INTERNATIONAL ENERGY FORUM

FUTURE MINERALS FORUM

Critical Minerals Outlooks Comparison

A Report by the International Energy Forum and The Payne Institute of Public Policy at the Colorado School of Mines

August 2023

The Payne Institute for Public Policy

COLORADO SCHOOL OF MINES

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About the International Energy Forum

The International Energy Forum (IEF) is the world's largest international organization of energy ministers from 71 countries and includes both producing and consuming nations. The IEF has a broad mandate to examine all energy issues including oil and gas, clean and renewable energy, sustainability, energy transitions and new technologies, data transparency, and energy access. Through the Forum and its associated events, officials, industry executives, and other experts engage in a dialogue of increasing importance to global energy security and sustainability.

About The Payne Institute

The mission of the Payne Institute at Colorado School of Mines is to provide world-class scientific insights, helping to inform and shape public policy on earth resources, energy, and environment. The Institute was established with an endowment from Jim and Arlene Payne, and seeks to link the strong scientific and engineering research and expertise at Mines with issues related to public policy and national security. The Payne Institute extends to public policy Mines' conviction that energy and the environment must – and can – fruitfully coexist.

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Introduction

Historically, the energy sector constituted only a minor part of critical minerals supply chains and markets. However, with the acceleration of energy transitions, clean energy technologies have rapidly emerged as the segment with the fastest growth in demand.

This has captured public attention globally, and created various trade, market, and geopolitical issues. As a result, numerous analytical scenarios have been produced to better understand this rapidly changing and complex landscape.

In a future trajectory aligned with climate goals, the proportion of total minerals demand accounted for by clean energy technologies will rise significantly over the forthcoming two decades. Electric vehicles (EVs) and battery storage technologies have already superseded consumer electronics to become the largest consumers of lithium, and they are projected to surpass stainless steel to become the primary end users of nickel by 2040, and battery anodes share of graphite demand has increased 250% since 2018.

As a result, several quantitative demand models have been developed to help understand the scale of growth, and whether material shortages will become an obstacle to the deployment of clean energy technologies.

This report is a non-comprehensive meta-analysis of 11 publicly available reports which include various assumptions for energy and technology scenarios, and their resulting critical mineral requirements. This exercise is meant to highlight key insights for critical minerals decisionmakers. The reports are from eight agencies and organizations across different geographies, spanning from 2019 to 2023.

- **International Renewable Energy Agency (IRENA)**
  - *World Energy Transitions Outlook, 2023*
  - *Geopolitics of the Energy Transition, 2023*
  - *Critical Minerals for the Energy Transition, 2021*
- **International Energy Agency (IEA)**
  - *The Role of Critical Minerals in Clean Energy Transitions, 2022*
  - *Critical Minerals Market Review, 2023*
- **World Bank**
  - *Minerals for Climate Action, 2020*
- **Institute for Sustainable Future (ISF)**
  - *The Role of Critical Minerals in Clean Energy Transitions, 2019*
- **McKinsey & Company**
  - *The Future of Critical Minerals in the Net-Zero Transition, 2021*
- **Catholic University of Luven (KU Luven)**
  - *Metals for Clean Energy: Pathways to Solving Europe’s Raw Materials Challenge, 2022*
- **Energy Transitions Commission (ETC)**
  - *Mineral and Resource Requirements for the Energy Transition, 2023*
- **German Mineral Resources Agency (DERA)**
  - *Raw Materials for Emerging Technologies, 2021*

All 11 reports considered concur on the increasing demand for minerals and their central role in the energy transition. However, across the 11 reports, 28 different minerals and metals are mentioned, with sufficient data to compare only eight: aluminum, cobalt, copper, graphite, lithium, neodymium, nickel, and silver.

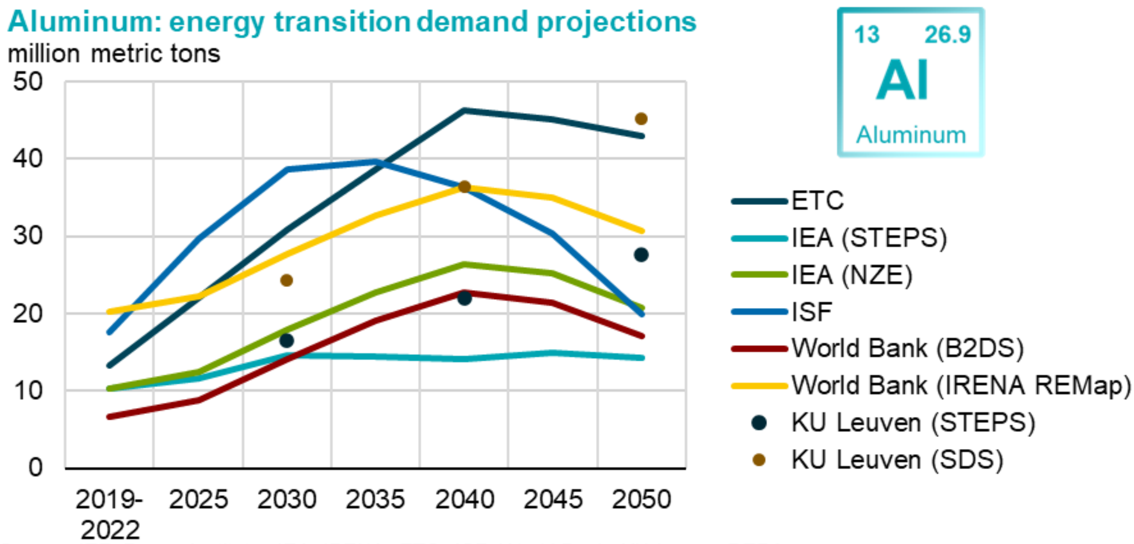
These demand projections are inherently subject to large variations. Disparities in their specific mineral demand projections reflect the different types of energy scenarios chosen, the mix of technologies deployed, assumptions on resource intensity, technology developments, and recycling rates.

While outside the scope of this report, the supply side also presents considerable challenges to long-term forecasts that merit additional study and discussion. Many of the reports surveyed highlighted the risks to their projections from supply side risks, but only a few incorporated supply forecasts alongside their demand projections. All reports surveyed noted the importance of responsible sourcing, supply chain transparency, recycling, and improved mining and processing efficiency.

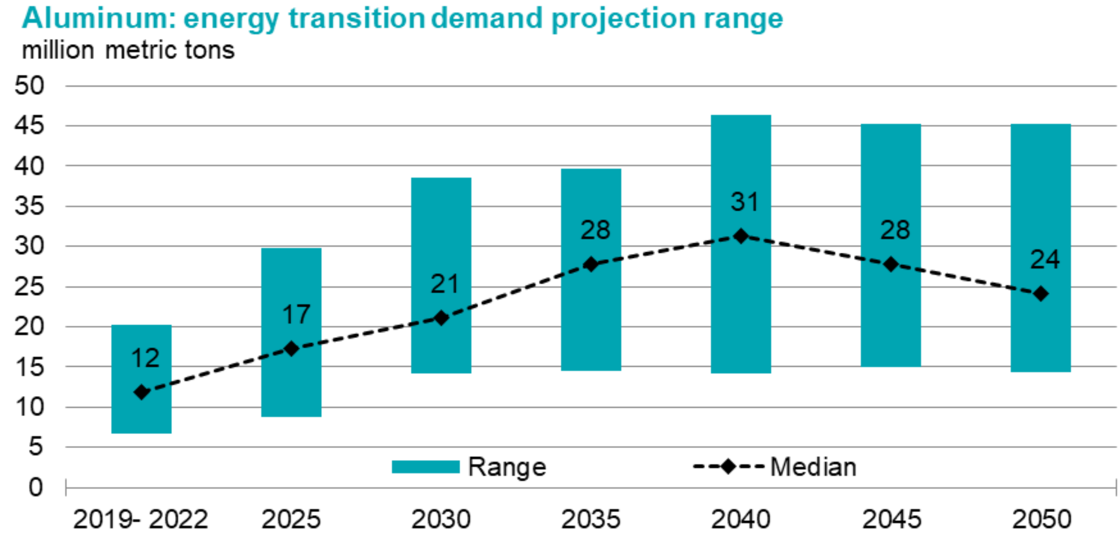
Understanding the potential mineral demands associated with the clean energy transition is crucial for policymakers, mineral producers, renewable energy developers, and civil society organizations to unlock investment, set achievable climate policies, and gain public acceptance of new mines.

Key Findings

Aluminum



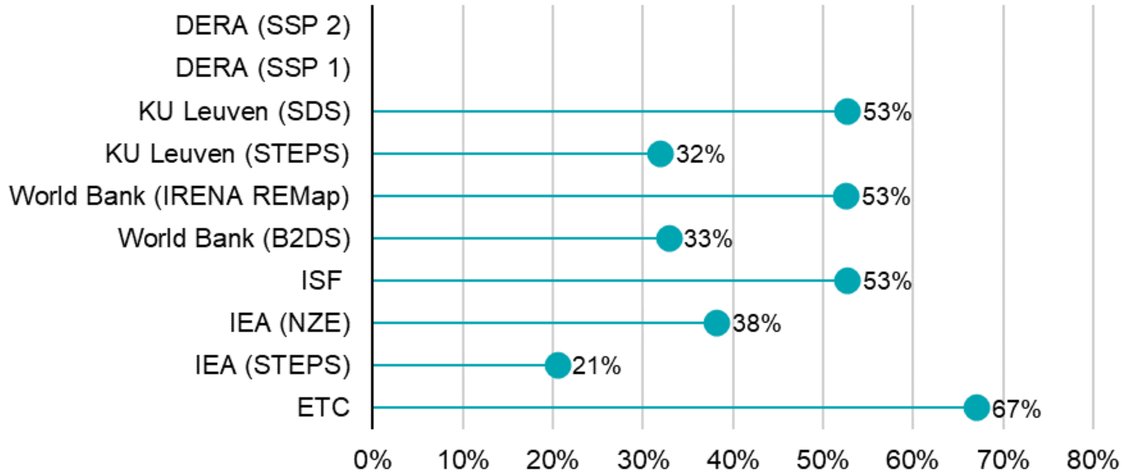
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA



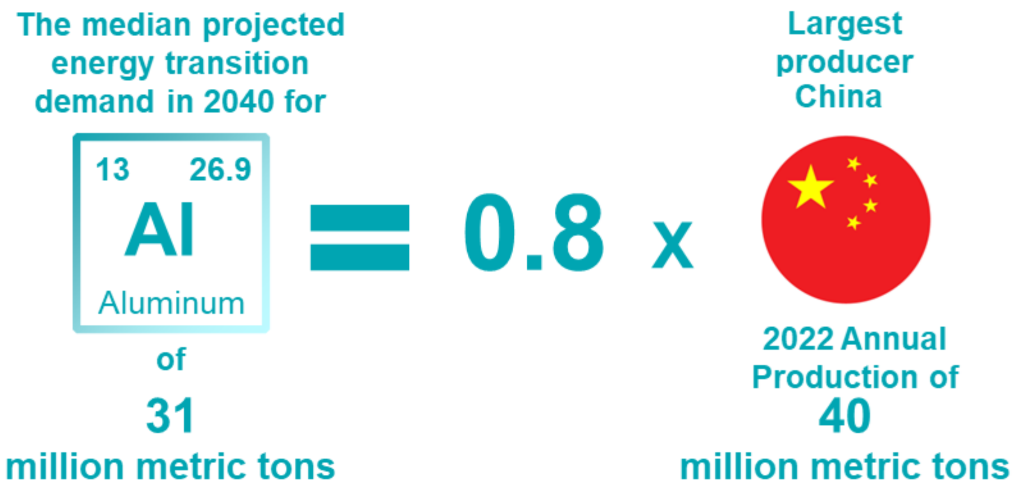
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Aluminum: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



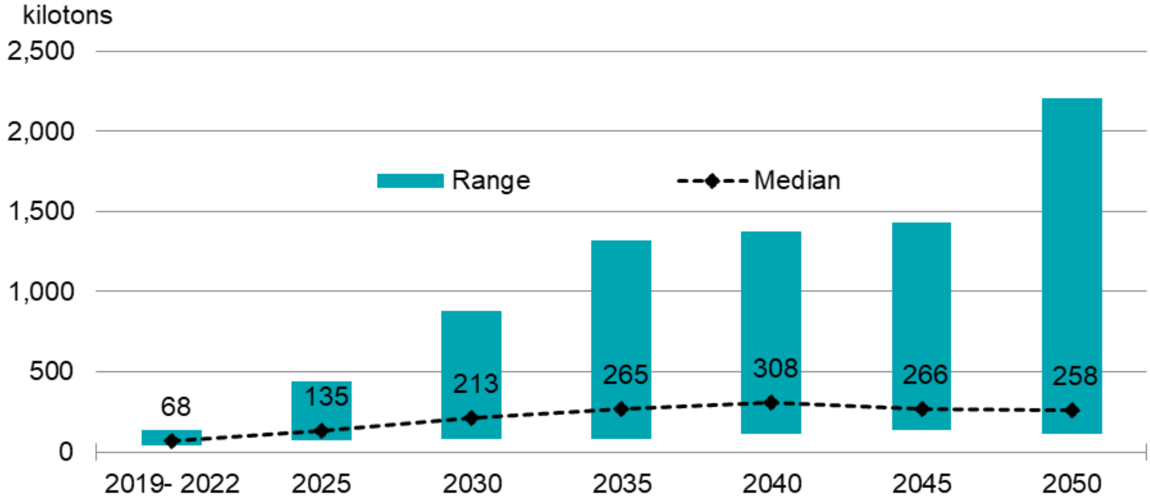
Note: 2022 World Smelter Production (primary)
Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA



Note: Primary aluminum production from smelters, multiples not exact due to rounding
Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

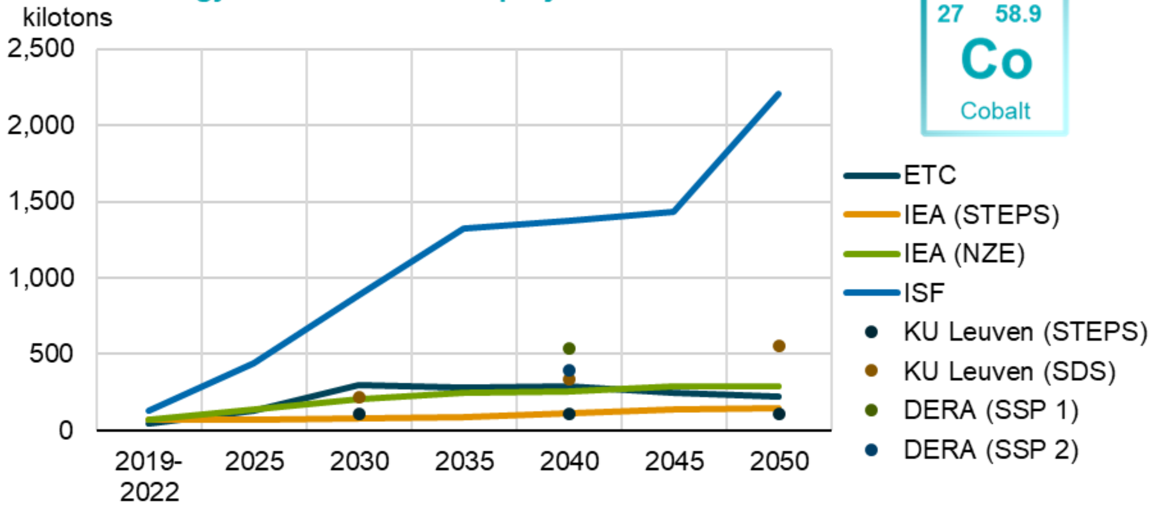
Cobalt

Cobalt: energy transition demand projection range



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

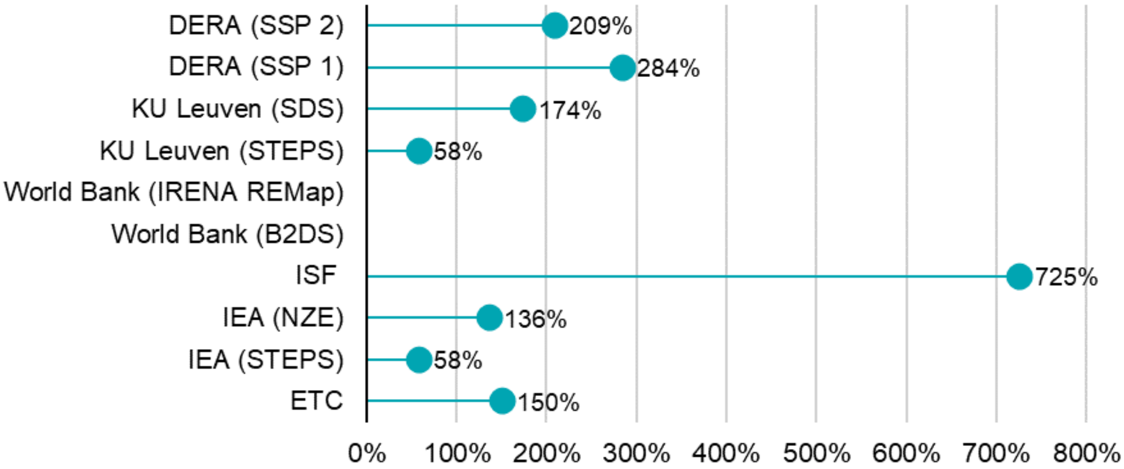
Cobalt: energy transition demand projections



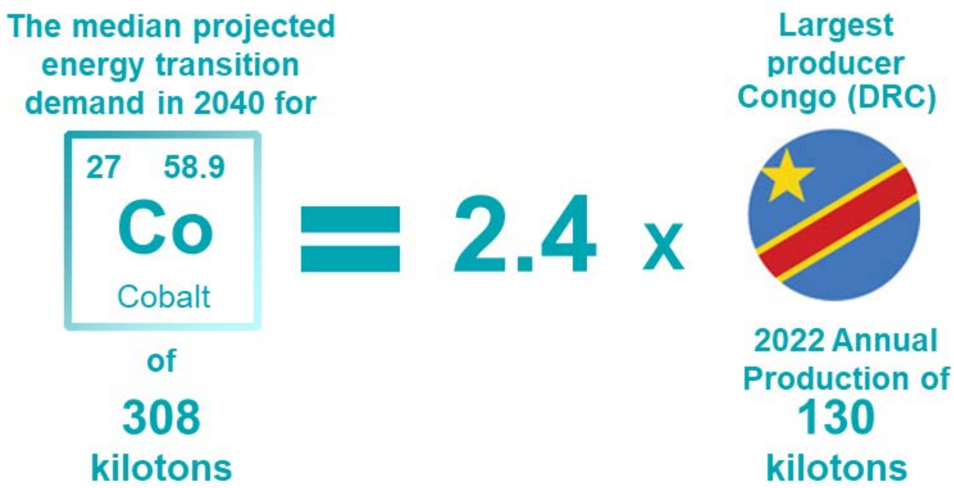
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Cobalt: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



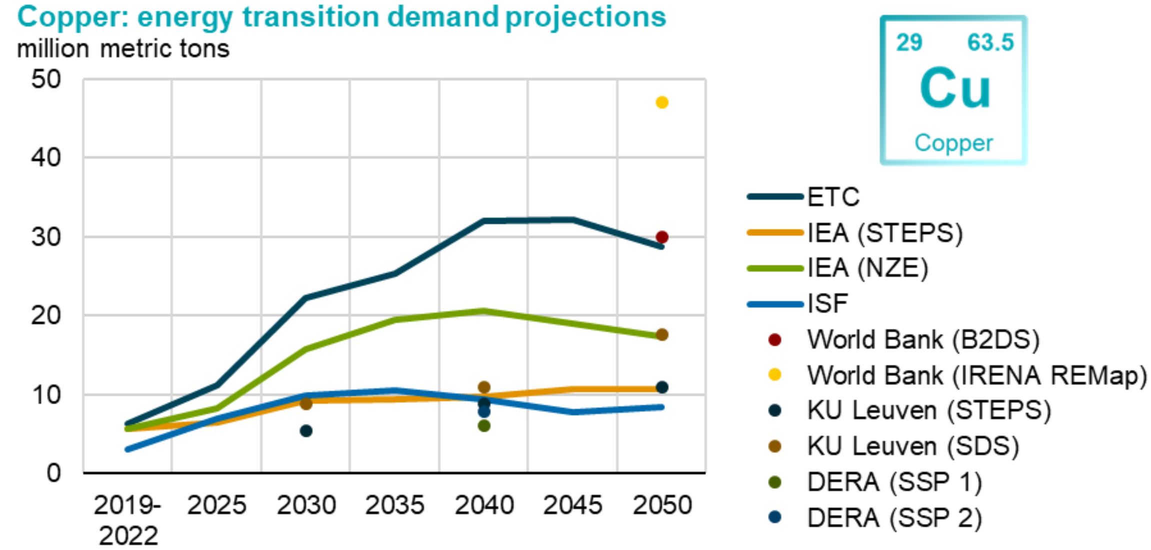
Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA



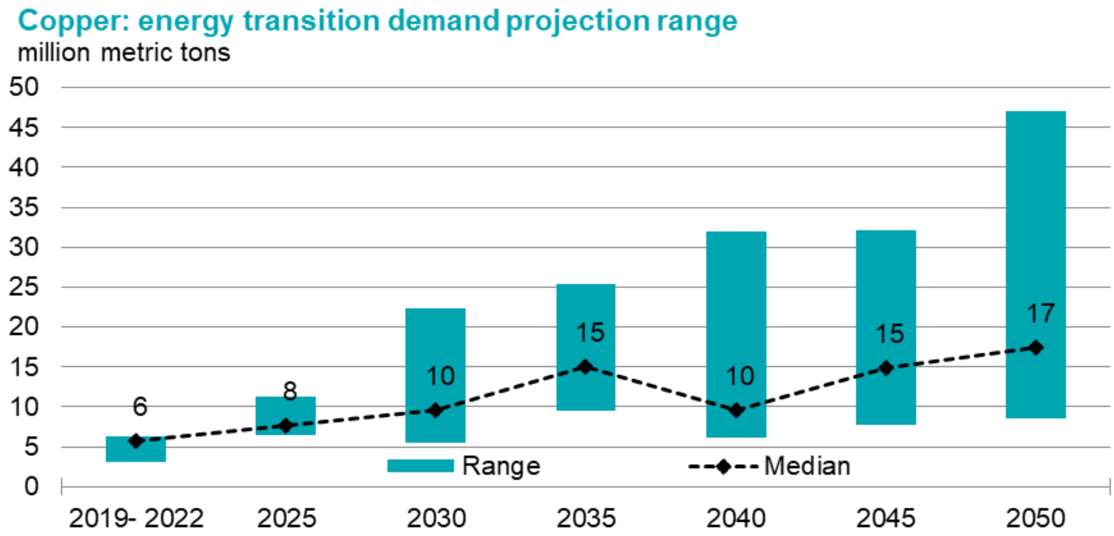
Note: Multiples not exact due to rounding

Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Copper



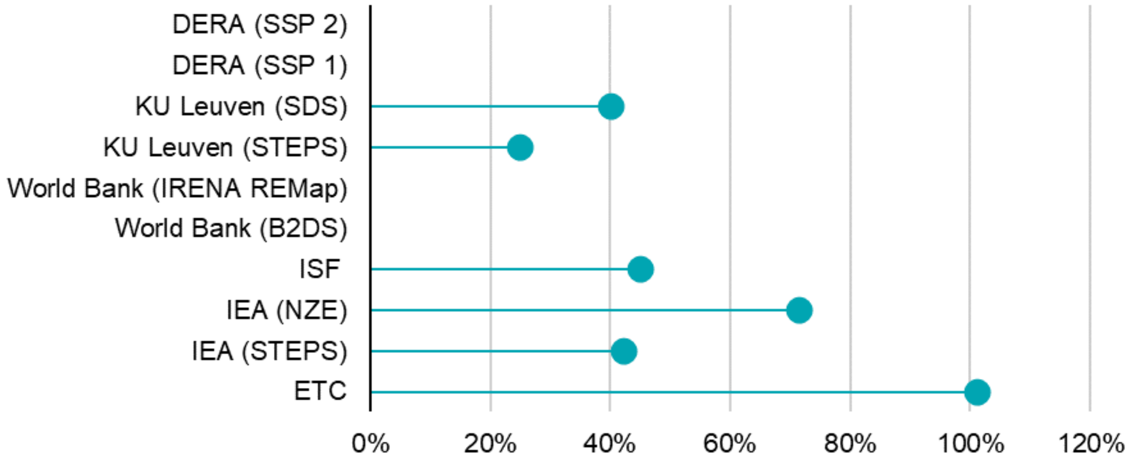
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA



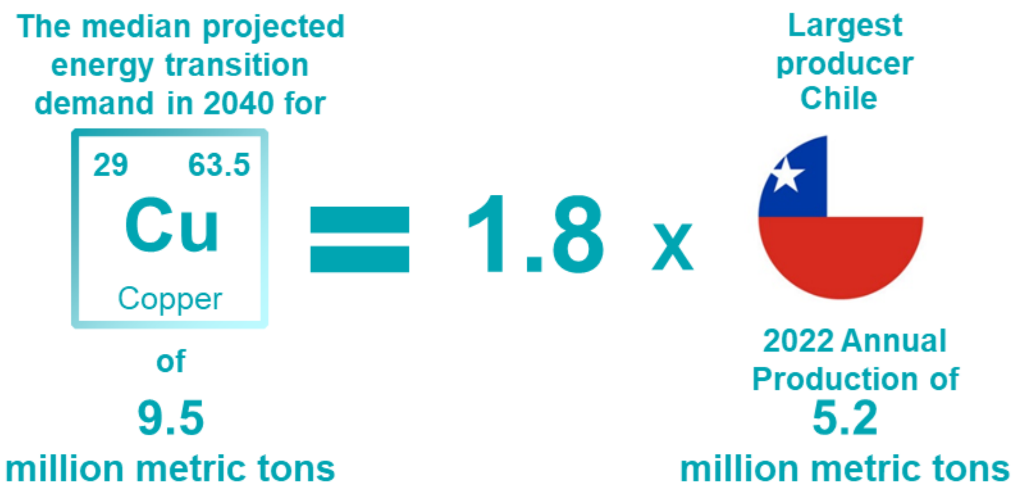
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Copper: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

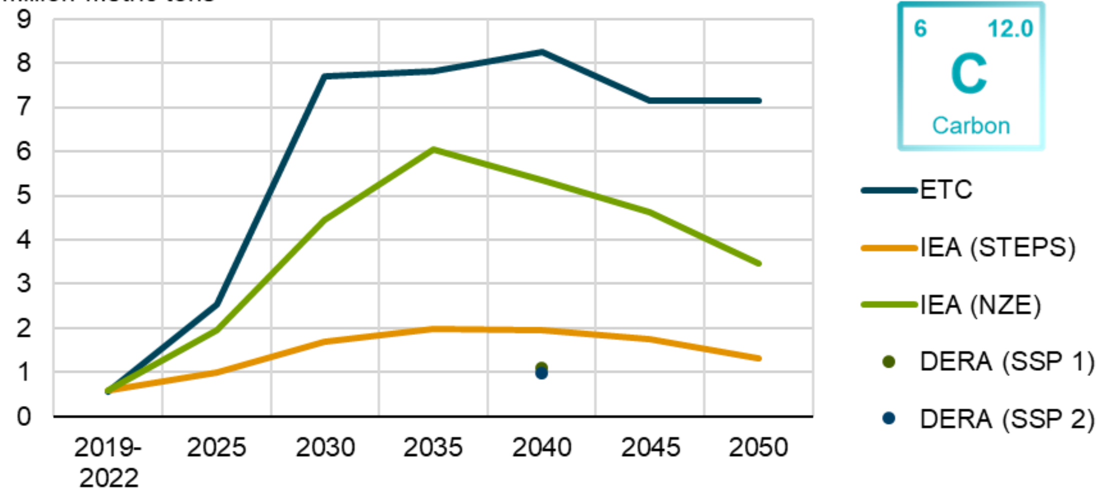


Note: Multiples not exact due to rounding
Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Graphite

Graphite: energy transition demand projections

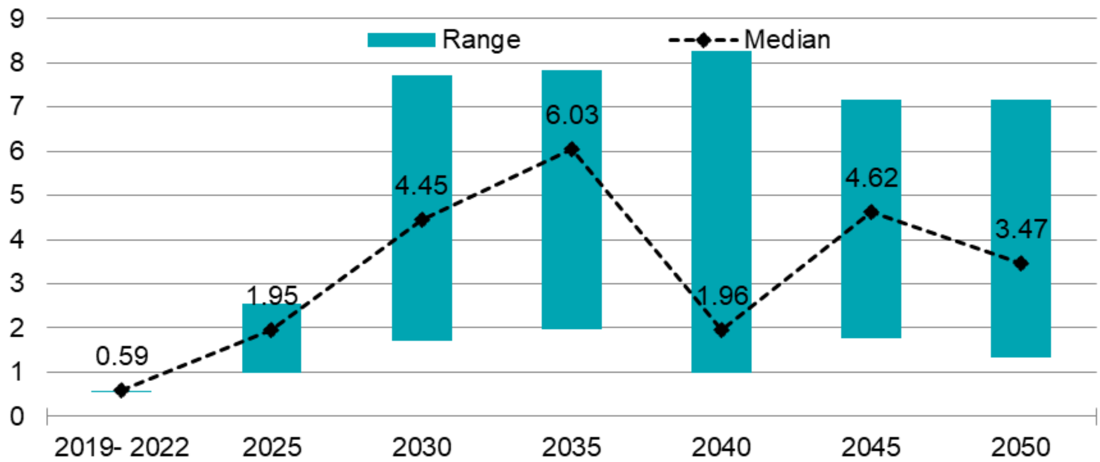
million metric tons



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Graphite: energy transition demand projection range

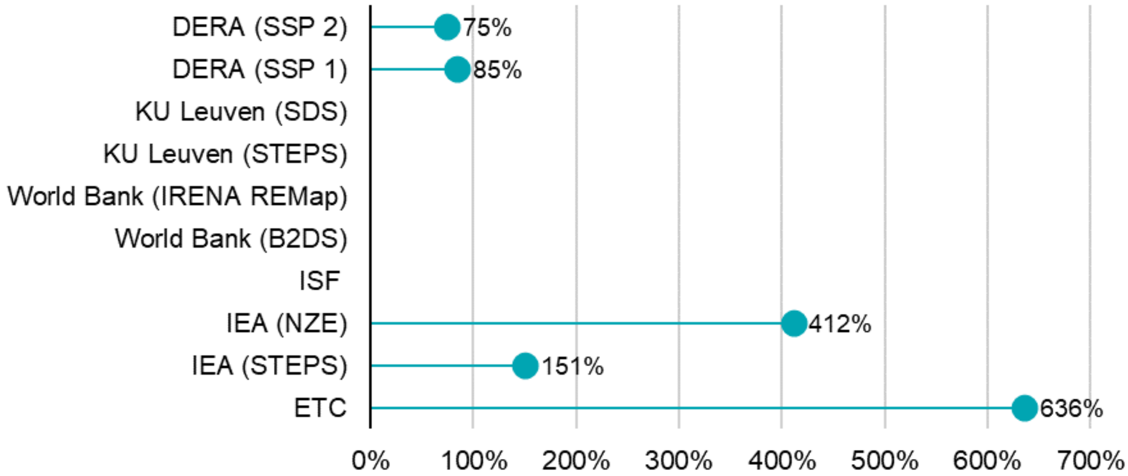
million metric tons



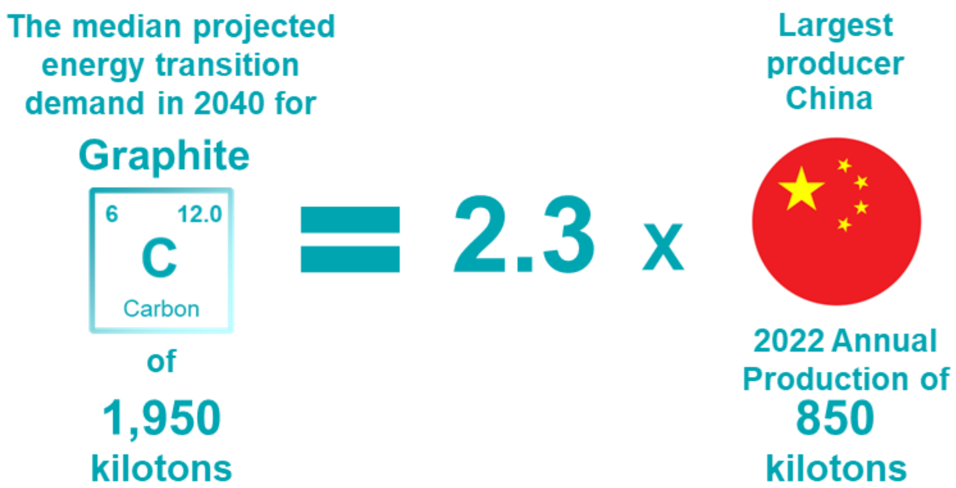
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Graphite: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

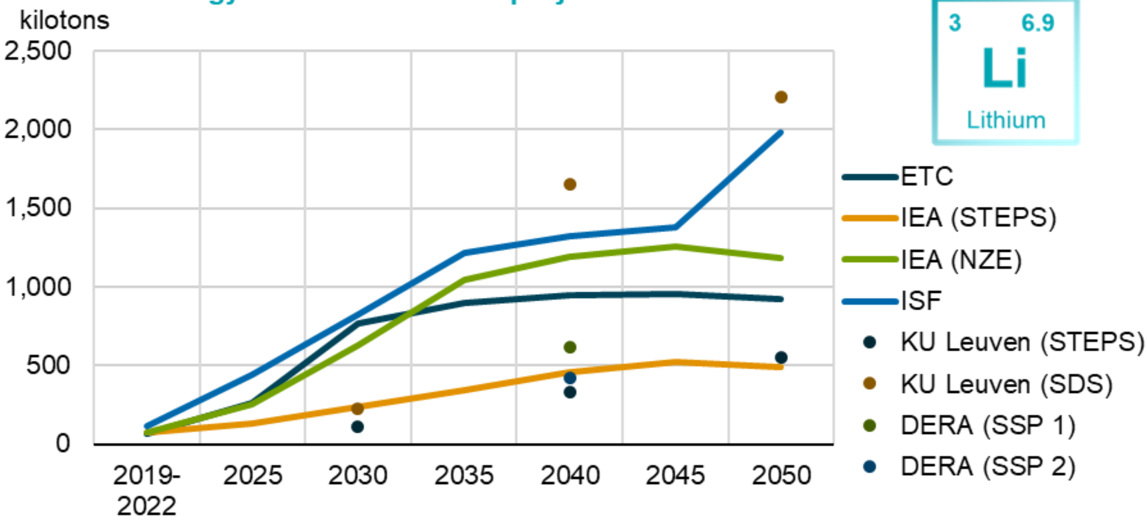


Note: Multiples not exact due to rounding

Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

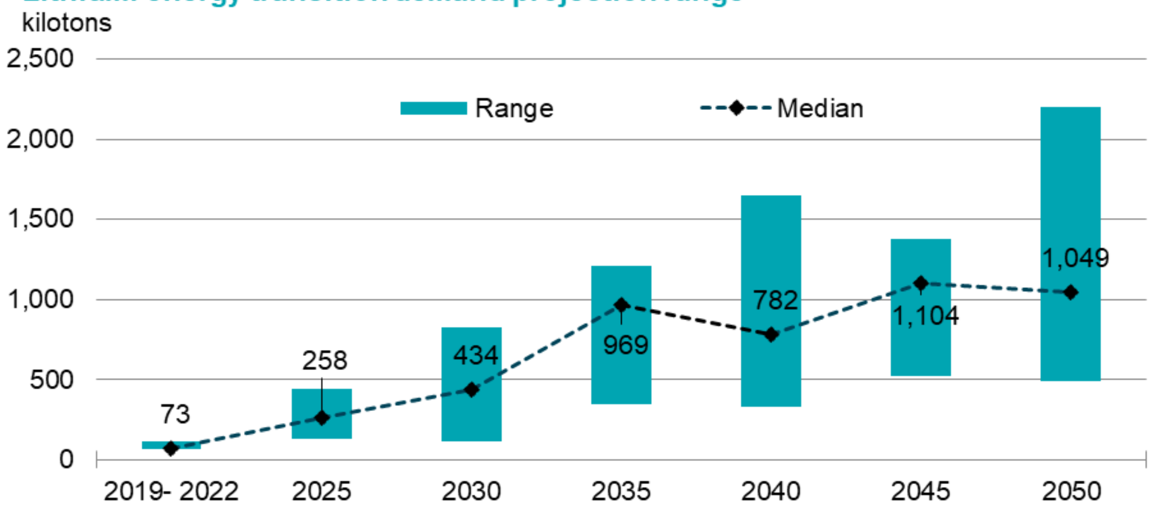
Lithium

Lithium: energy transition demand projections



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

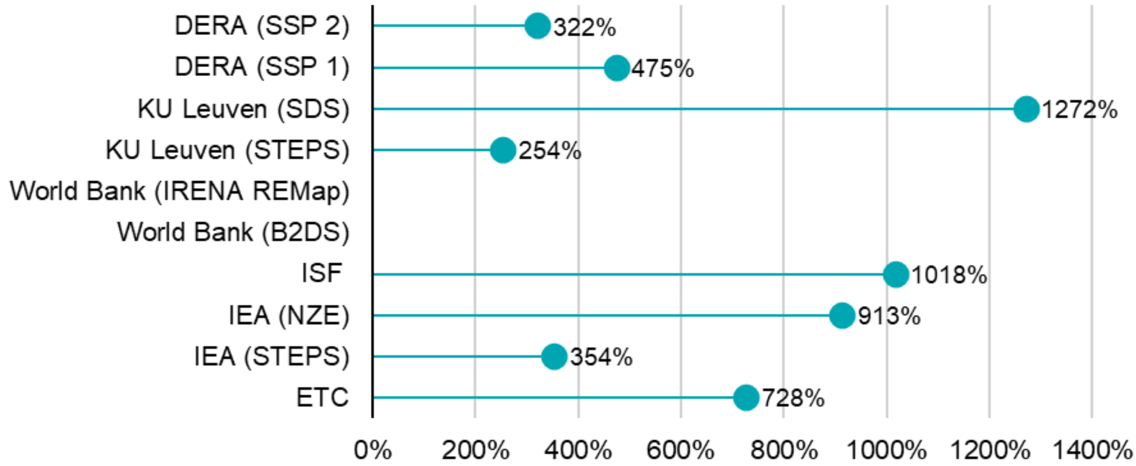
Lithium: energy transition demand projection range



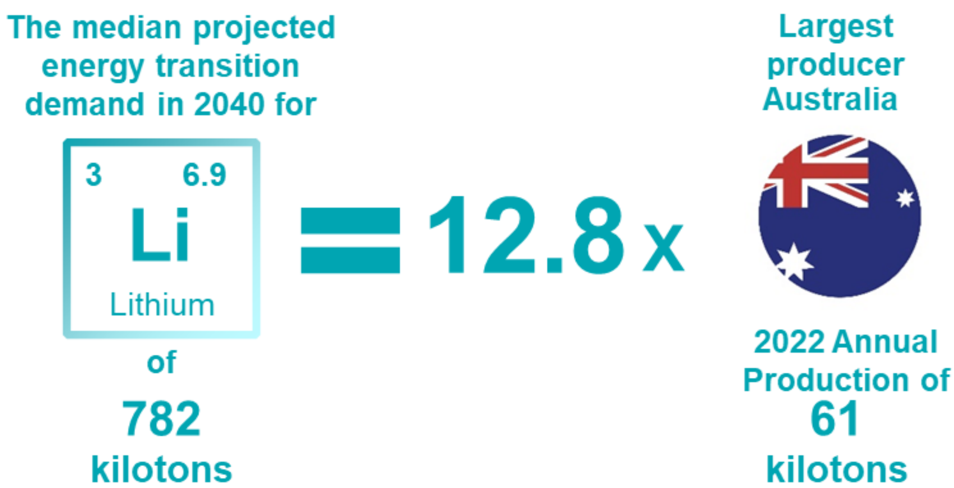
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Lithium: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

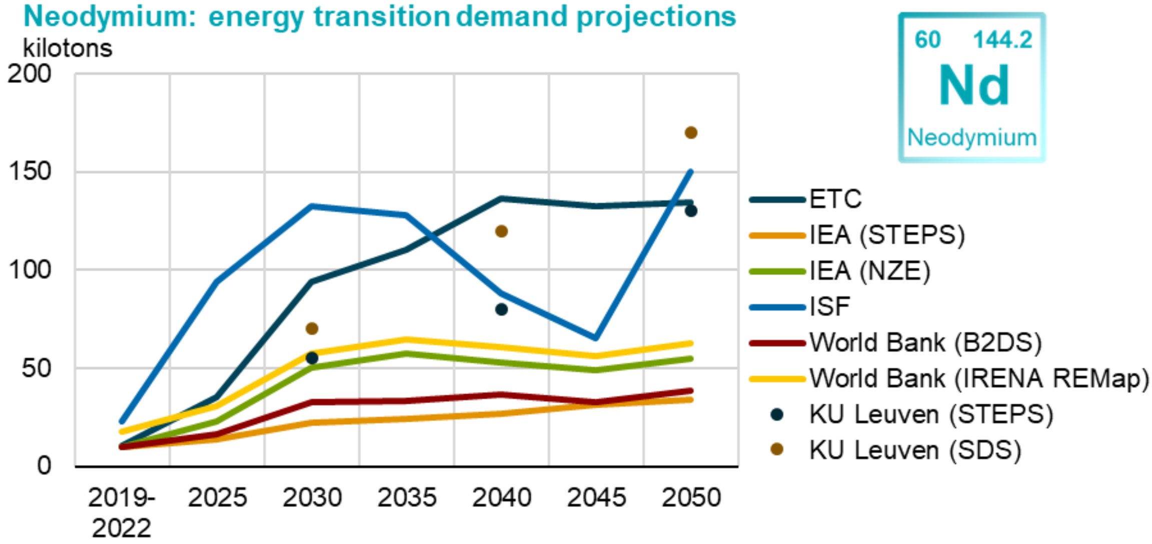


Note: Multiples not exact due to rounding

Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

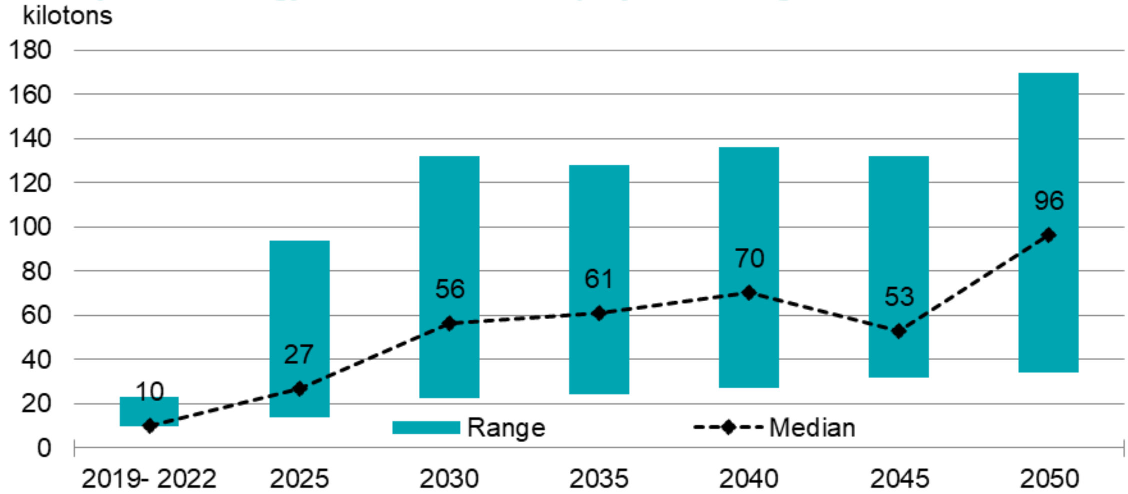
Neodymium

Neodymium: energy transition demand projections



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

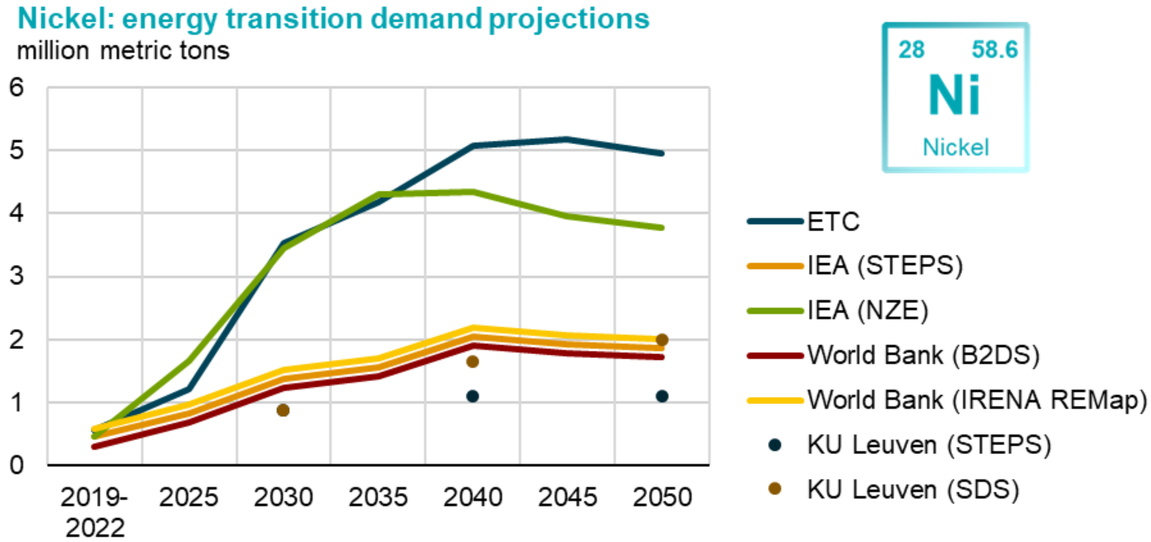
Neodymium: energy transition demand projection range



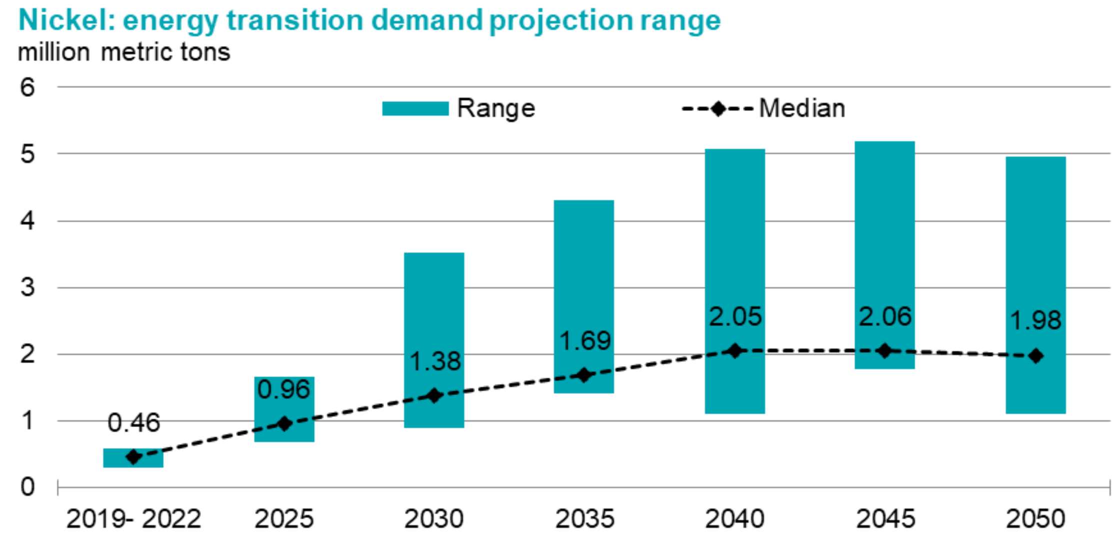
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Note: Production data of Neodymium in U.S. Geological Survey data is categorized with other "Rare Earth Elements" and not published individually.

Nickel



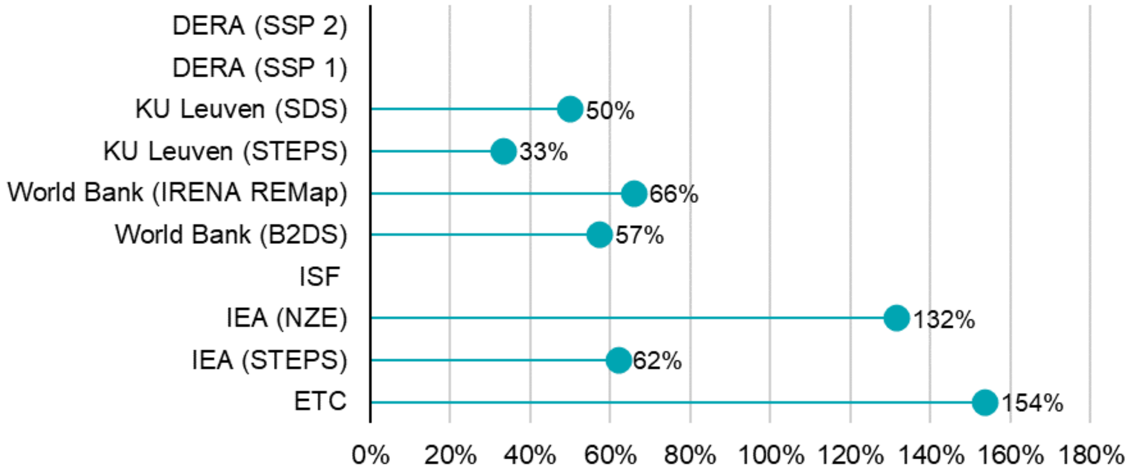
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA



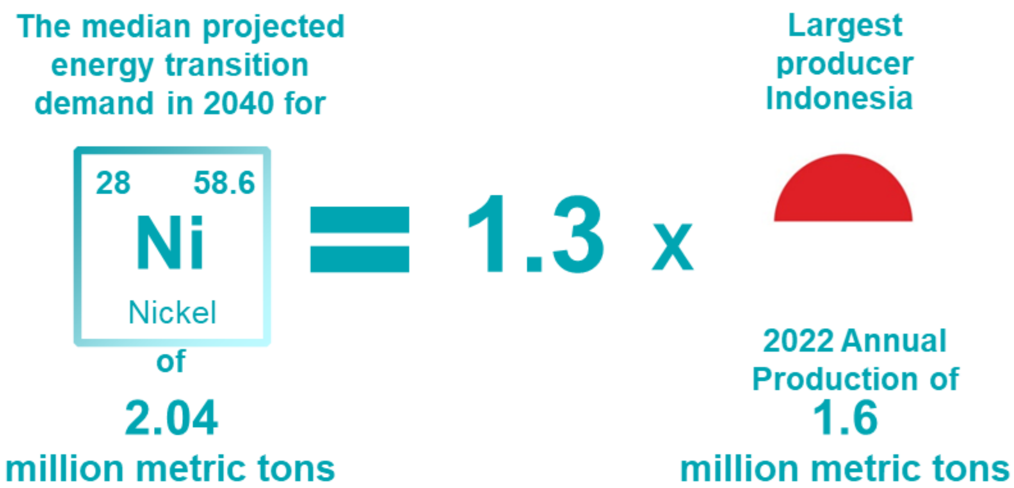
Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Nickel: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA



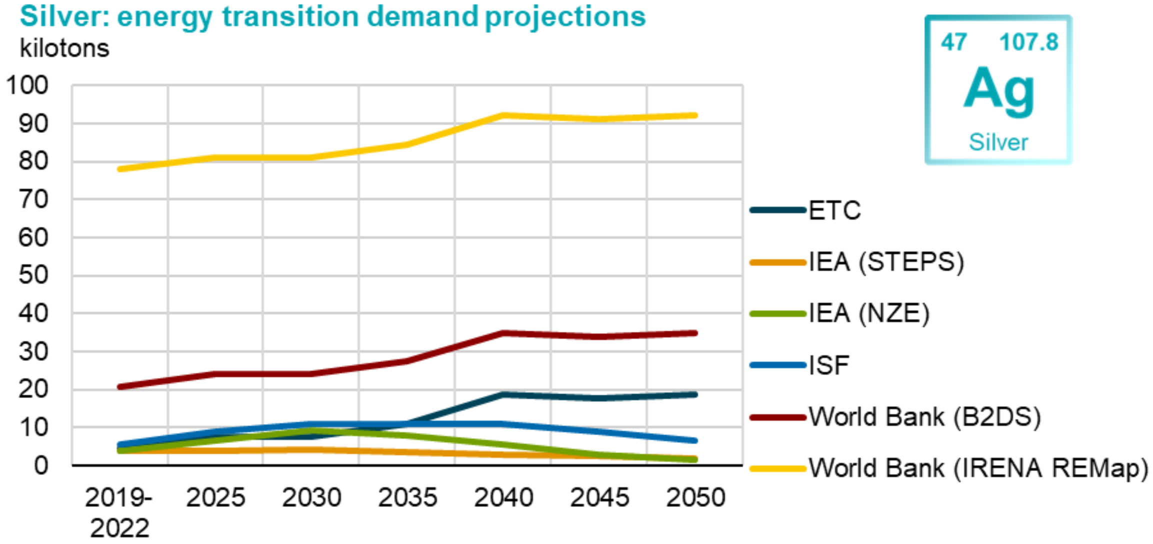
Note: Multiples not exact due to rounding

Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Silver

Silver: energy transition demand projections

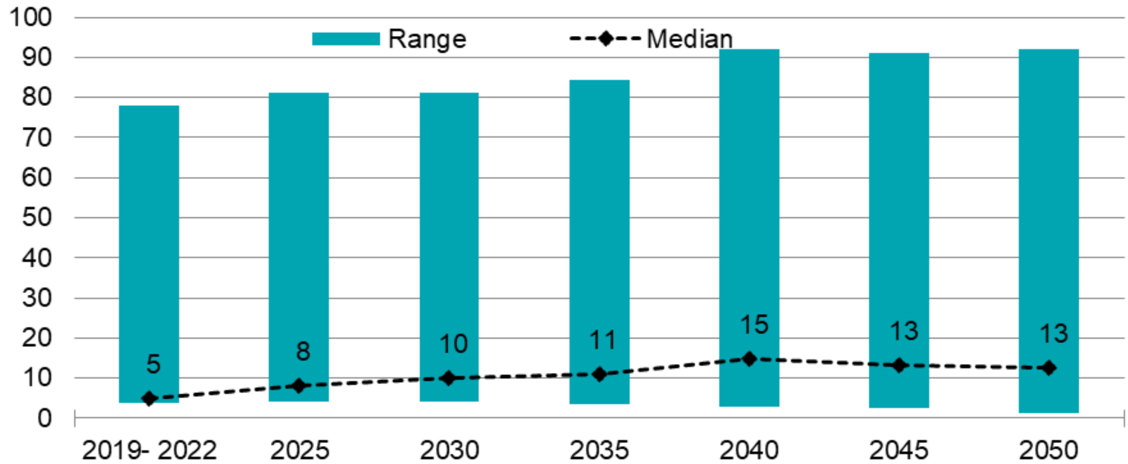
kilotons



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Silver: energy transition demand projection range

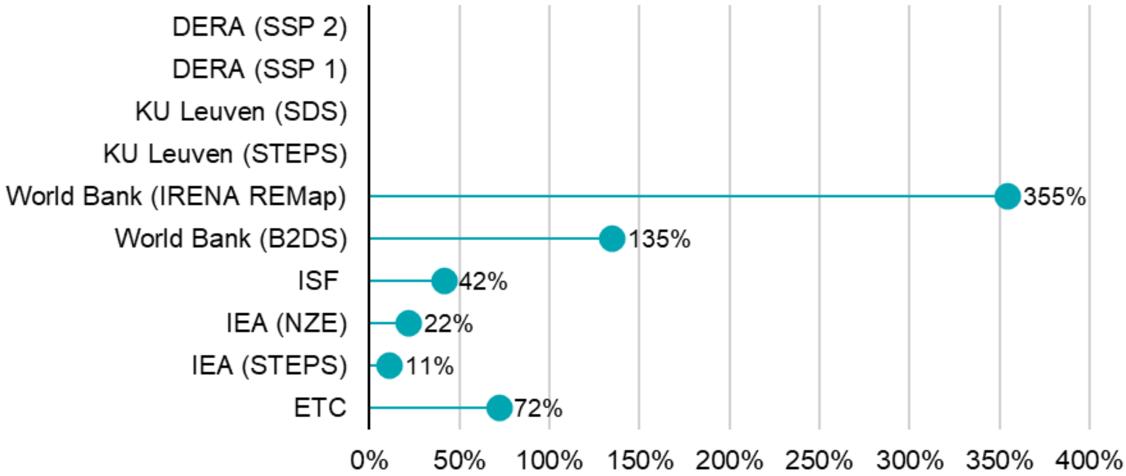
kilotons



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Silver: 2040 estimated transition demand vs. 2022 global production

2040 demand as a share of 2022 global annual production



Source: IEF, Payne Insitute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Note: Multiples not exact due to rounding
Source: IEF, Payne Institute, USGS, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

Energy Scenarios

The various reports have different energy and technology scenarios to calculate critical mineral requirements under a range of conditions.

Climate Outcome Driven

Multiple scenarios were created with a specific climate-based outcome by a certain date as the goal, and then models the energy system required to achieve that goal.

In this collection of reports, climate outcome driven scenarios ranged from limiting global average temperature rise to 1.5°C by 2050, aligned with the IPCC special report, to 1.7°C, or to 2°C increase.

Commonly used scenarios were derived from International Energy Agency scenarios, such as the Announced Policies Scenario (APS), associated with a 1.7°C temperature rise by 2100, and the Net-Zero Energy Scenario (NZE), associated with a 1.5°C temperature rise.

Additionally, several reports used IEA scenarios developed prior to the use of APS and NZE, such as the Stated Policies Scenario (SPS), and the Sustainable Development Scenario (SDS). The STEPS scenario embodies the present policy landscape, based on a sector-wise appraisal of specific policies in place and those announced by governments globally. In contrast, the SDS scenario envisions a pathway that fully realizes global goals to combat climate change in accordance with the Paris Agreement, ensures universal energy access, and significantly curbs air pollution. This scenario presupposes the fulfilment of all existing net-zero pledges, with concerted efforts to achieve near-term emissions reductions; advanced economies are projected to reach net-zero emissions by 2050, China by 2060, and all other nations by 2070 at the latest.

Shared Economic Pathways

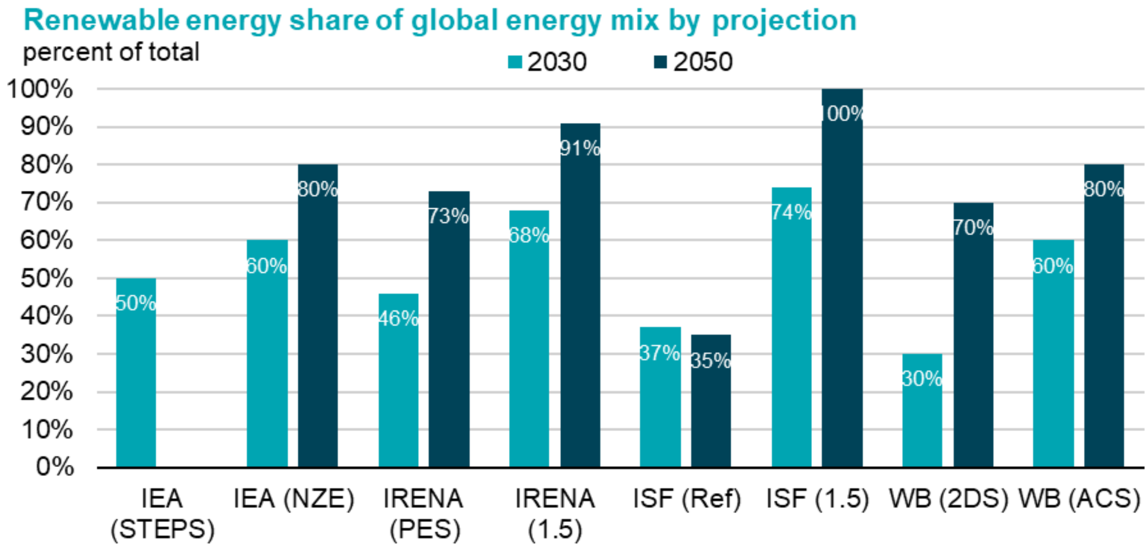
The Shared Socioeconomic Pathways (SSPs), were created as part of the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) for climate policy issues. Each SSP embodies different assumptions about the global energy system's future, and consequently can be used to calculate mineral demand estimates.

Speed of Transition and Technological Progress

Other reports created scenarios that varied the speed and intensity of the energy transition, technological progress, and increases in both technology and resource efficiency.

Technology mixes

Technologies emphasized in these reports are unanimous, solar photovoltaics (PV), wind turbines, electric vehicles (EVs), battery storage systems, and electrical grid expansion are all core components of these projections. These technologies are key to lowering greenhouse gas emissions and subsequently drive the demand growth for critical minerals throughout the projection period.



Source: IEF, Payne Institute, IEA, IRENA, ETC, ISF, World Bank, KU Luven, DERA

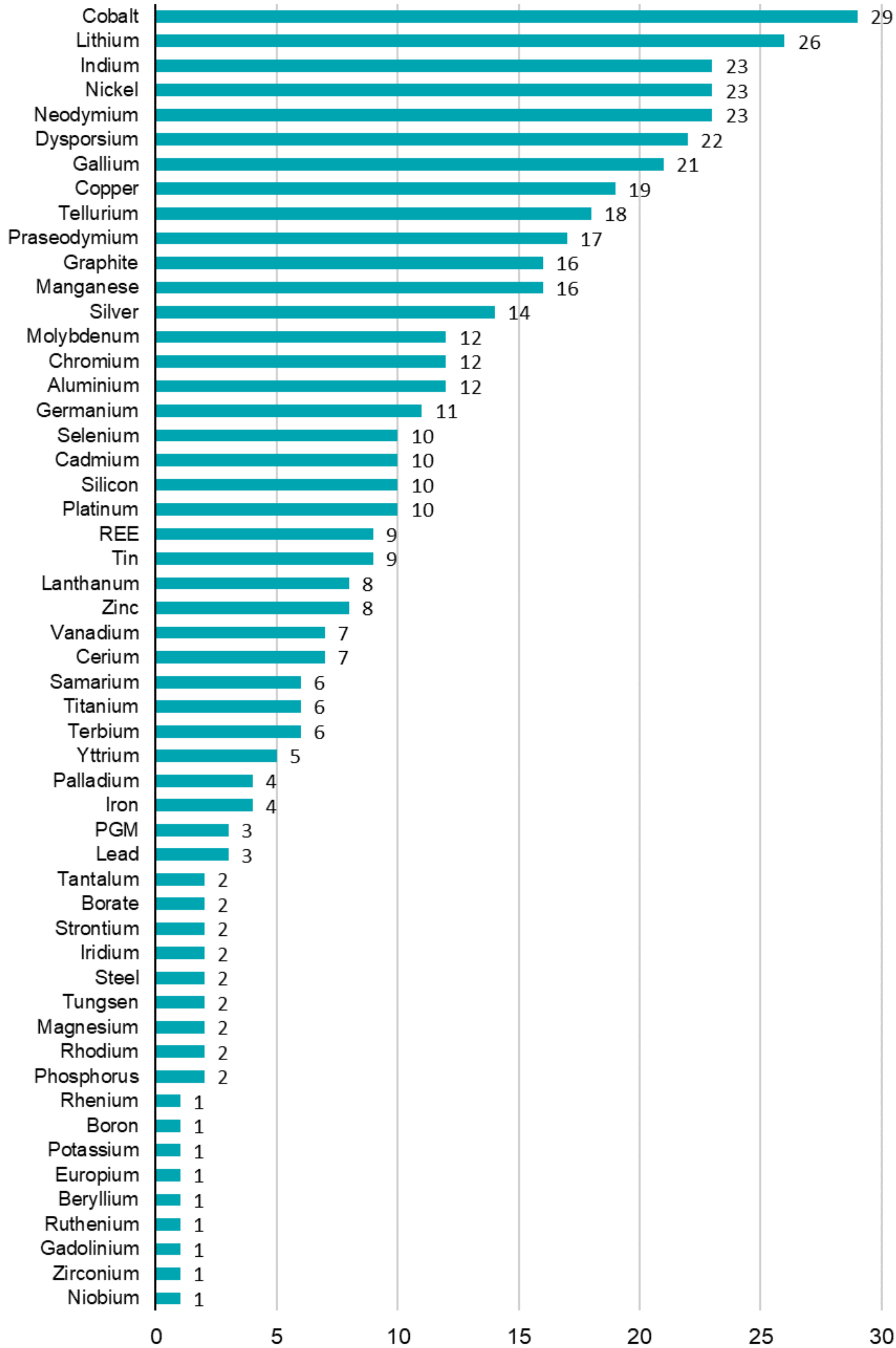
Other technologies with influence

Other climate-oriented technologies like carbon capture use & sequestration (CCUS), hydrogen, or key developments in other renewable energy sources like geothermal, can make previously less sustainable options more favorable for the future, or drastically alter the need and competitiveness of others. While not all the reports surveyed directly delve into alternative technologies or their deployments, they should be considered when comparing critical mineral demand projections.

Resource Requirements

While the technologies across the surveyed reports were nearly unanimous, the translation of those technologies into demand for critical minerals is where key methodological differences arise. For example, a total of twenty- eight (28) minerals and metals were mentioned in all the reports surveyed, echoing the diversity of what policy makers consider to be “critical” minerals. Governments have independently developed lists of which materials constitutes a “critical mineral” depending on domestically available resources, import dependencies, importance to domestic energy systems, manufacturing base, energy policy priorities, and other criteria.

Energy transition materials defined as "critical" by countries & regions (2023)



Source: IEF, Payne Institute, IRENA, NUPI

Top Down vs. Bottom Up

There are also differing approaches to estimate demand for critical minerals across the various technologies.

The “bottom-up" approach involves estimating the material requirements for each technology deployed, then modeling the growth of each technology across the projection period and scenarios to arrive at an estimate for the quantity of critical minerals required.

The “top-down” approach involves estimating the growth rate of various technologies across a scenario, and then estimating the required critical minerals based on this growth.

Intensity and Resource Efficiency Assumptions

With both bottom-up and top-down approaches, assumptions need to be made on the intensity of materials per technology deployed–kilograms of lithium per electric vehicle, for example. As well as assumptions on if that material intensity changes over time. These estimates can vary widely across scenarios and projections and are a major contributor to variance across the different reports surveyed.

Conservative assumptions are likely to take present rates of material intensity and hold them more or less constant across a projection period. Meaning, the quantity of a material required per unit of renewable energy technology is the same in 2050 as it is today.

More progressive assumptions include gradual or rapid increases in resource efficiency across the projection period. In other words, the quantity of material required per unit of renewable energy technology is less in 2050 than it is today.

Sub-Technologies and Chemistry Shifts

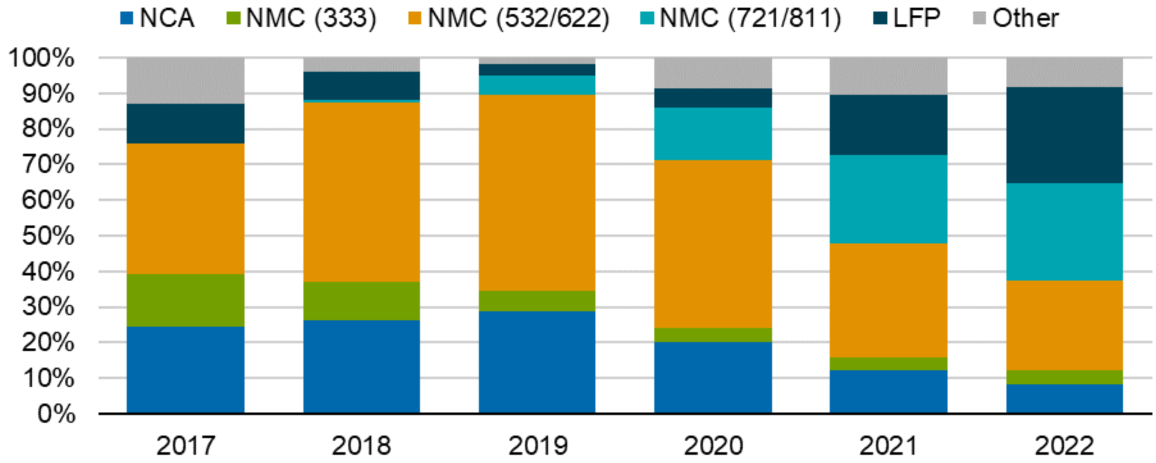
Estimates of required critical minerals can also vary based on changes within a renewable energy technology category. Factors such as cost, energy intensity, and consumer behavior and preferences can shape future markets and sub-technologies. These sub-technologies in turn can further influence the specific minerals required for the energy transition.

For instance, across solar energy there are different sub-technologies that have various chemistries and resource requirements. The potential preference for cadmium telluride (CdTe) solar cells over the currently prevalent technology - crystalline silicon photovoltaic cells - could shift the demand for minerals like cadmium and tellurium in the future.

However, the most prevalent example of sub-technologies driving chemistry shifts occurs in batteries. Changes in mineral prices, processing expenses, policy incentives, technological development, and other factors have resulted in a multitude of battery cathode chemistry mixes such as nickel, manganese, cobalt (NMC), nickel, cobalt, aluminum oxide (NCA), and lithium, iron, phosphate (LFP) batteries.

In general, NMC cathodes require nearly eight times more cobalt than NCA lithium batteries, but only half the nickel amount. LFP batteries, which do not require nickel, manganese, or cobalt, require more copper than NMC batteries and phosphorus, a key ingredient in large-scale fertilizer production.

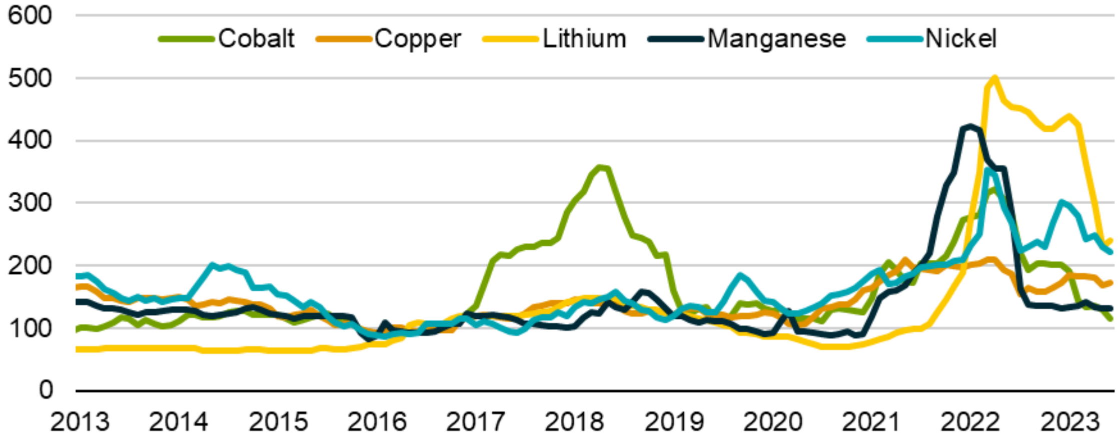
Sales of EVs by cathode chemistry
percent of total



Source: IEF, IEA, *Critical Minerals Market Review 2023*

As a result of the diversity in battery cathode chemistry, changes in the price for one or more battery raw materials can greatly influence the prevailing or predominant battery type deployed. Such shifts have already occurred over the course of the past 5-10 years and are likely to occur again in the future. Within the past 5-years, high cobalt prices and supply chain issues resulted in many battery manufacturers shifting to low-cobalt battery chemistries. Then high nickel prices reduced the price competitiveness of high-nickel content battery chemistries versus LFP batteries. Then in 2022, a surge in lithium prices led to an increase in LFP battery costs compared with other chemistries. While LFP batteries remain the most affordable battery technology per kilowatt-hour, a sustained increase in lithium prices could slow down the deployment of LFP as battery chemistry preference.

IMF Primary Commodity Price System - Electric Vehicle Metals (Indexes)
Index (2016 = 100)



Source: IEF, IMF, *Primary Commodity Price System*
Note: Index includes global benchmark prices for various metals

These differences and the changing advancements in technology make mineral demand models difficult to estimate. This results in a wide range of mineral demand estimates, even when researchers agree on the widescale deployment of a specific low-carbon or renewable energy technology.

Recycling

While all reports surveyed in this study suggest that recycling can be a useful tool in managing critical materials supply, it is also a major source of variance across critical mineral requirement estimates.

Recycling rates vary greatly across different minerals because of costs, complexities, compromised quality of final product, or material availability. Aluminum and copper are two of the most widely recycled materials as well as two materials that overlap across numerous low-carbon and renewable energy technologies. Meanwhile, recycling technology for certain critical materials is still being developed and not yet at scale. Additionally, data is often lacking for recycling rates be it either by material, feedstock source (batteries, solar panels, scrap, etc.), or region.

However, the assumptions made on recycling rates in these projections greatly influence the implications for new mine requirements, supply chain diversity, sustainability, and policy. Conservative assumptions of stagnant recycling rates into the future for many minerals would likely translate into projections showing a far greater need for new mines, mining investment, and supply chain expansion. Progressive assumptions of increasing recycling rates or near fully-cycle closed loop supply chains would likely result in projections with fewer long-term new mines requirements.

Cobalt and lithium are two critical materials that have the highest near-term risk of demand outpacing supply according to many of the reports surveyed in this study. A significant future source of both could be from increased recycling rates of end-of-life electric vehicle batteries. However, recycling infrastructure for EV batteries is still in its infancy, and there are still technological challenges to overcome. For example, lithium is technically recyclable but is challenging to isolate from other cathode materials without the use of costly organic reagents.

Across the projections surveyed, the medium-term, ~2035-2045, is the key make or break point for EV recycling rates and thus lithium, cobalt, and several other mineral supply requirements. This reflects both the time needed for recycling infrastructure and technology to mature as well as the time needed for EV's share of global vehicle fleets to generate sufficient feedstock (end-of-life batteries) for a scaled-up recycling industry.

Conclusions

The impending transition to low-carbon energy technologies has already affected critical mineral supply chains, prices, and demand. Still, it will continue to be very difficult to accurately forecast. While projections unanimously envision intense deployment of battery electric vehicles, wind, solar, and other mineral-intense energy technologies to achieve climate goals. Continuous variations in energy markets, technological advancements, costs, emissions, and consumer preferences result in an ever-changing mineral demand landscape.

Although outside the scope of this report, there are significant risks on the supply side to these projections. While most models do not anticipate scarcity and depletion of mineral resources, factors such as geopolitics, decades-long development timelines for new mines, high capital requirements, increasing ESG pressures, and declining ore quality indicate a high risk for periods of demand exceeding supply.

While projections of future critical minerals demand requirements are necessary to understand the scale of the challenge a mineral-driven energy transition presents, it is equally necessary to understand the vast amount of uncertainty that is inherent in such projections. The reports surveyed for this report should be considered the first generation of their kind. Improved data collection and increased collaboration between the energy modeling community and the metals and mining community will yield better, standardized, and more comprehensive outlooks in the future.

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Appendix: Backgrounds of Surveyed Reports

- **IRENA** (2021; 2023), broadly discuss how innovation will affect demand for critical materials and the need for a comprehensive policy framework that not only transforms energy systems but also protects people, livelihoods, and jobs. IRENA (2023), uniquely highlights the geopolitical aspects of critical minerals, including the concentration of production in a few countries and the potential for supply disruptions due to trade tensions or other factors. All three reports from IRENA depict strategies to mitigate critical materials dependencies, including recycling, substitution, and diversification of supply sources.
- **IEA** reports (2022;2023) highlight the importance of critical minerals for the transition to a low-carbon energy system and identify potential risks and challenges associated with their supply and demand. IEA provides some of the more detailed analysis and deep dives into the key mineral demand and supply projections. Also, these reports provide a comprehensive overview of the current state of critical minerals investments and market trends, and they respond directly to the requests in the G7 Five-Point Plan for critical minerals security.
- **World Bank** (2020) Minerals for Climate report examines the potential for different countries and regions to develop their own critical mineral resources and supply chains, and the potential implications for global trade and geopolitics. The paper is unique in its comprehensive analysis of the mineral intensity of the clean energy transition, its detailed examination of the potential environmental and social impacts of critical mineral production and disposal, and its global perspective on the implications of the clean energy transition for mineral markets, trade, and geopolitics.
- **University of Technology Sydney: Institute for Sustainable Futures, ISF** (2019), offers forecasts regarding the future need for metals, which are designed based on an aggressive renewable energy situation. The study evaluates the supply uncertainties connected with the centralized production and reserves, the percentage of renewable energy in end-use, and the critical nature of the supply chain. Moreover, the report critically examines the identified impacts of mining on the environment, health, and human rights.
- **McKinsey & Company** (2021) emphasizes the importance of sustainability in the transition to a net-zero emissions economy and how the industry should comply with or exceed the environmental, social, and governance standards. The paper provides recommendations for policymakers and industry leaders to ensure a secure and sustainable supply of critical minerals. The authors propose strategies for increasing the production of critical minerals, improving the recycling and reuse of these materials, and reducing the environmental and social impacts of mining and processing these materials.
- **German Mineral Resources Agency (DERA)** (2021) draws on a combination of literature reviews, expert consultation, and scenario analysis to provide a comprehensive analysis of the critical materials required for the energy transition. The paper highlights some global perspectives including the importance of international cooperation and coordination in managing critical material supply chains. It also provides guidance to policymakers and other stakeholders on strategies for ensuring critical minerals availability and sustainability in a rapidly changing global landscape.

- **Energy Transitions Commission (ETC)** (2023) This paper introduces four hypothetical energy pathways to probe into the prospective demand for critical minerals during the Energy Transition. These include the Baseline Decarbonization Scenario, the Rapid Innovation Scenario, the Resource Efficiency Scenario, and the Delayed Transition Scenario. The Baseline Decarbonization Scenario predicates a net-zero economy by mid-century, congruent with the Energy Transitions Commission's projections, coupled with conservative assumptions about technology's efficiency and innovative capacity, material intensity, and recycling rates. The findings of this scenario may be interpreted as the peak possible requirement for materials during the Energy Transition. The Rapid Innovation Scenario, on the other hand, posits a speedier trajectory of innovation and tech development than the Baseline Decarbonization Scenario, which results in reduced material demands for the Energy Transition. The Resource Efficiency Scenario prioritizes resource conservation and recycling, leading to a decrease in the material requirements for the Energy Transition. The Delayed Transition Scenario anticipates a more gradual evolution towards a low-carbon energy framework, thereby reducing the immediate demand for critical minerals but potentially amplifying it in the long run.
- **Catholic University of Luven (KU Luven)** (2022) The paper highlights that Europe's ambitions to cultivate domestic production of clean energy technologies will escalate its demand for an array of metals. This includes bolstering existing base metal markets like aluminum, copper, and nickel, and paving the way for novel commodity markets such as lithium and rare earth elements, referred to in the paper as Tier 1 (shortlist) or Tier 2 (longlist) minerals. While this paper does not explicitly define its own energy scenarios, it refers to two primary energy scenarios established by the International Energy Agency (IEA): the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS).

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