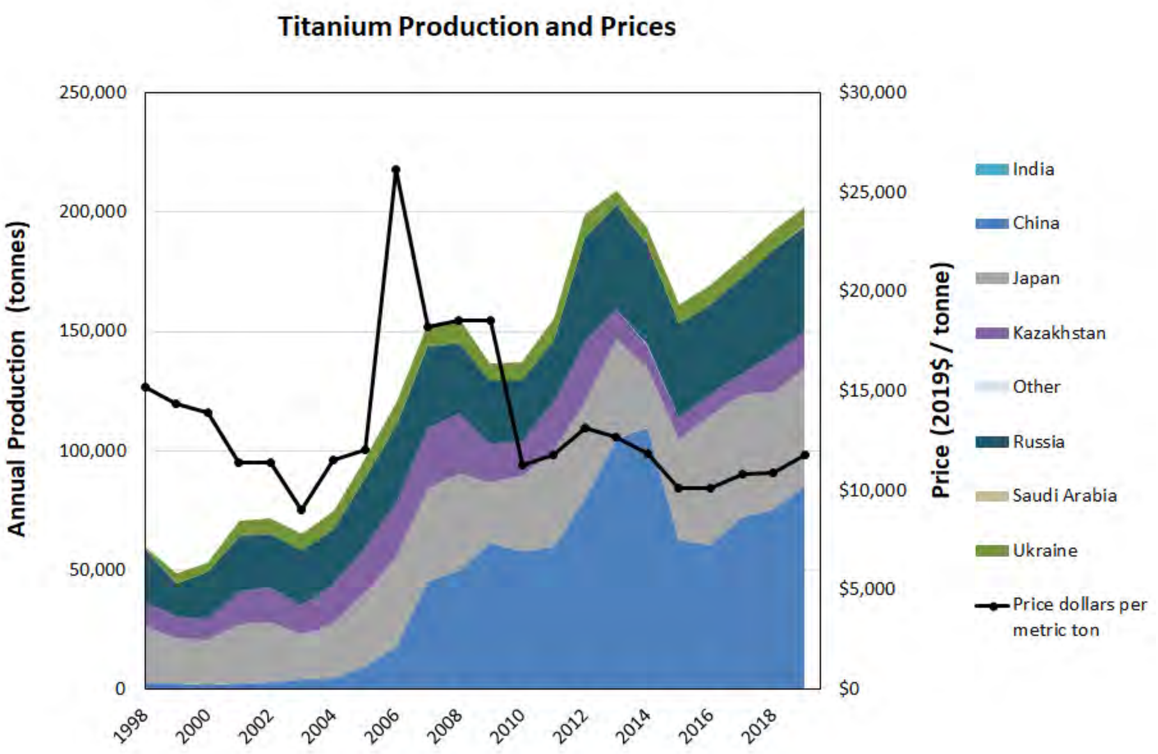
Supply Risk: *Short Term: 2, Medium Term: 2*

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 global production data for 2020, 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 of 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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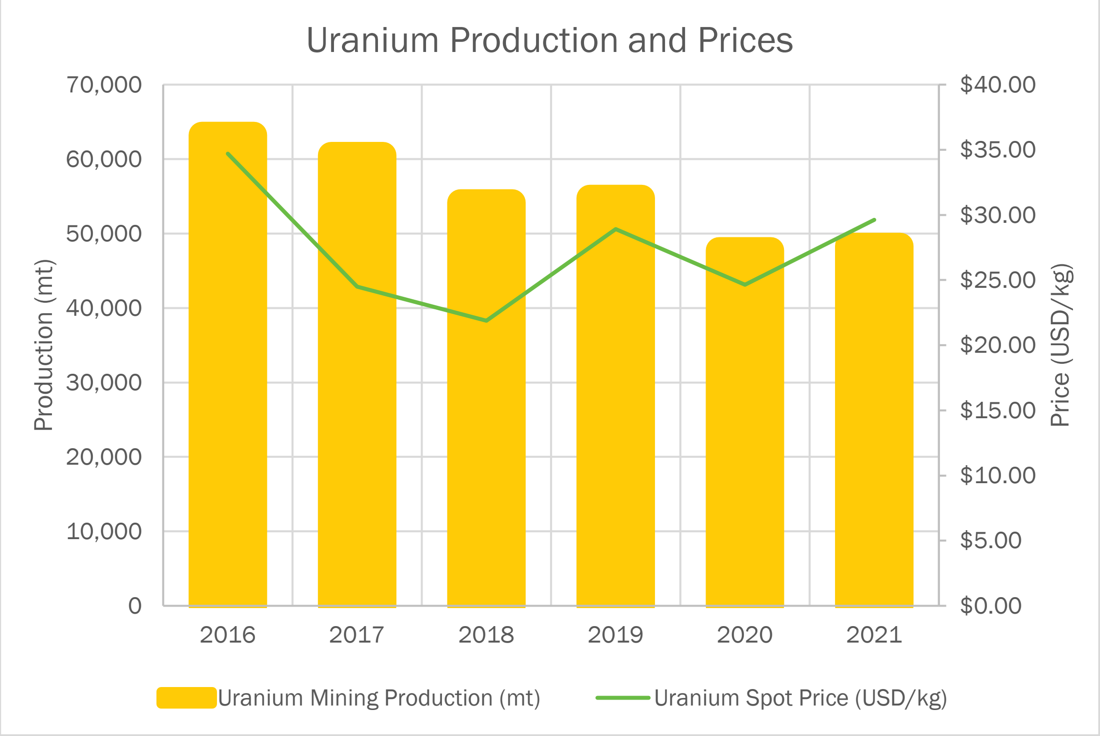
<table>
<tr><th colspan="2">Uranium (U) — Atomic number: 92</th></tr>
<tr><td colspan="2">Uranium is a silvery, white metal found in seawater and rocks and is used as a nuclear fuel source for nuclear energy generation. Isotope U-235 is the fissile component of natural uranium and typically makes up a small percentage (~0.7%) of typical, natural uranium.</td></tr>
<tr><th colspan="2">Importance to Energy: <i>Short term: 4, medium term: 4</i></th></tr>
<tr><td colspan="2">Uranium in nuclear fuels will continue to be the dominant application of uranium. Under optimistic growth scenarios for nuclear capacity, 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><th colspan="2">Supply Risk: <i>Short term: 2, medium term: 2</i></th></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 poses a threat to the nuclear fuel supply for those countries that are not 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, the 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

This appendix details information used for calculating demand trajectories as discussed in Chapter 4. There are four trajectories considered for each key material that passed the screening in Chapter 3. These trajectories are derived from two deployment scenarios of high and low for a given overarching technology such as vehicles or solar as shown in Chapter 4. These trajectories are obtained from various reports of the International Energy Agency (IEA) or market reports. For technologies that can be deployed by various sub-technologies (such as internal combustion engines [ICEs] and electric vehicles [EVs] for vehicles), assumptions for market penetration of those sub-technologies are required. Finally, to convert to material demand, material content or intensity is needed for each material. The intensity is in the form of mass per product unit (e.g., kg Cu/vehicle) or per energy output (e.g., kg Cu/MW) unless stated otherwise and summarized in Table B.1. This appendix provides market share assumptions for sub-technologies, as well as sources/calculations of material intensity.

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

Material	Application	Material Intensity	Production Yield(s)
Aluminum	Lightweighting	156.9–373.0 kg/vehicle	
	EV batteries	BEV LDVs[a]: 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 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: HEV = 3.99E-02 mton PHEV = 5.99E-02 mton 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: 41–136 g/vehicle BEV/PHEV/FCEV vans: 62–204 g/vehicle BEV/PHEV/FCEV buses: 82–272 g/vehicle BEV/PHEV/FCEV trucks: 123–408 g/vehicle	
	Wind turbine magnets	Direct Drive: 0.0–7.9 kg/MW Hybrid: 0.0–2.4 kg/MW Kumari et al., 2018 Imholte et al., 2018	

Material	Application	Material Intensity	Production Yield(s)
		Habib et al., 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
Electrical steel	Vehicle motor	40–100 kg per vehicle (Voestalpine, 2019)	
	Transformers	72.57–108.86 mt/unit of large power transformer (Deetman, Boer, Engelenberg, Voet, & Vuuren, 2021; IEA, 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 and 19.7 mt/GW (Zimmermann & Gößling-Reisemann, 2014)	Deposition yield = 45% Fabrication yield = 92% Production yield = 100% (Song, Wang, Sen, and 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: 4–15 g/vehicle BEV/PHEV/FCEV vans: 6–23 g/vehicle BEV/PHEV/FCEV buses: 9–30 g/vehicle BEV/PHEV/FCEV trucks: 13–45 g/vehicle	
	Wind turbine magnets	Direct Drive: 0.0–0.8 kg/MW Hybrid: 0.0–0.3 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 microchip applications, and there were no data available on specific material intensity or the numbers of microchips that contain Ge that are being produced in a given year;	

Material	Application	Material Intensity	Production Yield(s)
		therefore, using the current global Ge production that goes toward microchips and projecting demand based on expected sectoral growth rates provide the most accurate projections.	
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	6.4–24.0 kg/vehicle	
Manganese	Lightweighting	4.0–11.1 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 (Next Source Materials, 2013; 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: 309–464 g/vehicle BEV/PHEV/FCEV vans: 463–696 g/vehicle BEV/PHEV/FCEV buses: 618–928 g/vehicle BEV/PHEV/FCEV trucks: 927–1392 g/vehicle	

Material	Application	Material Intensity	Production Yield(s)
	Wind turbine magnets	Direct Drive: 117.8–176.6 kg/MW Hybrid: 36.2–54.4 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: 45–67 g/vehicle BEV/PHEV/FCEV vans: 68–100 g/vehicle BEV/PHEV/FCEV buses: 91–134 g/vehicle BEV/PHEV/FCEV trucks: 136–201 g/vehicle	
	Wind turbine magnets	Direct Drive: 21.3–31.9 kg/MW Hybrid: 6.6–9.8 kg/MW Kumari et al., 2018 Imholte et al., 2018 Habib et al., 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015	
Silicon	Solar	2.9–3.4 kg/kW (Frischknecht, Stolz, Krebs, de Wild-Scholten, and Sinha, 2020)	Yield – 60%; most waste is kerf from cutting the ingots (Li, Lin, Wang, Shi, Sun, Ban, Liu, and Chen, 2021) 67% yield according to Frischknecht et al. (2020)
	Lightweighting	9.4–26.5 kg/vehicle	
Tellurium	Solar (CdTe)	36 mt/GW in the high case (First Solar Correspondence)	Te Production Yield (High) = 99% (Marwede & Reller, 2012)

Material	Application	Material Intensity	Production Yield(s)
		20 mt/GW in the low case (European Commission Joint Research Centre, Alves Dias, Pavel, Plazzotta, and Carrara, 2020)	
Terbium	EV magnets	BEV/PHEV/FCEV cars: 4–17 g/vehicle BEV/PHEV/FCEV vans: 6–26 g/vehicle BEV/PHEV/FCEV buses: 9–35 g/vehicle BEV/PHEV/FCEV trucks: 13–52 g/vehicle	
	Wind turbine magnets	Direct Drive: 0.0–1.0 kg/MW Hybrid: 0.0–0.3 kg/MW Kumari et al., 2018 Imholte et al., 2018 Habib et al., 2014 Hill, 2010 Constantinides, 2011 Lacal-Arantegui, 2015 Adamas, 2023	
Uranium	Nuclear	159–187 mt U/GW (World Nuclear Association, 2022)	
Zirconium	Nuclear	11.9 t Zr/GW (Motta, Couet, and Comstock, 2015)	

[a] BEV = battery electric vehicle; CIGS = cadmium-indium-gallium-selenide; FCEV = fuel cell electric vehicle; HDV = heavy-duty vehicle; HVDC = high-voltage direct current; ICE = internal combustion engine; LDV = light-duty vehicle; LED = light-emitting diode; Li-ion = lithium-ion battery; NaS = sodium sulfur; NiMH = nickel metal hydride; PHEV = plug-in hybrid electric vehicle.

B1. Vehicles

B1.1 Electrical Steel in Vehicle Motors

Non-grain oriented electrical steel (NOES) is the type of electrical steel (ES) used most often in the construction of motors for electric vehicles. The total weight of NOES used in EVs varies between 40 to 100 kg (Steiniger, 2019), which constitute our lower and upper bounds, respectively, for the trajectory computations. The main assumption in these computations is that all types of EVs (vans, cars, trucks, and buses) have the same ES content, which is in fact not the case. Information for ES content per EV type was not available, so the total number was used. However, because the range used for high and low cases covers all EV types, it is safe to assume that the most accurate numbers would be somewhere in between.

B1.2 Wiring in Vehicles

The amount of Cu in vehicles varies by type and size. ICEs typically use between 8 to 22 kg/vehicle. Hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs) contain 38.6 kg/vehicle and 60 kg/vehicle, respectively. Battery electric vehicle (BEVs), hybrid electric buses, and battery electric buses contain 83.18 kg/vehicle, 89.1 kg/vehicle, and 370 kg/vehicle, respectively (Copper Development Association, 2022). To obtain high and low Cu content for non-ICE vehicle types, a value of ± 5% was used given the lack of data.

B1.3 Catalytic Converters in Vehicles

While vehicle sales increase over time, sales of vehicles that require catalytic converters (ICEs, PHEVs, and diesel engines) initially increase for both the Net-Zero Emissions (NZE) scenario and Stated Policies Scenario (STEPS), and then decrease after 2025. These market behaviors are reflected in Figure B.1.

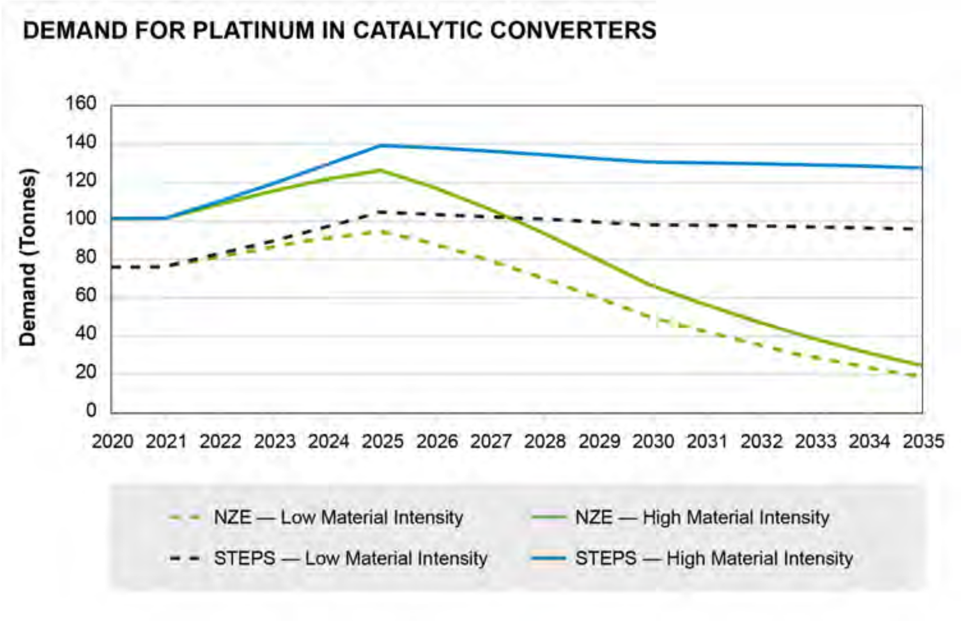

Figure B.1. Platinum demand trajectories for catalytic converters.

B1.3.1 Market Share

The high and low market shares for catalytic converters are developed from the IEA STEPS and NZE vehicle sales by type. Catalytic converters are assumed to be installed in all ICE vehicles (cars and vans), PHEVs, and diesel engine vehicles (trucks and buses). Catalytic converters are not installed in BEVs and FCEVs. Consequently, the market share of all vehicles that contain catalytic converters varies by year.

B1.3.2 Material Intensity

Low and high platinum material intensities for catalytic converters were derived from Johnson Matthey's (2022) automotive global demand data and this study's ICE, PHEV, and diesel vehicle sales for 2020 to 2022, following an approach adopted for a European platinum material flow analysis study (Saidani et al., 2019). This approach was adopted because of the wide range of proprietary compositions applied by manufacturers to meet exhaust regulations that vary by country and vehicle type. The estimates are in line with platinum intensities considered in the U.S. Department of Energy's Critical Materials Strategy (DOE, 2019). Intensities range from 0.9 g/vehicle to 1.2 g/vehicle.

B1.4 Lightweighting in Vehicles

B1.4.1 Market Share

This report assumes that there is a percentage of vehicles that will be sold with a standard lightweighting package and an advanced lightweighting package for each of the low-intensity scenarios, similar to that in the U.S Department of Energy's 2019 Critical Materials Strategy report (DOE, 2019). The amount of market share for standard and advanced lightweighting packages will differ based on the penetration assumption. In the low penetration scenario, the market share of vehicles sold with standard lightweighting will be 95% by 2035 whereas those sold with the advanced lightweighting package will be 5%. In the high penetration scenario, the market share for standard and advanced lightweighting packages are 60% and 40%, respectively. In 2020, the market share assumed for standard lightweighting packages is 100% for both the low and high penetration scenarios. For each year, the market penetration of the advanced lightweighting package increases exponentially until the respective market share assumptions for each scenario are reached by 2035.

The market share of the respective lightweighting alloys (high strength steel, advanced high-strength steel (AHSS), aluminum alloys, and magnesium alloys) differ by lightweighting package. The percentage of each lightweighting material is representative of the percentage material composition of a vehicle's mass per Das et al. (2016). For instance, in the standard lightweighting package, aluminum alloy is presumed to be 8.3% of the total vehicle's mass. For the vehicle's total mass, each lightweighting package utilized a weighted average vehicle mass for ICE, BEV, HEV, PHEV, and FCV light-duty vehicles (LDVs) (Argonne, n.d.) and heavy-duty vehicles (HDVs) (Argonne, n.d.) by vehicle type sold in each year. PHEV vehicle mass is assumed to be the average weight of vehicles with 20-mile and 50-mile ranges. BEV vehicle mass is assumed to be the average of 200-, 300-, 400-, and 500-mile range BEV vehicles. For HDVs, the mass is assumed to be the average of a Class 6 pickup and delivery truck, a Class 8 day-cab truck, and a Class 8 sleeper-cab truck. A summary of the weighted average vehicle weight and the market share of lightweighting material across different lightweighting packages can be found in Table B.2.

Table B.2. Lightweighting package weight and percentage of lightweighting materials.

	Standard Lightweighting	Advanced Lightweighting	
		Low Intensity	High Intensity
Reduction in Weight	0%	10%	22%
Vehicle Weight (2020 Weighted Average)	2,068 kg	1,861 kg	1,613 kg
Lightweighting Materials (share of vehicle weight)			
High-Strength Steel	11.0%	6.8%	5.7%
Advanced High-Strength Steel	3.2%	10.6%	25.2%
Aluminum Alloys	8.3%	15.6%	24.3%
Magnesium Alloys	0.3%	0.8%	1.3%

B1.4.2 Material Intensity

To assess the material content for each vehicle sold in a year, material percentage amounts are used for the low-intensity and high-intensity scenarios within the lightweighting materials of high-strength steel (HSS), AHSS, aluminum alloys, and magnesium alloys. Low intensity amounts are the lower range material amounts if listed in the source material. If no range is given, material amounts are presumed to be half of the maximum listed. The remaining balances of material amounts are calculated as the converse of the minimum or maximum scenario for alloying materials. For example, aluminum amounts in high-intensity aluminum alloys are the remaining balance of the other materials in the low-intensity aluminum alloy scenario. The following assumptions were applied to gather the material intensity ranges used in the analysis:

- **Material percentages for high-strength steel and advanced high-strength steel**: The amount of manganese and silicon within HSS can be found in Table B.3. For HSS, material amounts are assumed to be those found in steel grade ASTM A527 (AZO Materials, 2016), as it is considered the most widely used steel material (AZO Materials, 2016). For AHSS, percentages represent that of the first-generation grade of AHSS, which is more widely used in the automotive industry, because second- and third-generation AHSS is often too costly for automakers (Hu & Feng, 2021). Within first-generation AHSS, aluminum and silicon are both assumed to be present in equal amounts. Low intensity amounts represent the low end of the range provided, whereas high intensity percentages represent the high end of the range provided (Hu & Feng, 2021).

- **Material percentages for aluminum alloys:** Aluminum alloy percentages consist of both aluminum wrought and aluminum cast alloys. Aluminum wrought composition (Ota et al., 2020) is the weighted average of Series 5xxx and Series 6xxx aluminum alloy composition similarly calculated in the 2019 Critical Materials Strategy report (DOE, 2019). Series 5xxx is given a weight of 80% as it is the most popular aluminum series found in automobiles, whereas series 6xxx is given a weight of 20% (DOE, 2019). Aluminum cast composition is the chemical composition (The Aluminum Association, 2015) of aluminum alloy designation 356, as it is one of the most widely used cast aluminum alloys in engine blocks (Carley, 2017). The percentage range of materials in each can be found in Table B.3.
- **Material percentages for magnesium alloys:** Magnesium alloy percentages represent the average composition of AZ91D magnesium alloy, which is the most commonly used magnesium die cast alloy in automobile production (Dynacast). The range of material amounts present in magnesium alloys can be found in Table B.3.

Table B.3. Material percentages across different lightweighting materials.

Lightweighting Material	Material	Material Percentage Low Intensity	Material Percentage High Intensity
Advanced High-Strength Steel	Aluminum (AL)	0.50%	1.00%
	Carbon (C)	0.10%	0.30%
	Manganese (Mn)	1.00%	2.00%
	Silicon (Si)	0.50%	1.00%
Aluminum cast	Aluminum	90.10%	92.33%
	Magnesium (Mg)	0.20%	0.45%
	Manganese	0.18%	0.35%
	Silicon	6.50%	7.50%
	Titanium (Ti)	0.13%	0.25%
Aluminum wrought	Aluminum	95.00%	96.70%
	Magnesium	2.50%	3.40%
	Manganese	0.13%	0.31%
	Silicon	0.25%	0.46%
High-Strength Steel	Manganese	1.35%	1.65%
	Silicon	0.15%	0.40%
Magnesium alloy	Aluminum	8.30%	9.70%
	Magnesium	88.60%	91.10%

Lightweighting Material	Material	Material Percentage Low Intensity	Material Percentage High Intensity
	Manganese	0.15%	0.50%
	Silicon	0.05%	0.10%

B1.5 Batteries in Electric Vehicles

B1.5.1 Market Share

Lithium-ion batteries are assumed to make up 100% of new EV and PHEV batteries over this period. Alternative battery types such as Na-ion batteries are considered as possible substitution options, but are not expected to be a significant share of the market by 2035, and are not included in the penetration scenarios.

B1.5.2 Material Intensity

Battery capacities per vehicle are shown in Table B.4. The low ends of these ranges are based on 2019 average kWh per vehicle from Xu et al. (2020). The high end is based on the assumed continuation of the trend toward longer ranges in EVs; the average range for new BEVs increased from 211 km in 2015 to 338 in 2020 (IEA, 2021d). In the high scenario, this trend continues, leading to a 50% increase in battery energy per vehicle relative to 2019 averages. In the low scenario, this trend toward increasing range is offset through efficiency improvements, leaving battery energy per vehicle at 2019 levels.

Table B.4. Battery energy by vehicle type (kWh/vehicle) (IEA, 2021d; Xu et al., 2020).

Vehicle Types	BEV		PHEV	
	Low	High	Low	High
LDV	72	107	11	17
HDV	150	225	24	36

The share of different types of lithium-ion (li-ion) battery are based on scenarios from Xu et al (2020) and include a high lithium-ion phosphate (LFP) adoption scenario with 60% of electric vehicles batteries being LFP, and a high nickel-manganese-cobalt (NMC) adoption scenario with 97% of vehicle batteries being NMC or nickel-cobalt-aluminum (NCA). Material intensities for different types of battery are shown in Table B.5 (ANL, 2023).

Table B.5. Material intensities for different types of battery.

Material Intensity (kg/kWh)	NMC111	NMC532	NMC622	NMC811	NCA	LFP	LMO[a]
Li	0.12	0.11	0.10	0.09	0.10	0.09	0.10
Ni	0.32	0.44	0.52	0.62	0.66	-	-
Co	0.32	0.18	0.17	0.08	0.12	-	-
Mn	0.3	0.25	0.16	0.07	-	-	1.27

Material Intensity (kg/kWh)	NMC111	NMC532	NMC622	NMC811	NCA	LFP	LMO[a]
Total graphite, if no silicon is used	0.86	0.87	0.87	0.87	0.87	0.96	0.80
Al	0.57	0.56	0.56	0.54	0.56	0.71	0.67
F	0.06	0.06	0.06	0.05	0.06	0.08	0.08
P	0.01	0.01	0.01	0.01	0.01	0.4	0.01

[a] LMO = lithium-ion manganese oxide.

These material intensities are combined with the market share scenarios for the different cathode types to obtain a low and a high combined material intensity for each material, based on weighted average material intensities for the year and scenario that leads to the lowest and highest average material intensities. For example, the low material intensity for nickel is based on the 2035 cathode distribution in the high LFP scenario, while the high material intensity is based on the 2035 cathode distribution in the high NMC scenario (Table B.6). In addition, natural graphite is assumed to make up 29%–53% of total graphite used (Pillot, 2021; Els, 2022), and silicon may be substituted for up to 15% of the graphite (Eshetu et al., 2021; Wang et al., 2020).

Table B.6. Material intensities per battery.

Material Intensity (kg/kWh)	Low	High
Li	0.09	0.10
Ni	0.24	0.59
Co	0.05	0.14
Mn	0.03	0.08
Natural Graphite	0.13	0.49
Si	0	0.08
Al	0.55	0.65
F	0.06	0.07
P	0.02	0.24

B1.6 Magnets in Electric Vehicles

B1.6.1 Market Share

The share of electric vehicles that use neodymium-iron-boron (NdFeB) magnets is estimated to be between 50% in the low case and 100% in the high case. The current share of electric vehicles using NdFeB magnet motors is estimated to be 98%; however, Tesla has announced a plan to switch away from rare earth magnets in future models (Adamas, 2023). Tesla's 2022 share of global BEV and PHEV sales is about 13.6%, but its share of the EV magnet market is likely 25%–30% given that its motors have more than twice the power of average vehicles modeled (Kane, 2022; Lambert, 2020). It is assumed that in a low market share scenario, some additional car manufacturers could follow Tesla's lead and move away from rare earth permanent magnet (REPM) motors. However, the share of the market switching away from REPM motors is not likely to exceed 50%, because they are still the most efficient and reliable motor available; and Chinese car manufacturers are unlikely to shift away from REPM motors given that China is the primary supplier of rare earth metals.

Table B.7 shows motor power by vehicle type.

B1.6.2 Material Intensity

B1.6.2.1 Magnet Mass

Table B.7. Motor power by vehicle type (kW/vehicle) (Cullen et al., 2021).

Vehicle	BEVs	PHEVs	FCEVs	HEVs
Cars	100	100	100	50
Vans	150	150	150	75
Buses	200	200	200	100
Trucks	300	300	300	150

Magnet mass per kW of motor power is estimated to be 21.6 g/kW based on estimates of magnet mass and power for the 2009 Toyota Prius (Yano et al., 2016; Toyota, 2014).

High values for Nd, Pr, and Dy material intensities per magnet in Table B.8 are estimated using median values taken from analyses of electric vehicle magnets (Yano et al., 2016; Rasheed et al., 2021). Fe and B intensities are based on median values from studies of multiple magnet types, since they do not vary much by grade (Rasheed et al., 2021). Ga shares are based on the composition of N42SH magnets. Tb shares are based on the Tb-to-Dy ratio from Adamas (Adamas, 2023). The low material intensities for Nd and Pr are based on targets of 33% reductions in Nd/Pr use (Lacal-Arantegui, 2015). The low values for Dy, Tb, and Ga are estimated based on the adoption of technology such as grain boundary diffusion, which is estimated to reduce needed Dy in high-temperature applications such as vehicles by 70% (BJMT/IDEAL, 2023).

Material per Magnet

Table B.8. Low and high material intensities in magnets (BJMT/IDEAL, n.d.; Rasheed et al., 2021; Yano et al., 2016).

Material	Low intensity	High intensity
Nd	14.3%	21.5%
Pr	2.1%	3.1%
Dy	1.9%	6.3%
Fe	62.4%	62.4%
B	0.9%	0.9%

Material	Low intensity	High intensity
Ga	0.2%	0.7%
Tb	0.2%	0.8%

B1.7 Fuel Cells in Vehicles

B1.7.1 Market Share

Global FCEV sales for 2020–2021 assume data reported in Samsun et al. (2022). IEA forecasts for FCEV vehicle sales in the NZE scenario are used (see Section 4.2.1) (Table B.9). However, while the IEA reports the forecasts for BEV and PHEV global vehicle sales for the STEPS and NZE scenarios, FCEV sales forecasts are not reported for the STEPS scenario. In lieu of such forecasts, estimates for this study were derived from IEA STEPS forecasts for transportation hydrogen demand in 2030 and 2040. These forecasts were used to estimate yearly global sales of FCEVs (2022–2035) based on stock turnover estimates, forecasts of vehicle miles traveled, and fuel economy estimates by vehicle type from Argonne's VISION 2022 model (Argonne, 2022). Linear trajectories were assumed for FCEV sales growth in between the years for which data were available.

Table B.9. Low and high FCEV scenarios by vehicle type. (Source: Samsun et al., 2022.)

FCEV Type	Low Penetration (STEPS) (thousand vehicles)	High Penetration (NZE) (thousand vehicles)
Cars	320	7,593
Vans	17	410
Buses	19	448
Trucks	60	1,439

B1.7.2 Material Intensity

Platinum and graphite material intensity estimates were derived from high and low contents (kg/vehicle) by vehicle type. The values for high material content (Badgett et al., 2022) assumed are 0.182 kg/MW platinum and 574 kg/MW graphite. The low material platinum content assumed is 0.1 kg/MW (Reverdiau et al., 2021). No reduction in graphite content is assumed.

The estimated values for platinum and graphite content were then applied to average power estimates for FCEV cars, vans, buses, and trucks (Tables B.10 and B.11). These estimates were derived from ranges reported in (Cullen et al., 2021). Specifically, power estimates assumed are: 100 kW for cars, 150 kW for vans, 186 kW for buses, and 300 kW for trucks.

Table B.10. Platinum material intensities in FCEV by vehicle type and penetration.

FCEV Type	Low Intensity (STEPS) (kg Pt/vehicle)	High Intensity (NZE) (kg Pt/vehicle)
Cars	0.010	0.018
Vans	0.015	0.027
Buses	0.019	0.034
Trucks	0.030	0.055

Table B.11. Graphite material intensities in FCEV by vehicle type and penetration.

FCEV Type	Low Intensity (STEPS) (kg graphite/vehicle)	High Intensity (NZE) (kg graphite/vehicle)
Cars	57	57
Vans	86	86
Buses	107	107
Trucks	172	172

B2. Stationary Storage

B2.1 Market Share

Lithium-ion batteries are estimated to make up 76% of the battery stationary storage market, followed by sodium sulfur (NaS) at 9%, lead acid at 6%, and flow batteries at 3% (Global Market Insights, 2022); and it is assumed that nickel metal hydride (NiMH) batteries account for the remaining 6% of market share. IEA (2020) data show lithium-ion batteries accounting for more than 95% of all cathode chemistry, similar to the case for EVs. By 2040, IEA projects that lithium-ion batteries will still dominate the stationary storage market, with LFP chemistries accounting for 50%–70% and NMCs for 20%–40% (IEA, 2021). Vanadium flow batteries are expected to become commercially available by 2030 and to capture a wider market in the ensuing decade, up to 10%–15% by 2040 (IEA, 2021). Because this study projects out to 2035, it does not use the 2040 projections reflecting growth in flow battery market share.

B2.2 Material Intensity

The share of different types of li-ion battery are based on scenarios from Xu et al. (2020) and include a high LFP adoption scenario with 60% of electric vehicles batteries having the LFP chemistry and a high NMC adoption scenario with 97% of vehicle batteries having the NMC or NCA chemistry. These scenarios were designed for electric vehicles but are used here for stationary storage as well due to the lack of available scenarios for adoption of different cathode chemistries for stationary storage. The high LFP scenario is likely to more accurately capture the stationary storage market than the high NMC scenario. Material intensities for different types of Li-ion battery are shown in Table B.12 (ANL, 2023).

Table B.12. Material intensities for different types of Li-ion batteries.

Material Intensity (kg/kWh)	NMC111	NMC532	NMC622	NMC811	NCA	LFP	LMO
Li	0.12	0.11	0.10	0.09	0.10	0.09	0.10
Ni	0.32	0.44	0.52	0.62	0.66	-	-
Co	0.32	0.18	0.17	0.08	0.12	-	-
Mn	0.3	0.25	0.16	0.07	-	-	1.27
Total graphite, if no silicon is used	0.86	0.87	0.87	0.87	0.87	0.96	0.80
Al	0.57	0.56	0.56	0.54	0.56	0.71	0.67
F	0.06	0.06	0.06	0.05	0.06	0.08	0.08
P	0.01	0.01	0.01	0.01	0.01	0.4	0.01

These material intensities are combined with the market share scenarios for the different cathode types to obtain a low and high combined material intensity for each material, based on weighted average material intensities for the year and scenario that leads to the lowest and highest average material intensities (Table B.13). For example, the low material intensity for nickel is based on the 2035 cathode distribution in the high LFP scenario, while the high material intensity is based on the 2035 cathode distribution in the high NMC scenario. In addition, natural graphite is assumed to make up 29%–53% of total graphite used (Pillot, 2021; Els, 2022), and silicon may be substituted for up to 15% of the graphite (Eshetu et al., 2021; Wang et al., 2020).

Table B.13 Material intensities per Li-ion battery.

Material Intensity (kg/kWh)	Low	High
Li	0.09	0.10
Ni	0.24	0.59
Co	0.05	0.14
Mn	0.03	0.08
Natural Graphite	0.13	0.49
Si	0	0.08
Al	0.55	0.65
F	0.06	0.07
P	0.02	0.24

Material intensities for NiMH and NaS batteries are based on values reported in literature (Iloeje et al., 2022; Holmberg, 2017; Rodrigues and Mansur, 2010; Landi et al., 2022). For NiMH batteries, the maximum reported value for each material is adopted for the high-intensity scenario, and the minimum value for the low-intensity scenario. For NaS batteries, material intensity data are scarce. The high and low intensities are thus estimated using the literature value as the average, while assuming the same distribution as in the NiMH data. Table B.14 summarizes the material intensities for these two types of batteries.

Table B.14 NiMH and NaS critical material intensities.

Battery Type	Material	Low Intensity (kg/kWh)	High Intensity (kg/kWh)
NiMH	Ni	3.13	9.19
	Mn	0.10	0.50
	Co	0.21	0.76
	Al	0.04	2.50
NaS	Al	0.04	2.46

B3. Hydrogen Electrolyzers

B3.1 Market Share

Low and high penetration scenarios for electrolyzer technologies are based on the IEA STEPS and NZE hydrogen supply forecasts, respectively (Table B.15). The electrolyzer installations consider new construction only. The market shares of PEMEC and solid oxide electrolyzer cell (SOEC) are informed by the U.S. Department of Energy's (DOE's) EO 14017 *Water Electrolyzers and Fuel Cells Supply Chain* report (Badgett et al., 2022).

Table B.15. PEM Electrolyzer low and high penetration market shares.

	Low Penetration (STEPS)	High Penetration (NZE)
PEMEC demand in 2035 (% of electrolyzer market)	46%	46%
PEMEC installations (GW) in 2035	1.2	27
SOEC demand in 2035 (% of electrolyer market)	30%	30%
SOEC installations (GW) in 2035	0.8	17

B3.2 Material Intensity

For PEMEC, the high platinum, iridium, and titanium intensities are based on the EO 14017 report. The low values for platinum and iridium content are derived from the DOE Hydrogen and Fuel Cell Technologies Office technical targets for PEM electrolysis (Hydrogen and Fuel Cell Technologies Office, n.d.). The low intensity value for titanium content is based on the potential for replacing titanium bipolar plates and porous transfer layers with a thin film of titanium on a substrate (Keimel et al., 2021).

Considering the early developmental stage and many different chemistries under development for SOEC, only one chemistry is assumed, specifically the chemistry evaluated in the EO 14017 *Water Electrolyzers and Fuel Cells Supply Chain* report (Badgett et al., 2022) in Table B.16.

Table B.16. PEMEC and SOEC critical material intensities.

Electrolyzer Type	Material	Low Intensity (kg/MW)	High Intensity (kg/MW)
PEMEC	Pt	0.04	0.26
	Ir	0.06	0.45
	Ti	32	277
SOEC	La	74	74
	Sr	21	21
	Co	5	5
	Ni	1184	1184
	Y	138	138
	Zr	814	814
	Mn	25	25

B4. Photovoltaic Cells

B4.1 Market Share

Data from the International Renewable Energy Agency (IRENA) were used to estimate cadmium telluride (CdTe) solar baseline technology’s market share and thus to project yearly installation capacities (IRENA & PVPS, 2016). A 2% and 5% market share were maintained out to 2035 (SETO, 2023) to form the low and high penetration rates, respectively, for CdTe photovoltaic (PV). A low cadmium-indium-gallium-selenide (CIGS) demand scenario with 0% market share was used in light of the recent shutdown of the largest CIGS manufacturing plant in the world, which switched to producing silicon PV in 2021 (Bellini, 2021). A high of 2% market share for CIGS was used in keeping with historical market highs from 2010–2014 (Fraunhofer Institute for Solar Energy Systems, 2022). Silicon’s baseline projected market share of 87.7% was obtained from BCC research market reports (BCC Publishing Staff, 2022). High and low cases for silicon deviated from the current market share by an increase in 7% or a decrease by 5%. Thus, 7% was chosen because market capture greater than 95% did not seem realistic given CdTe’s current penetration level. A low of 5% was chosen to match the 2009 historic low of silicon market share (Feldman, Wu, & Margolis, 2021). All market shares for each solar technology were assumed to be constant in their respective demand scenarios. Table B.17 summarizes the low and high market shares for each technology used in the projections.

Table B.17. High and Low market percent capture for various solar technologies.

Solar PV Technology	Low Market Share	High Market Share
Si	82.7%	94.7%
CIGS	0%	5%
CdTe	2.0%	5.5%

It should be noted there is a significant uncertainty in any projections of future technology adoption rates in the solar PV market. For example, many industry experts in the past decade believed that silicon solar cells would be phased out with new technologies garnering larger market shares. However, the market share of silicon solar cells has remained high at more than 87% of the market share in 2021 due to its low cost (BCC Publishing Staff, 2022). Additionally, thin-film solar technologies, such as CIGS, were previously thought to be a promising future technology but have yet to capture more than 2.5% of the market (Fraunhofer Institute for Solar Energy Systems 2022). As of 2022, one of the last remaining CIGS manufacturers halted its production to produce silicon panels instead (Bellini, 2021; Solar Energy Technologies Office, 2023). Since its peak in 2013 at 2.5%, CIGS has experienced a continuous decline in market share (Fraunhofer Institute for Solar Energy Systems, 2022). CdTe has remained relatively stable at 4-5% market share but has also declined from its previous 7% peak market share in 2009 (Feldman et al., 2021). Future adoption rates of solar PV technologies will be highly dependent on multiple factors including cost, supply, demand, and incumbent technologies.

B4.2 Material Intensity

B4.2.1 Silicon Intensity in Silicon Solar Cells

The material intensity for silicon solar cells was calculated based on compositions of different panel types presented in Table 2 from Frischknecht et al. (2020). The total weight of a mono-Si and multi-Si panel was provided, as well as its material composition in terms of percentage, which was used to compute the Si content in the two different device types. The Si content of each device was then divided by its peak power rating to compute the material intensity. Potential future technological improvements, which may reduce the amount of material needed to fabricate a solar cell, were not estimated in this calculation. Using a yield of 60%–67%, Si content ranges from 2.9 to 3.4 kt/GW.

B4.2.2 Tellurium Intensity in CdTe

The two material intensity scenarios are derived from projections provided by the European Commission Joint Research Center (2020), where the material intensity of Te per GW of installed capacity is projected to fall to 20 t/GW in the low case while the high case is assumed to be 36 t/GW, which was confirmed through personal correspondence with First Solar as a suitable estimate for the current material intensity for CdTe thin-film solar.

For example, in the low material intensity case, if Te represents 53% of the 5.85 g/cm^3 of thin film included in a low thickness of 1.0 µm absorber layer with a 16.5% conversion efficiency, an 85% deposition efficiency, a 95% manufacturing yield, an 85% production scrap recovery, a 100% collection rate of rejected modules with a 97% rejected module material recovery rate and a 90% material refining efficiency, the material intensity for tellurium would be 20 t/GW of solar PV capacity (Nassar, Wilburn, & Goonan, 2016).

B4.2.3 Gallium Intensity in CIGS

The material intensity of gallium used in CIGS for the low and high case was 2 mt/GW and 11 mt/GW, respectively (Liang, Kleijn, Tukker, & van der Voet, 2022; Zimmermann & Gößling-Reisemann, 2014). These values were obtained by excluding the maximum extreme values provided by Zimmerman and Gößling-Reisemann and excluding the minimum and maximum extreme values by Liang, Kleijn et al. (2022). This was done to prevent these extreme values from overly impacting the analysis.

A raw material yield of 41% was utilized using a conjunction of yields such as a CIGS deposition yield of 45%, a CIGS fabrication yield of 92%, and a CIGS production yield of 100% (Song, Wang, Sen, & Liu, 2022).

B4.2.4 Indium Intensity in CIGS

The material intensity of indium used in CIGS for low and high cases was 9.8 t/GW and 23.1 t/GW, respectively (Zimmermann & Gößling-Reisemann, 2014). Other sources claimed a material intensity of 15.5 t/GW, which fell within the range of the first source (Fraunhofer Institute for Solar Energy Systems, 2022).

B5. Wind

B5.1 Market Share

Low and high market share assumptions for direct-drive (DD) and hybrid drive wind turbines are shown in Table B.18.

Table B.18. High and low market share assumptions for direct-drive and hybrid wind turbines.

Wind Farm Type	Turbine Design	Low Penetration %	High Penetration %
Onshore	Direct drive	6%	12%
	Hybrid	6.5%	25%
Offshore	Direct drive	50%	100%
	Hybrid	0%	0%

High values are calculated based on 30% of all turbines being DD or hybrid in 2020, growing to 50% in 2025 (GWEC, 2022). A total of 60% of these are assumed to be direct drive, and 40% are assumed to be hybrid (Serrano-Gonzales and Lacal-Arantegui, 2016). In the high scenario, all offshore turbines are assumed to be direct drive, with the remaining DD and hybrid turbines being onshore. Low values are based on an assumed 50% of direct drive and hybrid generators being replaced by ones that do not use rare earths, such as induction motors or superconducting magnets.

B5.2 Material Intensity

B5.2.1 Electrical Steel in Wind Turbines

The material intensity of electrical steel (ES) demand in wind turbines is obtained from OpenEI (n.d.). Onshore wind and offshore wind require 1500–5300 kg/MW and 2700–3600 kg/MW of electrical steel, respectively (OpenEI, n.d.).

B5.2.2 Copper in Wind Turbines

Copper (Cu) is indispensable to the appropriate functioning and efficiency of wind turbines (Copper Development Association, 2010). Cu needs for wind power depend on the turbine type: gearbox or direct drive, as well as projected deployment. Using the wind projections mentioned in the previous section, we consider the two most used gearbox wind turbine types, that is, the double-fed induction generators (DFIG) and permanent-magnet synchronous generator (PMSG). DFIGs require between about 2.4 ton/MW and 2.9 ton/MW, while PMSGs require about 8 ton/MW and 9.5 ton/MW (Copper Development Association, 2022b; IEA, 2021b). These ranges are used as high and low demands, multiplied by the IEA scenarios, the STEPS and NZE projecting wind trajectories.

B5.2.3 Magnets in Wind Turbines

Magnet sizes for direct drive and hybrid turbines are found to be 650 kg/MW and 200 kg/MW respectively, based on values from Imholte et al. (2018) and Arnold (n.d.), which were chosen for being median values from the range of values found in multiple sources (Habib et al., 2014; Hill et al., 2010; Arnold, n.d.; Lacal-Arantegui, 2015; Kumari et al., 2018; Imholte et al., 2018).

High values in Table B.19 for Nd, Pr, and Dy material intensities per magnet are estimated using median values taken from analyses of wind turbine magnets (Kumari et al., 2018; Imholte et al., 2018; Habib et al., 2014). Fe and B intensities are based on median values from studies of multiple magnet types, because they do not vary much by grade (Rasheed et al., 2021). Ga shares are based on the ratio of Ga to Dy in N42SH magnets, applied to the Dy level found in wind turbine magnets (Ormerod, 2023). Tb shares are based on the Tb-to-Dy ratio from Adamas (2023). The ratio to Dy is used, since Ga and Tb serve similar purposes to Dy and therefore are likely to be lower in wind turbines than in the higher-grade N42SH magnets typically used in EVs. The low material intensities for Nd and Pr (Table B.20) are based on targeted 33% reductions in NdPr per magnet (Lacal-Arantegui, 2015). The low value for Dy is estimated based on the adoption of technology such as grain boundary diffusion, which is estimated to reduce needed Dy in medium-temperature applications such as wind turbines by 100% (BJMT/IDEAL, 2023).

Table B.19. Low and high material intensity in wind turbine magnets (% magnet weight). (Sources: Kumari et al., 2018; Imholte et al., 2018; Habib et al., 2014; Rasheed et al., 2021; Ormerud, 2023; Adamas, 2023; Lacal-Arantegui, 2015; BJMT/IDEAL, 2023.)

Material	Low Intensity %	High Intensity %
Nd	18.2	27.2
Pr	3.3	4.9
Dy	0	1.2
Fe	62.4	62.4
B	0.9	0.9
Ga	0	0.13
Tb	0	0.15

Table B.20. Low and high material intensity in wind turbine magnets (kg/MW).

Turbine design	Material	Low Intensity (kg/MW)	High Intensity (kg/MW)
Direct drive	Nd	117.8	176.6
	Pr	21.3	31.9
	Dy	0.0	7.9
	Ga	0.0	0.8
	Tb	0.0	1.0
Hybrid	Nd	36.2	54.4
	Pr	6.6	9.8
	Dy	0.0	2.4
	Ga	0.0	0.3
	Tb	0.0	0.3

DOE recently conducted a study on material used in wind energy technologies, led by the National Renewable Energy Laboratory (NREL) (OpenEI, n.d.). The high end of the estimates in this report are similar to those in the scenario report, with the exception that we assume the same Nd/Pr ratio for land and offshore wind turbines. The fact that the numbers from Eberle et al. are closer to the high end of this report's ranges reflects the fact that the low material intensities are intended to capture potential future improvements (Table B.21).

Table B.21. Comparison of low and high material intensity in wind turbine magnets (kg/MW).

Wind Farm Type	Material	Material Intensity (kg/MW)	
		Eberle et. al.	2023 CMA Report
Onshore	Nd	40	10–29
	Pr	0.42	1.7–5.2
	Dy	1.9	0–1.3
	Tb	0.0	0–0.2
Offshore	Nd	105	59–177
	Pr	43	11–32
	Dy	6.6	0–7.9
	Tb	0.4	0–1.0

B6. Nuclear

B6.1 Market Share

B6.1.1 Moderators

A moderator in a nuclear reactor is a material like water, heavy water, or graphite that is used to slow down the neutrons in the reactor core from their high velocities (NRC, 2021). Moderator material selection varies by reactor design and technology. The 2021 market share, by reactor count, of moderators for operational reactors for graphite, water, and heavy water were 5.3%, 83.3%, and 10.8%, respectively (IAEA, 2021; World Nuclear Association, 2022b). The remainder of the market consists of fast neutron/breeder reactors (FNRs/FBRs), which do not utilize a moderator (World Nuclear Association, 2022b).

Calculation of natural graphite demand in nuclear reactors relied on computing the quantity of natural graphite required for moderators in different reactor designs. With only one currently operating high-temperature gas cooled reactor (HTGR), natural graphite demand is relatively low. To calculate projected natural graphite demand, a future HTGR market share was projected as a percentage of total projected nuclear capacity. The utilization of only HTGR reactors was a simplification performed due to uncertainty in reactor technology and deployment dates that are all likely too far in the future to accurately assess. Due to the high degree of uncertainty surrounding Generation IV (Gen-IV) reactor designs (HTGRs included), a maximum nuclear capacity of 2.5% by 2035 was assumed. This market share increased linearly from 0% in 2020 and was added to graphite demand from the only operating HTGR in the world.

B6.1.2 Fuels

The market for nuclear fuel is dominated by uranium-based fuels with nearly all fuels requiring zirconium-based alloys as a cladding material. A variety of different grades of enrichment of uranium nuclear fuel can be used in reactors depending on the reactor type. However, most pressurized water reactors (PWRs) require low-enriched uranium (LEU) fuel, which is typically enriched to 3%–5% U-235 concentrations (World Nuclear Association, 2021). Advanced reactor designs, Gen-IV technologies, typically require high-assay low-enriched uranium (HALEU) fuel, which is defined as U-235 concentrations between 5%–20%. The only current alternative from strictly uranium-based fuels is mixed oxide (MOX) fuel, which represents about 5% of the nuclear fuel market (World Nuclear Association, 2017). MOX fuel is composed of depleted uranium and plutonium. Depleted uranium is a by-product from the enrichment process from natural uranium to higher enrichment level fuels (World Nuclear Association, 2020). For the purposes of the calculations in this report, the market share of fuel types is indirectly accounted for by the variation in material intensity for uranium.

B6.2 Material Intensity

B6.2.1 Moderators

In a 1-GWe HTGR reactor in a pebble bed configuration, a range of 2400–3600 mt of graphite is required upon startup of the reactor (BCC Research, 2017; Next Source Materials, 2013). A range of 800–1200 mt of graphite is required for annual fuel loads to run the same 1-GWe reactor (BCC Research, 2017; Next Source Materials, 2013).

B6.2.2 Fuels

A material intensity of 159–190 mt of uranium/GWe was used for development of the low and high demand scenarios. These values were calculated from the World Nuclear Association’s *Nuclear Fuel Report* by using the reported uranium requirements and associated nuclear capacities (World Nuclear Association, 2022a). Additionally, this range accounts for potential MOX fuel usage in certain reactors, simplifying the usage of the market share of MOX fuel directly in the calculations.

B7. Electric Grid

B7.1 Material Intensity of Cu

The amount of Cu needed for the projected grid expansion is obtained directly from the IEA (2021b). This data provides the demand volume of Cu in the distribution and transmission systems. Information on transformers Cu content is also provided. Scenarios considered are STEPS and SDS. By 2035, it is estimated that a quantity of about 7 M tons and 9 M tons, respectively, in STEPS and SDS will be needed. Using projected capacity for the grid expansion in GW (EIA, 2021), the material intensity in mton per GW can be deduced. The ratios of Cu content to grid capacity for each year from 2020 to 2035 were averaged, amounting to about 28 kton per GW for STEPS and 32 kton per GW for SDS.

B7.2 Material Intensity of ES

Estimation of the ES content in the electric grid was derived using projection of grid network expansion. Using STEPS and the Announced Pledged Scenarios (APS), it is estimated that about 19M km and 20M km of lines (distribution and transmission) will be constructed, along with transformers and other needed equipment (IEA, 2020, 2022b). The ES content in transformers is found in the Fact.MR (2023) report, capturing quantities of the material in transformers needed in the transmission and distribution systems. Information on portable transformers (mainly used in the distribution system) is also used. The amount of ES needed per km is computed by the ratio of demand volume to additional distance of grid expansion on a yearly basis. For the STEPS and APS scenarios, the material intensity are approximately between 16 and 22 mton per km, and 14 and 20 mton per km, respectively. High and low values are the maximum and minimum ratio values, respectively, over the years from 2020 to 2035.

B8. LED Lighting

B8.1 Market Share

The market share of lighting for the purposes of this report can be divided into two segments: (1) light-emitting diode (LED) lighting and (2) other lighting sources. LED lighting market share projections were obtained from the U.S. DOE’s “Energy Savings Forecast of Solid State Lighting in General Illumination Applications” report (Elliott, Yamada, Penning, Schober, & Lee, 2019). The report projected LED installed stock market share to be 35% in 2020, 60% in 2025, 76% in 2030, and 84% in 2035 (Elliott et al., 2019). It is important to note that the values reported were for the U.S.; however, by assuming that the U.S. represents 20% of the LED lighting market, it is possible to convert the U.S. data to global data.

In order to calculate the gallium demand for LED lighting, the amount of LED lighting demand per year first needed to be calculated. Because data on LED lighting quantity were available as installed stock, it was necessary to convert these values to a yearly sales or demand quantity. To accomplish this, several steps needed to be taken. First, because the literature reported installed stock in incremental years of five, the installed stock was interpolated linearly between the reported data values. Next, a retirement value for installed stock needed to be developed to capture LED lighting leaving the market. This was done assuming a 10-year renovation cycle (Elliott et al., 2019) and a 20-year life span for LED lights (Lighting Electrical, n.d.), which together made up the retirement of the LED lighting installed stock each year. Last, the difference in installed stock from one year to the next could be computed, which, when combined with the retirement value, yielded the annual sales or demand of LED lighting.

B8.2 Material Intensity

A material intensity of 0.02–0.03 grams of gallium/LED lamp was utilized for the low and high demand scenarios, respectively (HSSMI, 2021). It should be noted that there are a variety of different gallium-containing compositions used to manufacture LEDs (see Section 2.8.3). However, no public data exist to decipher the market shares between different compositions, so only a single value for gallium material intensity was used.

Low and high raw material yields of 25%–50% were used based on information obtained from other applications' gallium-based semiconductor manufacturing processes (Song et al., 2022). A large amount of uncertainty surrounds the raw material yields for most semiconductor manufacturing processes due to a lack of public data and manufacturer confidentiality.

B9. Power Electronics

B9.1 Market Share

As discussed in Chapter 2, Si is dominating the power electronics market with more than 90% market share by value in 2022 (Chiu & Dogmus, 2022). It is projected that by 2027, Si will still dominate this market at 80% market share, allowing room for growth in silicon carbide (SiC) use. GaN market share will grow but at a much slower rate compared to SiC. Within the SiC market, 70% of the demand driver is the fast-growing EV market and is projected to reach 80% in 2027 (Chiu & Dogmus, 2022). Regarding the GaN market, the power supply for consumer, telecom/datacom, and industrial markets are the dominant applications for GaN with 88% market share by value in 2022 and projected to reach 80% in 2027. EV application for GaN accounts for only less than 3% market share currently but it is expected to grow to 11% in 2027.

For the purpose of calculating trajectories, high and low market growth rates of 0.9% and 4.4%, respectively (Rosina & Villamor, 2022) are used to calculate the low and high deployment scenarios. Market shares of SiC and GaN by wafer unit are used instead of by market value. The SiC market shares by wafer unit of 1.2% and 5.4%, respectively, were used to derive low and high penetration (Ayari & Chiu, 2022; Chiu & Dogmus, 2022; Rosina & Villamor, 2022). GaN market shares of 0.23% and 2.91%, respectively, were used to calculate GaN trajectories (Ayari & Chiu, 2022; Chiu & Dogmus, 2022; Rosina & Villamor, 2022).

B9.2 Material Intensity

GaN is fabricated using epitaxial growth technology. The heteroepitaxial growth or coating of GaN is performed on a carrier substrate made of a single crystal material such as sapphire, silicon, silicon carbide, or GaN. The carrier substrates are manufactured in long logs or very thin cylinder-shaped slices, known as wafers. During the coating process, gases and metals react with the substrate material under controlled conditions and high temperatures, creating thin layers of GaN on a wafer. The layering technique allows use of the current silicon manufacturing infrastructure, reducing the cost of building new facilities for specialized GaN semiconductor production. There has been development of 4-, 6-, and 8-inch diameter silicon wafers for GaN—on-Si and GaN—on-sapphire. GaN has a density of 6.15 g/cm^3, of which 83.27% is Ga on a weight basis (Chemical Aid, n.d.). Considering the GaN density and weight percentage of Ga, the material intensity for Ga is 5.12 g/cm^3 of GaN.

Silicon and synthetic graphite are the raw material needed for compositing SiC wafer. Graphite needs to be purified before going into the wafer manufacturing process. As for silicon, Section 2.2 discusses it in detail, where silica (SiO_2) is used for SiC composition. According to the Power SiC 2022 Market and Technology report by Yole Development (Chiu & Dogmus, 2022), the manufacturing losses of SiC, from powder to wafer to device, is quite high. Only 50% of the raw material powder can be transferred to wafer, and 30%–50% of a wafer can be converted to a SiC device. In terms of material intensity, SiC's material intensity is 19.9 g–28.4 g per 6-inch wafer unit, where the high/low intensity is based on wafer dimension difference (e.g., 350 um or

500 um thickness for a 6-inch wafer), and with a density of 3.22 g/cm^3 considering the manufacturing losses stated above.

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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 is an overview of material scores by alphabetical order.

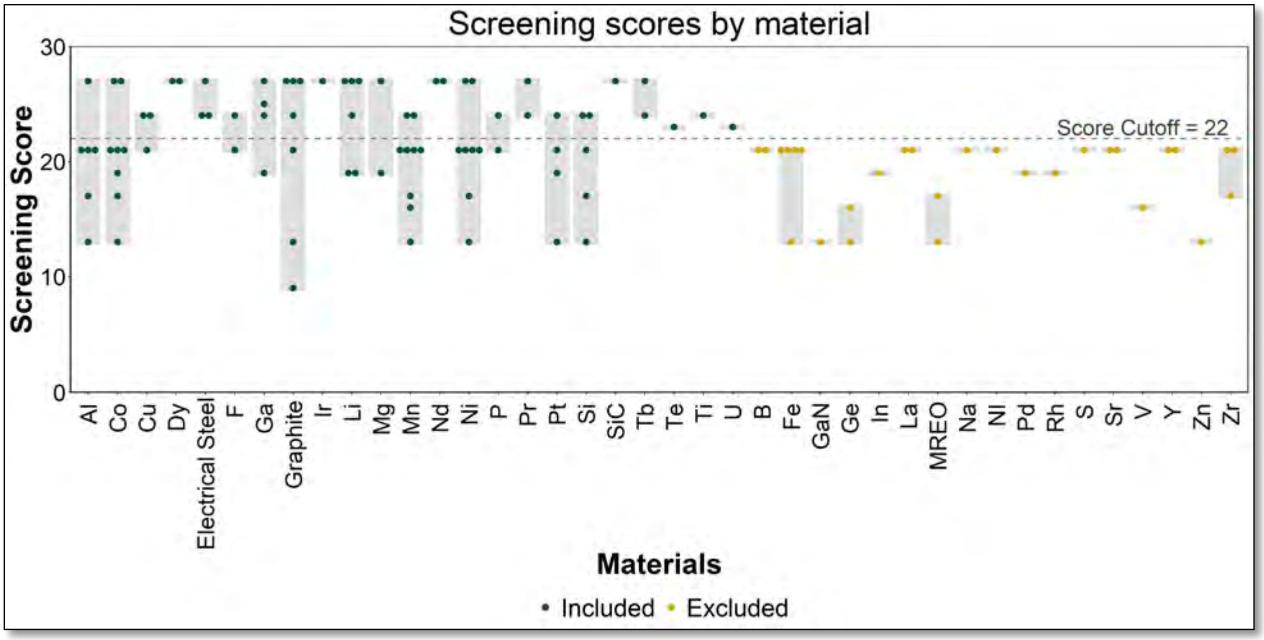

Figure C.1. Screening scores of candidate materials by alphabetical order.

Table C.1 organizes materials by technology group.

Table C.1. 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 and converters	Cu	3	3	1	21
	Ge	3	1	1	13
	Ni	3	3	1	21
Transformers	Electrical steel	3	3	3	27
Motors and 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
	Tb	3	3	2	24
	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

Technology/ Component	Material	Technology Importance in 2030 (x2)	Material/ Component Specific Technology Adoption in 2030 (x4)	Additional Material Demand Share (x3)	Total Score
	P	3	3	1	21
Vehicles – wiring	Cu	3	3	2	24
Vehicles – magnets	Nd	3	3	3	27
	Pr	3	3	3	27
	Dy	3	3	3	27
	Tb	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
	Pt	3	1	1	13

Technology/ Component	Material	Technology Importance in 2030 (x2)	Material/ Component Specific Technology Adoption in 2030 (x4)	Additional Material Demand Share (x3)	Total Score
Fuel cell electric vehicles	Graphite	3	1	2	16
H_2 electrolyzers – PEM	Pt	3	3	2	24
	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

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