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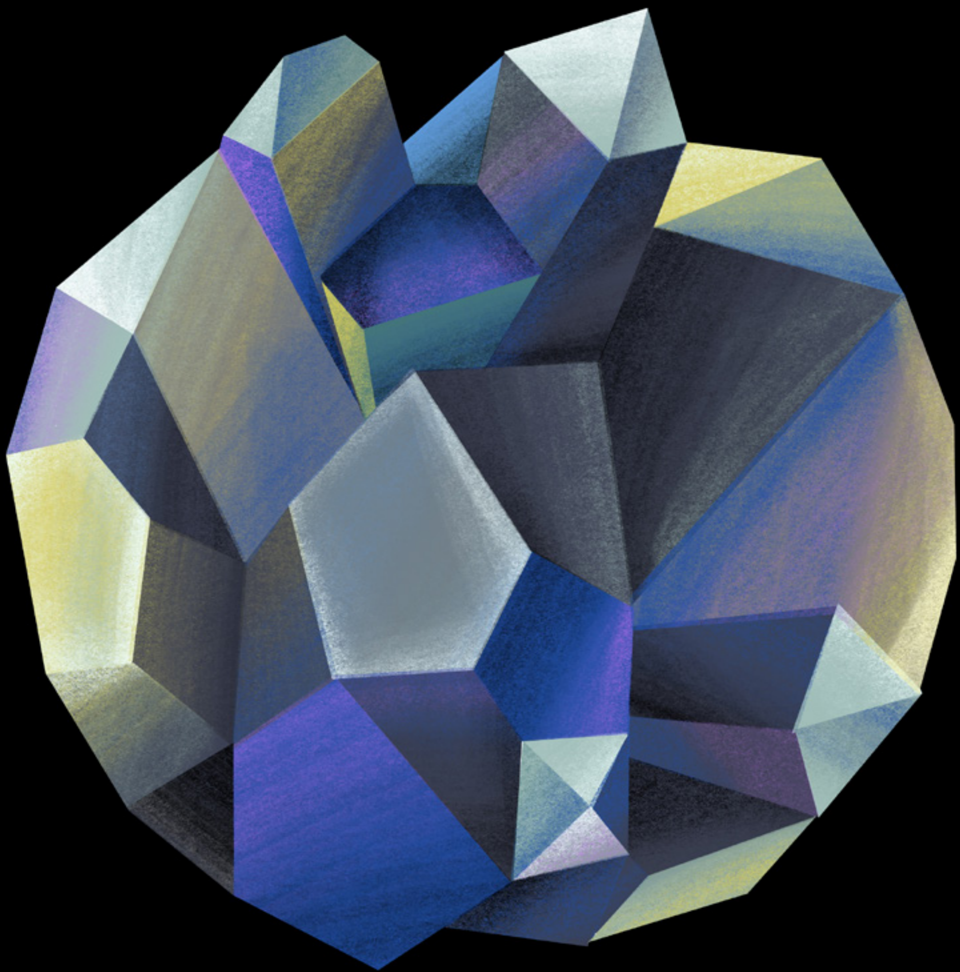


Rare earth minerals and their role in the energy transition

Introduction

The world is undergoing an energy transition, as it seeks to move away from reliance on fossil fuels. This shift has created new demand and supply chain dependencies for a different kind of natural resource, one that is relatively unfamiliar to the everyday consumer.

As climate goals and policymakers emphasize the need for investment in green technology, there is a growing requirement for more mineral inputs, particularly rare earth minerals, to drive this growth and meet climate targets. In addition to their critical role in enabling renewable energy technologies, rare earth minerals are widely used in modern technologies such as smartphones, televisions, computers, light-emitting-diode (LED) lights, and defense systems. The key challenge now is determining whether a secure and sufficient supply of rare earth minerals is available to support this energy transition.

Background

Rare earth minerals (REMs) are composed of rare earth elements (REEs), a group of 17 chemically similar elements. These elements are categorized into two groups; light rare earth elements (LREEs) and heavy rare earth elements (HREEs).

Period \ Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16	9 F 19	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Aġ 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	**21 Sc** Scandium 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.9	36 Kr 83.8
5	37 Rb 85.47	38 Sr 87.62	**39 Y** Yttrium 88.91	40 Zr 88.91	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.82	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 ġ 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	**57 La** Lanthanium 138.91	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 ġr 192.2	78 Pt 195.1	79 Au 197	80 Hg 200.5	81 Tġ 204.4	82 Pb 207.2	83 Bi 209	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 Ds (271)	111 Rq (272)	112 Uub (285)	113 Uut (284)	114 Uuq (289)	115 Uup (288)	116 Uuh (292)	117 Uus 0	118 Uuo 0

6	**58 Ce** Cerium 140.1	**59 Pr** Praseodymium 140.9	**60 Nd** Neodymium 144.2	**61 Pm** Promethium (147)	**62 Sm** Samarium 150.4	**63 Eu** Europium 152	**64 Gd** Gadolinium 157.3	**65 Tb** Terbium 158.9	**66 Dy** Dysprosium 162.5	**67 Ho** Holmium 164.9	**68 Er** Erbium 167.3	**69 Tm** Thulium 168.9	**70 Yb** Ytterbium 173	**71 Lu** Lutetium 175
7	90 Th 232	91 Pa (231)	92 U (238)	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

Transition elements   Lanthanides

Rare earth uses

Rare earths possess unique properties due to their magnetic, luminescent and electrochemical characteristics, making them essential in a wide array of high-tech applications, including:

The many uses of rare earths

Rare earths

Catalysts
- Petroleum refining
- Chemical processing
- Catalytic converter
- Diesel additives
- Industrial pollution scrubber

Electronics
- Display phosphors (CRT, PDP, LCD)
- Medical imaging phosphors
- Lasers
- Fiber optics
- Optical temperature sensors

Glass
- Polishing compounds
- Optical glass
- UV resistant glass
- Thermal control mirrors
- Colorizers/Decolorizers

Ceramics
- Capacitors
- Sensors
- Colorants
- Scintillators

Metal alloys
- Hydrogen storage (NiMH batteries, fuel cells)
- Steel
- Lighter flints
- Aluminium/Magnesium
- Cast iron
- Superalloys

Magnets
- Motors
- Disc drives & disk drive motors
- Power generation
- Actuators
- Microphones & speakers
- MRI
- Anti-lock brake system
- Automotive parts
- Communication systems
- Electric drive & propulsion
- Frictionless bearings
- Magnetic storage disk
- Microwave power tubes
- Magnetic refrigeration
- Magnetostrictive alloys

Other
- Water treatment
- Fluorescent lighting
- Pigments
- Fertilizer
- Medical tracers
- Coatings

Historical context

The term 'rare earth' (RE) originated in the late 18th and early 19th centuries when these elements were first discovered. Despite the name, they are neither rare nor earths. At the time, however, they were challenging to isolate and were found only in relatively scarce mineral deposits. In reality, REs are relatively abundant in the Earth's crust, but they are seldom found in concentrated and economically exploitable forms compared to ores of other metals.

How do rare earths impact the energy transition?

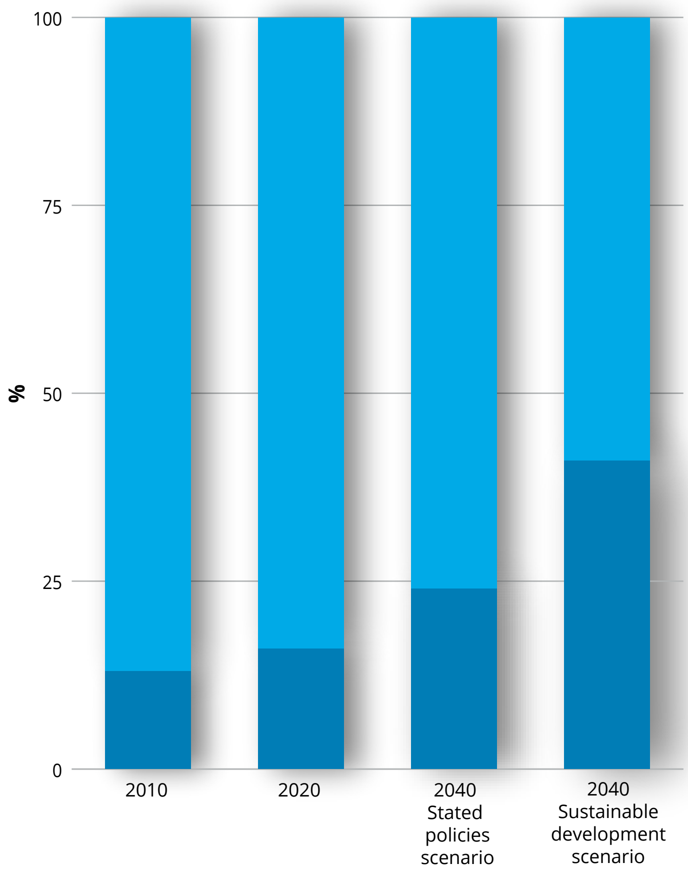
The Paris Agreement's overarching goal is to limit the increase in global warming temperatures to under 2°C (above pre-industrial levels) and pursue efforts to cap the rise at to 1.5°C.[16]

However, experts increasingly view this as unattainable. To achieve these targets, countries need to decarbonize and transition to zero-carbon renewable energy technologies such as wind turbines, solar panels, electric vehicles (EVs), and storage batteries. These technologies are significantly more mineral-intensive than 'traditional' energy sources.

Rare earth permanent magnets are essential for improving the efficiency, size, and weight of EVs. They also play a crucial role in the production of direct-drive wind turbines, which offer efficiency and reliability advantages over gear-driven alternatives. This positions rare earth elements as a key component in developing technologies that will drive the green revolution and support the energy transition.

Global demand and supply trends

Share of clean energy technologies in total demand for rare earths by scenario, 2010-2040



Source: IEA

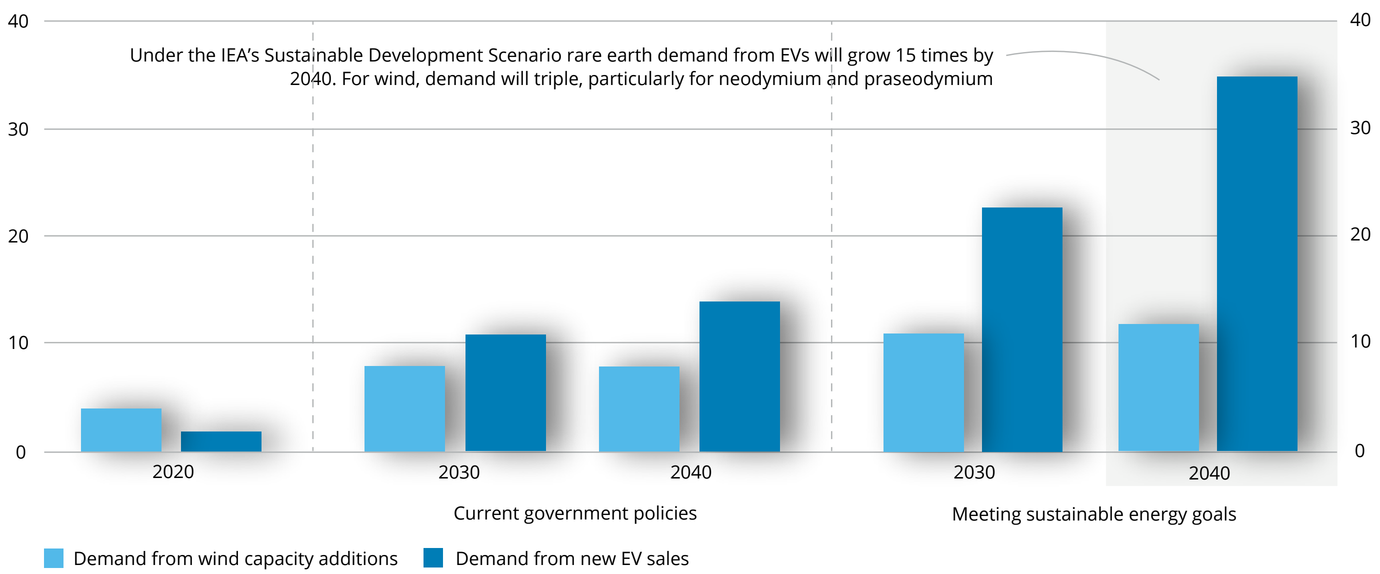
The shift to clean energy is a key driver in the demand for rare earths, with demand projected to increase by 300-700% by 2040. The share of clean energy in total rare earth demand is also expected to rise from 13% in 2010 to 41% in 2040.[1]

Clean energy technologies require significantly higher rare earth inputs than traditional hydrocarbon-based systems. For instance, an electric vehicle requires six times the mineral input (including REs) of an internal combustion engine vehicle, while an onshore wind plant demands nine times more mineral resources than a gas-fired plant.[1] In 2023, approximately 18% of global cars sales were EVs[11], a figure expected to rise to 73% by 2040[13]. Similarly, global wind power capacity increased from 904 gigawatts in 2022 to 1,021 gigawatts in 2023 (onshore and offshore), marking a 13% increase in one year.[12] This growth relies heavily on rare earths such as neodymium, praseodymium, dysprosium, and terbium, which are critical to renewable technology development.

China has taken a leading role in clean energy adoption, accounting for approximately 60% of global EV sales in 2023. By August 2024, China announced it had achieved its wind and solar generation capacity target six years ahead of schedule, surpassing 1,200 gigawatts.[5] However, solar and wind power accounted for only 14% of the country's electricity generation so far this year. As a result, significant future investment will be needed to meet renewable energy targets that depend on rare earths.[5]

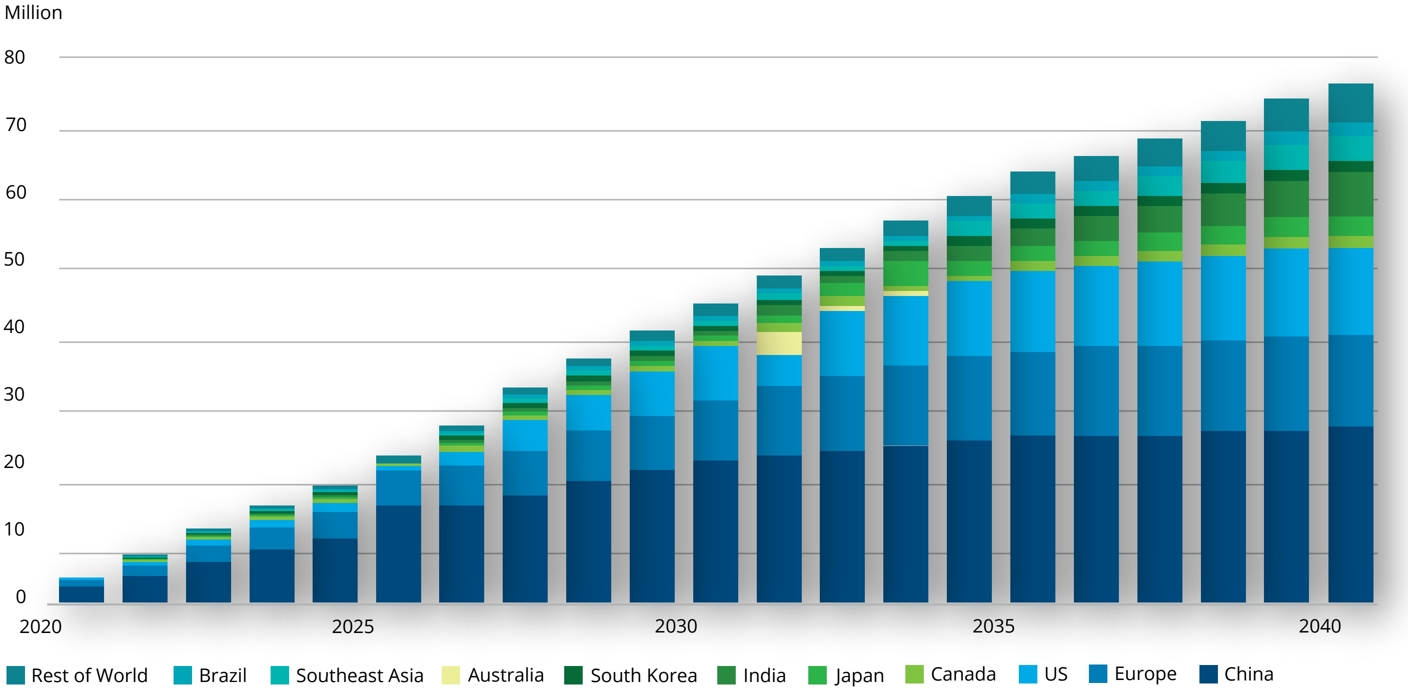
Rare earths are essential to the green energy transition

Demand by scenario (kilotonnes)



Source: IEA

Global long-term passenger EV sales by market in BNEF's Economic Transition Scenario



Note: Europe includes the EU, the UK and European Free Trade Association (EFTA) countries. EV includes battery EVs and plug-in hybrid EVs.

Source: BloombergNEF

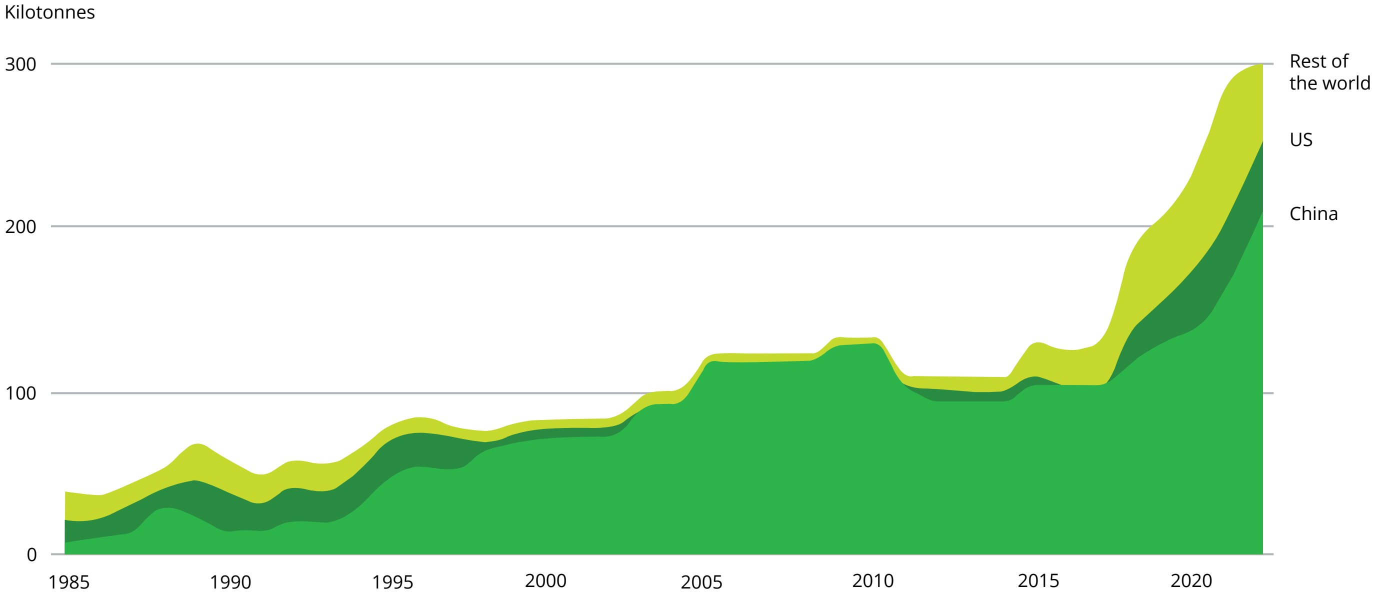
Rare earth supply is much more concentrated than the oil and gas industry, with China supplying 60% of the global market. Extraction is only the first step, with rare earth processing involving a highly specialized multi-stage process (separation, refining, and forging) where China has established a controlling competitive edge, responsible for 90% of process operations worldwide.[1] China's influence has extended further, as the country has also been investing in overseas assets, which include USA, Australia, and Chile, growing its geopolitical power, which raises risks of potential trade restrictions and supply disruptions.

Geographical distribution

Total estimated worldwide reserves of REs amount to 110 million MT, largely located in China, which holds 44 million MT (mainly found at the Bayan Obo mine). Other countries with notable reserves are Vietnam (22 million MT), Russia (21 million MT), and Brazil (10 million MT). The USA has reserves of 1.8 million MT.[2]

In terms of production, China is also the largest producer of REs, amounting to 240,000 MT in 2023, with the USA producing 43,000 MT, Myanmar 38,000 MT, and Australia 18,000 MT.[3]

Chinese rare earth production continues to dwarf efforts elsewhere



Source: USGS

Rare earth supply security is therefore a critical issue. The EU, for example has negligible mining and processing capacity, with the bloc being a world leader in wind turbine and EV development. However, they are dependent on crucial components from China. The USA reopened its only RE mine (Mountain Pass mine) in 2018 after being purchased out of bankruptcy (caused by competition from Chinese suppliers) by a consortium that included a Chinese-owned firm. All rare earths are sent to China for processing; however the USA is working to recommission a separation plant to process REs domestically.[4]

The industry faces other issues such as long project lead times. If investment in new projects is delayed until deficits appear, it could result in a period of market tightness and price instability, raising questions about the ability to ramp up RE production. Resource quality is another important issue, as lower-grade ores in more difficult locations may require greater energy for extraction, further increasing production costs and environmental impacts.

Due to these variables, a growing number of automakers and suppliers are working on EVs that either do not contain or are less reliant on REs, with the likes of Tesla, the world's largest EV maker in 2023, looking to cut heavy rare earths by 25% per vehicle, with the target of going rare-earth free in its next generation EV models. An important technological advancement to support this transformation is the use of externally excited synchronous motors (EESMs) which differ from conventional electric motors as they generate magnetic field through electric current and therefore do not rely on permanent magnets made from REs.[6]

The development of EESM technology by the likes of Renault and Vitesco Technologies has driven improved performance output, with this option providing potential supply security and sustainability, as well as cost and energy savings when compared to the more common permanent magnet synchronous motors (PMSMs).[14]

Technological trade-offs are present in many industries, however the trajectory of non RE reliant technology raises bigger questions on whether projected demand will be achieved, and what impact this will have on the feasibility of future investment.

Ultimately, the direction of demand is dependent on the advancement of technology and policymaking. This uncertainty is driven by climate policies and how strictly government and international bodies will enforce regulation. Policymakers play a vital role in reducing this uncertainty by clearly defining their goals and translating targets into actions. This will be critical in building trust and investment, opening the flow of capital to green tech.

Supply security

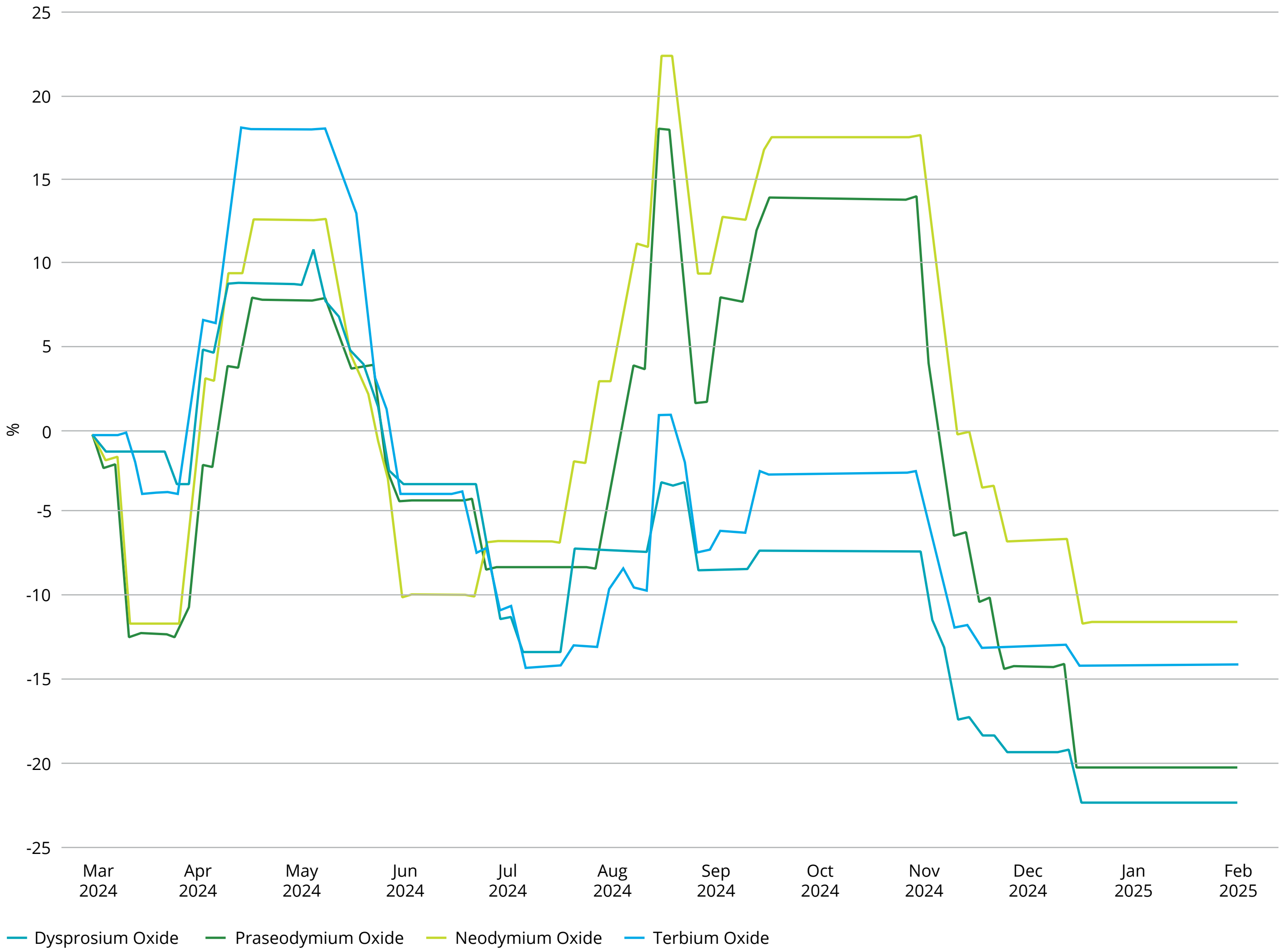
Dependence on China has led countries to diversify their supplies, though little progress has been made on this. Due to China's dominance in the supply and processing of REs, the most effective strategy to reduce reliance is to find technological solutions away from REs which manufactures are pursuing, however, as discussed, the proliferation of alternative technology with reduced REs is still very much under development.

The EU and USA have initiated an investigation into potential alternative supply options. The United Nations Economic Commission for Europe (UNECE) reported in 2022 that Sweden has a large reserve of REs, with a capacity to supply forecast HREE's requirements for Europe for more than 20 years.[17] Regions of southern and eastern Europe also exhibit RE extraction potential that could be explored, however any investment decision and its feasibility will need to be evaluated in the context of China's near quasi-monopolistic market presence.

Rare earth pricing

Since the pandemic, there has been a downward trajectory in RE market prices, driven largely by a slowdown in China's economy and an oversupply. Because of these factors, producers are finding it more difficult to remain profitable, with two major rare earth suppliers outside of China (Lynas Rare Earths Ltd and MP Materials Corp) looking at operational efficiencies to reduce production costs.[15] China's economic recovery is therefore seen as a significant factor that could turn prices around.

Price development of selected rare earths



Source: Tradium

In the short term, lower prices could result in more predictable supply chains and stable costs for consumers, however future investment will no doubt be impacted, with an increase in prices needed to support the development of new projects and with new tariffs imposed by the US administration, market prices may see further volatility.

Mining process and environmental challenges

The extraction of REs brings a wide variety of environmental issues that cannot be ignored. The main problem with rare earths as a sustainable solution is that they are difficult to mine without causing environmental damage. One extraction process involves the removal of topsoil, and creating a leaching pool where chemicals separate REs from the ore. Another method involves drilling into the ground, pumping chemicals into the earth, with the resulting mix pumped into leaching pools for separation. Both processes can cause pollution of land, water and air, spreading toxic waste, deforestation and biodiversity loss, which can often be difficult to contain.

Environmental problems are just one part of RE extraction issues, with The Harvard International Review finding that mining produces huge waste issues, with one ton of RE resulting in nearly 2,000 tons of toxic waste altogether (30 pounds of dust, 9,600-12,000 cubic meters of waste gas, including hydrofluoric acid and sulfur dioxide, 75 cubic meters of wastewater, and one ton of radioactive residue).[7]

At China's Bayan Obo mine, the largest mine in the world, the tailing pond that stores 70,000 tons of radioactive thorium has begun to seep into the groundwater and may eventually hit the Yellow River, a key water source.[7] There are many other examples of unsafe mines that could have catastrophic environmental impacts if not properly monitored and safeguarded.

This is where governments and international bodies should take active roles, with greater technological investment required in cleaner methods of extraction and alternative technologies that rely less on REs.

How can rare earths support the energy transition more sustainably?

Firstly, time must be taken to evaluate RE opportunities, ensuring social and environmental safeguards are considered and government and international policies are adhered to. Advancement of technology has driven the extracting process to be more sustainable, with alternative methods including;

Bio-leaching where naturally produced organic acids are used to pull REs. These bacterial acids are less efficient compared to hydrochloric acid, impacting the commercials of extraction.

Electricity currents have been used to free heavy REs like dysprosium and terbium from ores. This reduces the need for chemicals, polluting less, however is energy intensive.

Substituting materials is an alternative approach, with companies investing in R&D and adapting product designs with less or no need for REs.[8] Alternative technologies, which have been discussed previously, show manufacturers like Tesla, Renault and BMW investing in substitute materials, however this may make batteries less powerful, though cars that are mainly driven in cities may not need as long a battery life.[8] With continued technological advancement in this area, including magnetic substitutes, the reliance on REs has pushed R&D into new avenues which could provide cleaner solutions to supplying green tech.

What about recycling rare earths?

The amount of EV batteries becoming obsolete will surge after 2030 at a time when demand will be rising, and development in recycling could alleviate supply requirements, as well as provide security benefits to countries more reliant on clean energy or with little reserves.

The problem is that REs are often blended with other metals (e.g. in smartphones), making their removal difficult. Traditional recycling methods require hazardous chemicals (such as hydrochloric acid) and a lot of heat (and therefore energy). The environmental impact of this process and the cost of recovery could impact the viability of recycling as a solution.

Research into recovering rare earths from EVs drive units determined that recycled REs would cost double compared to mined rare earths from China.[9] If market prices changed, then the viability of recycling could shift, however investment into developing this technology is limited due to the competitiveness of China and its relative low production costs, meaning capital could be better focused elsewhere.

In the absence of an alternative to REs, only global regulations that try to balance commercial motivations with environment obligations may be the driver for increased recycling.

Rare earths in the Middle East

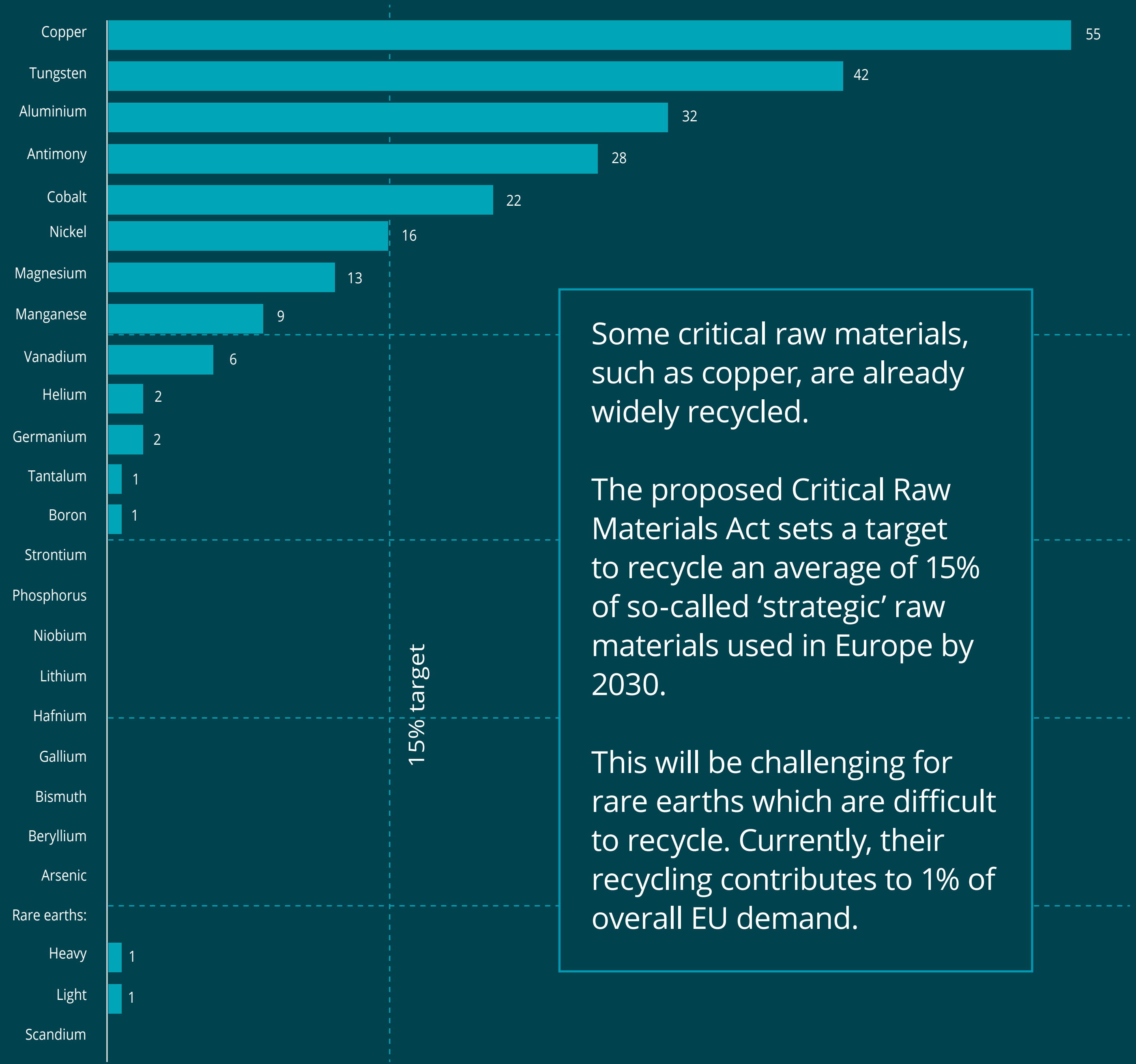
In the Middle East, Saudi Arabia has significant mineral and metal reserves. The Arabian Shield, which flanks the Red Sea, contains valuable REs such as tantalum. Saudi Arabia holds a quarter of the world's reserves, which are used in electronics, medical devices, and chemical processing equipment. Additionally, Saudi Arabia holds niobium reserves used in energy storage technologies like batteries, as well as in aerospace and steel production.[10]

As part of KSA's Vision 2030, the mining sector has been identified as a key market for diversifying away from oil and gas, aiming to more than triple the sector's contribution to GDP. The ongoing clean energy transition and increase in EVs will no doubt impact global oil demand. KSA and UAE are therefore focusing on a non-fossil fuel-dependent model by increasing investment in mineral supply chains, with KSA establishing a joint venture with Japan to explore development projects.[18] This potential new supply option is expected to bring greater stability to the market.

Given the water-intensive process required in a desert region, such a mining initiative may not be feasible without considering the use of expensive desalinated water, high energy costs, and environmental risks to aquifers, which could be contaminated from these mining methods.

The recycling of many critical raw materials makes a marginal contribution to the EU's consumption

% of overall demand that can be satisfied through recycled raw materials



Some critical raw materials, such as copper, are already widely recycled.

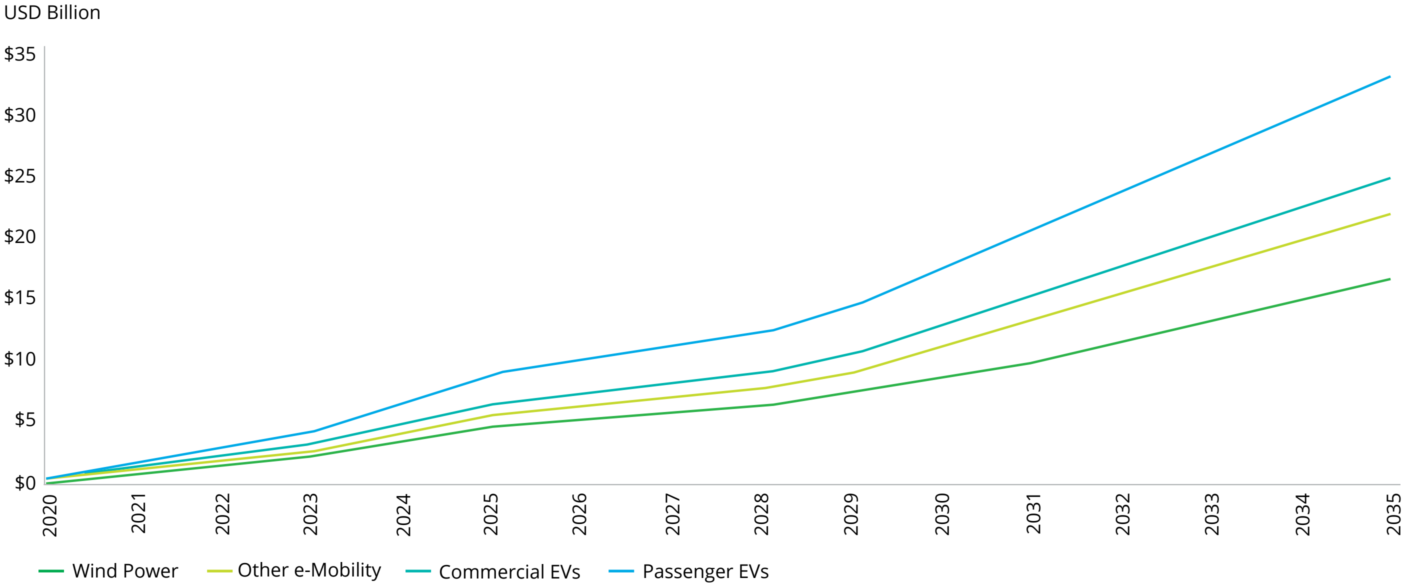
The proposed Critical Raw Materials Act sets a target to recycle an average of 15% of so-called 'strategic' raw materials used in Europe by 2030.

This will be challenging for rare earths which are difficult to recycle. Currently, their recycling contributes to 1% of overall EU demand.

Only materials with available data are shown

Source: EU

Value of rare earths used in energy transition to skyrocket by 2035



Source: Adamas Intelligence

Recommendations

The supply of rare earths offers new and distinct challenges that require coordinated efforts in research, policy, and industry to ensure a stable and sustainable supply of these vital resources. This will be enabled by the following:

Sufficient investment is required to diversify sources of new supply. Governments need to create the right environment to incentivize new project development. Providing clarity on the direction of energy transition will support timely investment.

In the wake of COVID-19 and the Ukraine War, supply chain resilience has become an increasingly critical aspect of national risk management. Ongoing market assessments for vulnerabilities are essential, with responses to potential supply disruptions or government restrictions (such as tariffs) supported by expanded supply routes and stockpiling options.

Technological advancements across the value chain are essential for improving efficiencies and reducing waste. Innovation in extraction, manufacturing, and recycling processes should bring significant environmental and security benefits, particularly through the adoption of circular economy principles offering secondary supply options.

Environmental and social standards should be established by governments and supported by international frameworks with sustainable and responsible practices monitored. Incentives to reward efficient production processes will encourage investment in cleaner energy transitions. Collaboration among global partners will be crucial to ensuring rare earths are extracted and processed in the most environmentally friendly manner.

Conclusion

Environmental challenges resulting from the rare earth supply chain do not diminish the significant climate benefits of clean energy. The expected increase in demand raises concerns about the availability and reliability of supply, as well as geopolitical autonomy and economic competitiveness. If investment opportunities are delayed, this could cause price volatility, potentially delaying the clean energy transition. Given the pressing need to reduce emissions, these are risks that should be managed to achieve a low carbon economy.

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