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Most In-Demand Rare Earth Elements for the Green Transition and AI Revolution

Rare earth elements (REEs) have become *strategic enablers* of both clean energy technologies and advanced electronics. These 17 metals (the 15 lanthanides plus yttrium and scandium) feature unique magnetic, optical, and chemical properties that make them *indispensable* in electric vehicle (EV) motors, wind turbine generators, energy-efficient lighting, and high-tech devices. In particular, **neodymium (Nd)** and **praseodymium (Pr)** are vital for the strongest permanent magnets, while **dysprosium (Dy)** and **terbium (Tb)** are critical heavy REEs used to enhance magnet performance at high temperatures. **Yttrium (Y)**, often grouped with heavy REEs, is widely used in phosphors, lasers, and advanced ceramics. Demand for these elements is *surging* as nations pursue electrification and as computing/AI hardware proliferates. This report profiles the key REEs expected to be most in-demand over the next decade (to mid-2030s), examining their applications, demand growth, geological sources, major producers, and recent supply chain developments.

Rising Demand in Clean Energy and High-Tech Applications

Global demand for critical minerals is rising rapidly due to the clean energy transition. Rare earth magnets are essential for high-performance *electric motors and wind turbines*, giving these technologies high power density and efficiency. The International Energy Agency notes that wind turbines alone could account for as much as 60% of rare-earth magnet demand in ambitious net-zero scenarios, with EVs adding further pressure. As a result, rare earth demand growth is outpacing most other minerals. For example, **magnet rare earths** (Nd, Pr, Dy, Tb) represented ~30% of REE volume in 2022 but over 80% of total REE market value. Driven by EV adoption and renewable energy, global demand for these magnetic REEs is projected to *triple*, from about 59,000 tonnes in 2022 to 176,000 tonnes by 2035. This represents an ~8–9% annual growth rate – a trend that far exceeds historical production growth and is already leading to projected shortages. Analysts forecast that by 2030–2035, demand could exceed supply by ~30% (on the order of tens of thousands of tonnes) **if new mines and separation facilities are not brought online**. In short, **the 2020s and 2030s will see unprecedented REE demand growth**, largely concentrated in a few elements used for clean tech magnets. Table 1 provides an overview of the most critical REEs, their roles, and demand outlook.

Table 1. Key Rare Earth Elements – Applications and Demand Outlook (2025–2035)

Element (Symbol)	Category & Key Uses	Demand Trend (Next 10+ Years)
Neodymium (Nd)	Light REE; main component in Nd-Fe-B permanent magnets (EV motors, wind turbines); also in lasers (Nd:YAG) and audio equipment.	**Surging:** Core magnet metal. EV/wind growth driving multi-fold increase in Nd demand. Projected Nd (with Pr) shortages ~16,000 t by 2030 absent new supply.

Element (Symbol)	Category & Key Uses	Demand Trend (Next 10+ Years)
Praseodymium (Pr)	Light REE; alloyed with Nd in magnets (improves thermal stability); used in high-strength alloys for aircraft engines and in specialty glass (welding goggles).	**Surging (with Nd):** Demand closely linked with Nd for magnets. Included in combined NdPr oxide output; expected to rise in tandem with Nd as EV/wind expand.
Dysprosium (Dy)	Heavy REE; additive in NdFeB magnets for high-temperature resilience (EV motors, generators); also in laser materials and nuclear control rods.	**Critical & Constrained:** High growth from magnet sector. By 2030, Dy demand may exceed supply by ~1,850 t (≈100% of current output), making Dy a major bottleneck for EV and wind tech.
Terbium (Tb)	Heavy REE; added to magnets for extreme high-temp performance; key phosphor for green light in LEDs and fluorescent lamps; used in magnetostrictive alloys (Terfenol-D for actuators).	**High Growth, Very Scarce:** Strong demand in magnets (small % but essential). Global Tb supply is only a few hundred tonnes; rising needs in magnets and efficient lighting will strain limited ionic clay sources. Tb is among the highest value REEs due to rarity.
Yttrium (Y)	Often classified as heavy REE; widely used in red and white phosphors (TV and LED displays, efficient lighting), YAG lasers (industrial, medical), ceramics (Y-stabilized zirconia in fuel cells), and superconductors (YBCO).	**Steady Growth:** Increasing use in energy-efficient lighting and high-tech electronics. Not as explosive as magnet metals, but Y remains in **high demand** for LEDs, lasers, and emerging tech. Primary supply as a heavy REE by-product; potential growth in *fuel cell and quantum tech* could boost demand.

Sources: Clean energy and electronics applications from ; demand projections from .

Each of these five REEs plays a **strategic role**. Below, we examine each in detail, including its industrial applications, projected demand growth, typical geologic occurrence, major producing regions, and supply chain outlook (including recycling and innovation where applicable).

Neodymium (Nd) – The Magnet Powerhouse

Industrial Applications: Neodymium is the cornerstone of high-strength permanent magnets. $Nd_2Fe_{14}B$ (neodymium-iron-boron) magnets incorporate Nd (often alloyed with a bit of Pr) to achieve extremely high magnetic strength. They are *indispensable* for **EV traction motors** and **direct-drive wind turbine generators**, enabling compact, efficient electric drivetrains and generators. A typical EV uses 1–2 kg of Nd-Fe-B magnets in its motor(s), and a large wind turbine can contain hundreds of kilograms of Nd magnets. Nd-based magnets also appear in countless electronics (computer hard drives, headphones, MRI machines, robotics) due to their superior performance. Beyond magnets, neodymium compounds are used in specialty **optics and lasers** – for example, Nd:YAG (yttrium aluminum garnet) crystals are a common solid-state laser medium. Nd oxides also color glass (providing the purple tint in protective welder's goggles and studio lighting filters). However, **over 80% of Nd's value** comes from its role in magnets, making it *strategically vital* for clean energy and defense technologies.

Demand Trends: Neodymium demand is **skyrocketing** thanks to the global shift toward electrification. EV sales are growing exponentially (tens of millions of EVs per year by 2030), and ~90–97% of new EV models use NdFeB magnet motors for efficiency. Likewise, wind power installations (especially offshore turbines) are booming, many using direct-drive systems packed with Nd magnets. As a result, analysts project Nd (and Pr) consumption to **double or even triple** over the next decade. By one estimate, global demand for Nd-Pr oxide will reach ~125,000 tonnes per year by 2030 – more than double 2020 levels. McKinsey forecasts magnetic REE demand (dominated by Nd) will triple from 59 kt in 2022 to 176 kt in 2035. This growth far outpaces planned supply. Adamas Intelligence warns that **NdPr oxide demand will exceed supply by ~16,000 tonnes in 2030** – equivalent to roughly three times the annual output of Lynas (the largest non-Chinese producer). In other words, a significant *shortfall* is looming unless new mines and recycling considerably ramp up. The value of Nd is rising accordingly. Neodymium oxide prices spiked during previous shortages (e.g. the 2010–11 China export embargo) and could do so again as demand outstrips supply. Governments now classify Nd as a **critical material** given its irreplaceability in motors and generators.

Geologic Occurrence: Neodymium is a **Light REE (LREE)**, typically enriched in *carbonatite* and *alkaline igneous* deposits. It occurs alongside other light lanthanides (La, Ce, Pr, Sm, etc.) in minerals like **bastnäsite** (a REE fluorocarbonate) and **monazite** (a REE phosphate). The world's major Nd sources are bastnäsite-rich carbonatites such as **Bayan Obo** in China and **Mountain Pass** in the USA. Bayan Obo, the largest known REE deposit, is an iron-rich carbonatite in Inner Mongolia containing bastnäsite and monazite; it has been the workhorse of China's REE production. Mountain Pass in California is another carbonatite bastnäsite deposit historically mined for Nd (and other LREEs). Monazite sands (placers) are another source – these beach or river sand deposits (in India, Brazil, Australia, etc.) contain monazite that can be processed for Nd (and often yield thorium as a by-product). **Table 2** below shows common deposit types for rare earths. Notably, Nd is *abundant* (relative to many REEs) – it's more common in Earth's crust than lead – but **economic concentrations** are rare, hence the focus on these specific deposit types.

Table 2. Common Rare Earth Deposit Types and Associated Elements

Deposit Type	Primary REE Minerals	Typical REEs Enriched	Example Regions
Carbonatite & Alkaline Igneous (intrusive or volcanic)	*Bastnäsite, Monazite, Loparite, Eudialyte*	LREEs (La, Ce, Nd, Pr, some Sm, Eu); lesser heavy REEs in some peralkaline rocks	China (Bayan Obo), USA (Mountain Pass), Brazil, Russia, Angola, South Africa (Steenkampskraal)
Ion-Adsorption Clays (weathered granites)	*REE ions adsorbed on clay minerals*	HREEs (Dy, Tb, Y, Eu, etc. with some Nd, Pr) – highly enriched in mids and heavies	China (Jiangxi, Guangxi clays), Myanmar (Kachin clays)

Deposit Type	Primary REE Minerals	Typical REEs Enriched	Example Regions
Monazite-Bearing Placer Sands (alluvial or beach)	*Monazite, Xenotime*	Mixed REEs (typically rich in LREEs La, Ce, Nd, Pr, but also some Y, Gd, Dy in xenotime fraction); often high Th/U	India (Odisha sands), Australia, Brazil, Southeast USA (historically), South Africa
Other (Pegmatites, Veins, Sedimentary Phosphorites)	*Xenotime, Apatite, others*	Variable: e.g. some granite pegmatites yield Y, Er, etc. (xenotime); phosphorite nodules can have Y, La, etc.	Malaysia (tin mine xenotime by-product), Florida/Morocco (phosphate rock with REEs), Greenland (Kvanefjeld – rare peralkaline deposit with U/REE)

Neodymium is primarily mined from carbonatites and monazite placers (top rows).

Major Producers & Reserves: China is the dominant producer of Nd. It accounts for roughly 60–70% of global mine output of Nd-bearing ores and an even greater share of refined Nd oxide and metal supply. China's output is heavily focused on LREEs like Nd and Pr – for example, the **China Northern Rare Earth Group** (which runs Bayan Obo) produces large quantities of Nd-Pr. In 2024 China mined ~270,000 tonnes of rare earth oxides (REO) – a record high – with Nd and Pr being key outputs. Outside China, **the United States** (Mountain Pass mine) produced about 45,000 tonnes REO in 2024, mostly Nd-Pr concentrate that is exported for refining. **Australia** (Lynas Corporation's Mt. Weld mine) produced ~13,000 tonnes in 2024; Lynas is expanding to produce 12,000 tonnes of NdPr oxide annually by 2025. **Myanmar**, through ionic clay operations, also yields some Nd as co-product (though its 31,000 t production in 2024 is richer in Dy/Tb). Other countries with significant Nd reserves/projects include **Vietnam** (large reserves in NW highlands, though production is currently small), **Russia** (Lovozero loparite deposit on Kola Peninsula), **India** (beach sand monazite, modest production ~2,900 t), and **Africa** (e.g. Burundi's trial mining of monazite, South Africa's monazite at Steenkampskraal, and Malawi's carbonatite at Songwe). Many of these are future sources under development. The global rare earth reserve base is ample (over 120 million tonnes REO), but the **challenge is developing new mines and separation capacity** in time to meet Nd demand.

Supply Chain & Outlook: Neodymium's supply chain faces *significant bottlenecks*. Mining and processing are highly concentrated – in 2023 China still accounted for **>60% of NdPr mining and >80% of refining** worldwide. This concentration creates vulnerability. In late 2025, China expanded export controls to cover rare earth magnet materials and even finished products containing Chinese REEs. Earlier, in April 2025, China had suddenly imposed export licenses on certain rare earth compounds and magnets (initially targeting heavy REEs), causing **sharp drops in magnet exports and price spikes** for manufacturers abroad. While those specific April controls mainly hit Dy/Tb, they sent a warning that even NdPr supply could be indirectly choked (since NdFeB magnets were affected). Automakers in the U.S. and Europe reported struggles securing enough magnets, with some forced to slow production. Going forward, **diversifying Nd supply** is a priority in the West: the U.S. has deemed NdPr magnets critical for defense and has funded processing facilities (e.g. MP Materials and Lynas are building separation and magnet plants in the US). The EU and Japan are also investing in rare earth projects and magnet recycling.

On the *demand management* side, manufacturers are exploring innovations to use less Nd. Some EV makers (BMW, Renault) have developed motors that **contain no rare earth magnets**, opting for induction or wound-rotor designs. These avoid Nd entirely but sacrifice some efficiency and range. Others (Toyota, VW) are tinkering with magnet chemistry – for instance, Toyota in 2018 announced a new Nd-reduced magnet that uses 20–50% less neodymium by substituting more abundant lanthanum and cerium, while eliminating Dy/Tb. This “didymium alloy” approach maintains performance with cheaper REEs, though it’s not yet widely adopted. In summary, **neodymium will remain in high demand** and short supply. Even aggressive recycling and substitution won’t fully bridge the gap in the coming decade. By 2035, secondary recycled Nd from end-of-life magnets could contribute meaningfully, but still only ~10–15% of total magnet material according to IEA forecasts. Thus, significant new primary production (and processing capacity) must come online to avoid Nd shortages that could bottleneck the green transition.

Praseodymium (Pr) – Magnet Alloy and Specialty Glass Metal

Industrial Applications: Praseodymium is another light lanthanide that is typically found and used in conjunction with neodymium. In NdFeB magnets, Pr can substitute for some Nd; in fact, many commercial magnet alloys use a mix of Nd and Pr (often called didymium after the historical name for the Nd-Pr oxide mix). Adding praseodymium confers **greater thermal stability** to magnets, which is beneficial in EV motors that run hot. Praseodymium is also used in **high-strength metal alloys**: for example, it’s added to magnesium and aluminum alloys used in aircraft engines and aerospace components to improve strength and creep resistance. Another notable use is in specialized **optical materials** – Pr ions impart a yellow-green color in glass and enamel, used in makers of safety goggles (to filter certain light) and in studio lighting. Praseodymium-doped glass (along with neodymium) is responsible for the distinctive coloration of welder’s goggles which block the bright yellow sodium D-line emissions. In combination with neodymium, praseodymium is used in **didymium glass filters** for glass-blowing and in certain camera optics. Praseodymium is also a component of some **catalysts** and carbon arc lamp electrodes, and has niche roles in ceramic glazes and UV-blocking glass. Overall, however, its **primary strategic role is as a magnet alloying element**, paired with Nd. Four REEs dominate the magnet sector – Nd and Pr as main ingredients, Dy and Tb as additives – underscoring Pr’s importance despite its lesser fame than Nd.

Demand Trends: Praseodymium’s fate closely tracks that of neodymium. Demand for Pr will **rise steeply** because virtually every Nd-iron-boron magnet contains Pr as well. Industry reports often quote combined **NdPr** oxide demand growth. As mentioned, magnet rare earth demand is set to *triple* by 2035, and NdPr oxide shortages of >16,000 t are projected by 2030 if new supply lags. Praseodymium usually comprises about 20–25% of the didymium (Nd+Pr) mix in bastnäsite-derived concentrates, so it is somewhat less abundant than Nd. Nonetheless, **Pr is indispensable**: without praseodymium, magnets would have lower intrinsic coercivity and less temperature stability, impairing performance. We can expect Pr demand to **grow in tandem with Nd** at roughly ~8–10% CAGR through the 2020s. There are a few independent demand drivers for Pr: for instance, if *metal-hydride batteries* (like NiMH) see renewed use in some hybrid vehicles or stationary storage, Pr is often used (with Nd) in the mischmetal alloy for NiMH electrodes. However, NiMH is generally declining as lithium-ion batteries dominate EVs. On the other hand, **high-tech alloy demand** (e.g. in jet engines) for Pr may rise modestly with aerospace growth. Overall, Pr’s demand outlook is tightly coupled to the magnet market and thus to EV/wind trends. Current prices for Pr oxide have followed Nd’s upward trajectory and will likely remain elevated given the supply tightness for NdPr feedstock.

Geologic Occurrence: Praseodymium is a **light REE** commonly found in the exact same ores as neodymium. In bastnäsite, monazite, and other LREE-rich minerals, Pr typically constitutes a few percent of the total rare earth oxide (with Nd, La, Ce being the largest fractions). Thus, **carbonatite deposits** (like

Bayan Obo, Mountain Pass, etc.) and **placer monazite sands** are primary Pr sources, identical to Nd sources. There are no known deposits where praseodymium is uniquely concentrated more than Nd; they are chemically so similar that they invariably occur together. In fact, early rare-earth chemists initially did not distinguish Pr and Nd, thinking they were one element ("didymium") until Carl Auer von Welsbach separated them in 1885. Some peralkaline (alkaline igneous) complexes, like **Mount Weld** (Australia) or **Nolan's Bore** (Australia), have high Nd and Pr as well. **Ion-adsorption clays** (in China) are typically richer in heavy REEs and yttrium, but they do contain some Pr (and Nd) at lower concentrations; however, clays are not a primary Pr source due to low yields of light REEs. In summary, Pr shares the geology of Nd – wherever Nd is mined, Pr is co-produced in a fixed proportion.

Major Producers & Regions: The production profile for praseodymium is essentially the same as for neodymium, since they come out of the ground together. **China** is the leading Pr producer (as part of its NdPr output) – Bayan Obo's bastnäsite ore, for instance, contains roughly 5% Pr_2O_3 by weight (alongside ~18% Nd_2O_3, ~50% CeO_2, etc.). Chinese REE separation plants (e.g. in Baotou, Sichuan, Jiangxi) refine mixed RE carbonate or chloride into individual oxides including Pr. **Lynas** in Australia produces a combined NdPr oxide (didymium) from Mt. Weld ore and has been one of the few non-Chinese suppliers; in 2022 Lynas produced ~7,000 tonnes NdPr oxide and plans 12,000 t in 2025. **MP Materials** (USA) similarly produces a didymium concentrate (they ship ~5,000–6,000 tonnes NdPr oxide equivalent to China for toll separation, although a new separation plant in Texas is under construction). **Myanmar's** ionic clay operations yield little praseodymium (their output is focused on Dy/Tb), so they are not a major Pr source. Other potential future producers of NdPr include **Arafura Resources** (developing the Nolans NdPr project in Australia's Northern Territory, with government backing), **Pensana** (Angola/UK project), **Peak Rare Earths** (Ngualla in Tanzania), and **Greenland** (Kvanefjeld, stalled due to uranium issues). Given the lengthy timelines, these will likely come online gradually over the next decade. Meanwhile, **global reserves** of praseodymium are ample in situ (found wherever Nd is), but *processing bottlenecks* make refined Pr relatively scarce.

Supply Chain & Innovations: Praseodymium faces the same supply chain vulnerabilities as neodymium – heavy reliance on Chinese mining/quota systems and separation facilities. Any disruption in China's LREE production (whether from quota cuts, export restrictions, or environmental crackdowns on illegal mining) affects Pr availability. Interestingly, China has become a **net importer** of some rare earth concentrates in recent years, seeking more feedstock to meet magnet demand – meaning even China's huge Bayan Obo mine is not enough for the world's NdPr needs. Western governments are therefore keen on *securing NdPr supply chains*. The U.S. Department of Defense has funded Lynas and MP for domestic separation of NdPr, and the EU's Critical Raw Materials Act aims to have 15% of its REE demand met by recycling by 2030. For Pr (and Nd), **magnet recycling** is the most promising secondary source. Recycling initiatives (Hitachi in Japan, Urban Mining Co. in the US, etc.) can extract NdPr from scrap magnets and end-of-life motors. The IEA estimates that by 2040, recycling retired EV motors and wind turbine magnets could supply about 15% of overall REE magnet material – which will include Pr. However, near-term (2020s) recycled volumes are small; globally, projects announced so far aim to process ~8,000 tonnes of REEs from magnet waste by 2026 (roughly 7% of forecast 2026 demand). On the innovation front, praseodymium will benefit from any advances in magnet tech that reduce reliance on heavy REEs: for example, some new magnet alloys use **Praseodymium-rich formulas** to avoid dysprosium. Research has shown that adding a bit more Pr (and less Nd) can slightly enhance coercivity without needing Dy, since Pr has a lower Curie temperature. These nuanced tweaks, along with grain boundary engineering, are being explored to create **Dy-free magnets** for EVs. If successful, such magnets would actually increase Pr consumption (while reducing Dy). In summary, praseodymium's strategic importance is *tightly intertwined* with neodymium – ensuring adequate NdPr supply is critical for the green transition. Pr will continue to be produced and discussed in tandem with Nd, rather than on its own, but it is no less important an element in the equation.

Dysprosium (Dy) – High-Temperature Magnet Strengthener

Industrial Applications: Dysprosium is a **heavy rare earth** that is crucial for making NdFeB magnets function under high-temperature conditions. When added in small amounts (typically 2–6% of the alloy), Dy dramatically increases a magnet's **coercivity** (resistance to demagnetization) at elevated temperatures. This is vital for **EV motors, wind turbines, and aerospace electric drives**, which can run hot – pure $Nd_2Fe_{14}B$ magnets start losing strength above ~80°C, but Dy-doped magnets maintain performance up to ~180°C or more. In practice, almost every NdFeB magnet in a traction motor or generator contains some dysprosium (or terbium) to ensure reliability in service. Beyond magnets, dysprosium's neutron-absorbing property makes it useful in **nuclear reactor control rods** (though gadolinium is more common there). Dy is also used in certain laser materials and phosphor compounds, but these are minor uses compared to magnets. A unique alloy, **Terfenol-D** (TbDyFe), uses dysprosium and terbium for giant magnetostrictive actuators in sonar and precision positioning devices. In summary, dysprosium's strategic value lies in enabling **high-performance magnets for demanding applications** – there is *no easy substitute* for its role in raising the high-temp capabilities of magnets.

Demand Trends: Dysprosium is often cited as one of the most critical and constrained rare earths. Demand for Dy is **soaring** in step with the expansion of EVs and wind turbines. Even though only a few percent of a magnet is Dy, the sheer volume of magnets being produced means Dysprosium requirements are climbing quickly. Adamas Intelligence projects that **global Dy oxide demand will increasingly exceed production each year through 2030, leading to the depletion of stockpiles and acute shortages if supply doesn't expand**. Specifically, by 2030 dysprosium demand is forecast to surpass annual output by **~1,850 tonnes**, roughly equal to the entire world mine production of Dy today. In other words, a doubling of Dy supply would be needed to balance the market, which is a tall order. For perspective, global dysprosium oxide production in recent years has been on the order of only 1,500–2,000 tonnes (mostly from China's ionic clays). A 2023 analysis noted that dysprosium, terbium, and neodymium are all at risk of severe deficits by the late 2020s if EV and renewable trends continue unabated. The *value* of Dy reflects its scarcity – it commands one of the highest prices per kg among REEs. During the 2011 rare earth crisis, Dy oxide prices spiked above \$1,000/kg. While they are lower now, any sign of export restriction or supply shortfall sends dysprosium prices sharply up. For example, when rumors of China reducing Dy export quotas emerged, magnet manufacturers scrambled to thrift dysprosium usage. Indeed, companies have been actively **reducing Dy per magnet** (via improved grain alignment, or partial Tb substitution) to mitigate dependency. Tesla famously designed its Model 3 motor to use a *no-dysprosium magnet* (using terbium instead in a smaller amount). Nevertheless, aggregate Dy demand will continue to increase due to overall magnet volume growth, even if the Dy % per magnet is slightly reduced. Projections by the U.S. Department of Energy and others foresee dysprosium consumption in magnets growing several-fold by 2035, making it *one of the rate-limiting elements* for EV deployment if new sources are not developed.

Geologic Occurrence: Dysprosium is a **Heavy REE (HREE)**, and nature distributes it differently than the lights like Nd/Pr. The principal Dy ores are the **ion-adsorption clay deposits** of southern China (and more recently, Myanmar). In those deposits, HREEs like Dy and Tb are not in distinct minerals but rather *adsorbed* as ions on clay particle surfaces, formed by deep weathering of REE-rich granites. These clays have relatively low REE concentrations (0.05–0.3% typically) but are easily mined and leached with mild chemicals – and, importantly, they are *HREE-enriched*, sometimes containing over 1% of the total REEs as Dy (which is high relative to other ores). **China's Jiangxi, Guangdong, Guangxi, and Fujian provinces** have been the traditional source of Dy/Tb from such clays. In the last decade, similar ionic clays in **northern Myanmar** have become a major source supplying China. Outside of clays, some **xenotime**-rich deposits (xenotime is YPO_4 which contains heavy REEs) can yield dysprosium. Historically, xenotime sand by-products from tin mining in Malaysia provided small quantities of Dy and other HREEs. Additionally, certain hardrock deposits like **Brown's Range** (Australia) are hosted in altered xenotime and are being developed explicitly for Dy and Tb production. However, no hardrock mine has yet produced significant dysprosium – nearly all of it comes from clay adsorption ores. This means dysprosium geology is concentrated in a few regions with specific weathering environments. Notably, **carbonatite LREE mines (like Bayan Obo, Mountain Pass)** produce very little Dy (their ore is LREE-heavy, with Dy typically <0.1% of total REEs). Thus, expanding overall REE mining (Nd, etc.) doesn't automatically yield enough Dy; dedicated heavy RE sources are needed.

Major Producers & Regions: China and Myanmar effectively control dysprosium mining. China's output of dysprosium comes primarily from ionic clay operations in the south. To illustrate, China obtained about **70% of its medium-to-heavy REE ore feedstock from Myanmar in recent years** – reflecting how Chinese merchants import HREE-rich clays from across the border (Myanmar's Kachin State) to process in China. In 2024, Myanmar produced ~31,000 t of REO, heavily weighted toward Dy/Tb, although production was down from 43,000 t in 2023 due to conflict-related disruptions. When fighting in Myanmar flares (as happened in late 2024 with a local militia seizing a key mining region), China's heavy RE supply is directly impacted. Within China, official production is quota-limited; the 2022 mining quota for ionic clays was around 19,000 t REO. Illegal mining has at times exceeded that, causing environmental damage. The Chinese government has consolidated state-owned RE firms and cracked down on wildcat miners to better control HREE output. Outside China/Myanmar, **Australia** is poised to become a new producer: Northern Minerals Ltd. has a pilot plant at **Browns Range (Western Australia)** which produced small quantities of Dy/Tb in a test phase, and a full-scale project feasibility is underway. If developed, Browns Range could be one of the first non-Chinese Dy mines, albeit its planned scale (~200 t Dy oxide/yr) would only modestly dent global needs. Other countries with heavy RE potential include **Madagascar**, which has ionic clay resources (the Ampasindava deposit is estimated to be rich in Dy, Nd, Eu [1]) – though environmental and community concerns have stalled development. **Indonesia, Vietnam, Thailand** also have ion-clay prospects: notably, **Thailand** rapidly ramped up RE output to ~13,000 t in 2024 (from just 1,000 t in 2018), possibly indicating ionic clay exploitation there as well. If so, Thai clays might become a new source of Dy sold to China. The **USA and Europe** currently have *no primary Dy production*. Projects like Round Top (Texas) could yield some Dy as byproduct of Y-rich deposits, but those are still in early stages. Thus, in the short term, dysprosium supply remains *heavily concentrated* in China/Myanmar, with Australia and others striving to add diversity.

Supply Chain & Developments: Dysprosium's tight supply-demand balance has made it a focus of recent geopolitical moves. In **July 2023**, China hinted at export controls on HREEs in response to semiconductor chip material sanctions; and indeed in **April 2025, China implemented new export controls on seven rare earth elements – mainly heavy REEs like dysprosium, terbium, holmium, etc. – as well as related alloys and magnets**. This move caused immediate anxiety among magnet makers worldwide. Even though Chinese officials framed it as protecting national security (preventing advanced military tech exports), the effect was to underscore China's leverage. Prices for dysprosium and terbium outside China jumped (European prices went up to 6× higher than Chinese domestic prices in mid-2025). Then, in October 2025, China *escalated* restrictions by requiring licenses even for foreign products containing Chinese-sourced rare earths, and added **five more elements to the controlled list (holmium, erbium, thulium, europium, ytterbium)**. This effectively means **the entire suite of heavy REEs is now under export control**, since Dy and Tb were in the initial April list and others like Ho, Yb, Eu were added in November. These policies pose a major risk for industries relying on dysprosium-containing magnets (energy, automotive, defense, even AI data centers which use powerful electric motors and cooling systems). Western countries are scrambling to respond. The U.S. Inflation Reduction Act and defense procurement policies aim to develop **stockpiles and alternative supply** for Dy. Japan, since the 2010 scare, reduced its Dy usage significantly (through technological efficiency and recycling) – Japanese manufacturers cut rare earth consumption by nearly 50% over a decade. This was achieved by research into **low-Dy or Dy-free magnet designs**. Many automakers are following suit: for example, **Toyota**'s new magnet design entirely eliminates Dy and Tb by substituting other elements, and **Tesla** managed to avoid Dy in some motors. However, these innovations often rely on terbium or on more complex motor designs, and may not fully eliminate performance trade-offs.

Another avenue is **recycling**: End-of-life magnets from hybrid vehicles, large electric motors, and wind turbines contain dysprosium that can be recovered. As first generations of hybrid/EV motors reach scrap (and old wind turbine generators get decommissioned in the 2030s), a substantial "urban mine" of dysprosium will emerge. The IEA projects that by 2040, recycled magnets from wind/EV could supply ~25% of heavy REE requirements for those sectors and by 2050 up to 50% for wind turbines. Current pilot projects – in Europe (Solvay, Less Common Metals), Japan (Hitachi's rare earth magnet recycling line), and the US – are developing the tech to extract and separate Dy and Nd from magnet scrap. **Direct recycling of magnets** (re-melting or re-sintering magnet scrap into new magnets) is also being explored, which would retain dysprosium without needing full chemical separation. These efforts are promising but need scaling. As of mid-2020s, less than 5% of REE magnet material is recycled.

In the interim, **material efficiency innovations** are helping reduce Dy per unit of output. Grain boundary diffusion technology allows adding a dysprosium-rich coating to finished NdFeB magnet grains, greatly enhancing coercivity with less total Dy usage (since Dy concentrates at magnet grain boundaries where demagnetization starts). This has cut Dy needs by 30–50% in some magnet grades. Additionally, some companies substitute terbium (even more effective per atom, albeit rarer) for part of the Dy in magnets, achieving the same effect with a smaller atomic fraction. However, terbium itself is extremely scarce (see below).

Looking ahead, dysprosium will likely remain a **choke point** for the green tech supply chain. Its unique role in magnets means that *if* supply cannot keep up, industries may be forced into suboptimal solutions (heavier motors without REEs, or reduced performance). Governments and industry are treating Dy (and Tb) with the same strategic urgency as semiconductors or lithium – efforts are underway to establish secure supply lines through friendly nations and to invest in new HREE mines. The next 5–10 years will tell whether alternatives can meaningfully reduce dysprosium dependence or whether new sources (e.g., clays in other countries) can alleviate the pressure. For now, **dysprosium's demand trajectory is sharply upward, while its supply is constrained and concentrated**, making it one of the most critical elements in the clean energy materials matrix.

Terbium (Tb) – The Green Phosphor and Magnet Booster

Industrial Applications: Terbium is another heavy rare earth with a few specialized but crucial uses. In NdFeB magnets, terbium can play a similar role to dysprosium: Tb^{3+} also increases the magnet's coercivity when substituted into the $Nd_2Fe_{14}B$ crystal lattice. In fact, terbium is even more effective than dysprosium on a per-atom basis, allowing for high-temperature magnets with slightly less total addition. However, terbium is exceedingly rare and expensive, so it is typically used sparingly – often **only a small fraction** of the heavy REE content in magnets (the rest being Dy). Some high-performance magnet grades for extreme conditions (e.g. certain aerospace or EV applications) may use Tb to partially replace Dy, or in combination (Terfenol-D alloy is one example where Tb and Dy are combined in an iron matrix for magnetostrictive actuators). Outside magnets, terbium has an important legacy use in **phosphor materials**. Tb^{3+} emits bright green light when excited, making it the key ingredient in green phosphor for color display tubes and fluorescent lamps (the classic tri-color phosphor mix in fluorescent lights used Tb for green, europium for red, and Eu/Tb for blue). Even today, in **LED lighting**, terbium is used in some phosphor blends to create high-quality white light – for example, "terbium-doped phosphors" can broaden the spectrum of LED emission to improve color rendering. Terbium oxide (Tb_4O_7) is used to make these phosphors. Additionally, terbium is used in certain high-index **optical glass** and as a dopant in solid-state devices (Tb-doped garnets for specialized lasers or scintillators). Another niche: terbium alloys are used in magneto-optic data storage (TbFeCo alloys in rewritable optical discs) due to their Faraday rotation properties. Summing up, terbium's main strategic roles are: **(a)** enabling top-tier permanent magnets (with minimal addition) and **(b)** providing green light in efficient lighting and displays.

Demand Trends: Although the absolute volume of terbium required is small, demand is growing and supply is tight, placing Tb in the category of *highly critical* rare earths. For magnets: if manufacturers reduce dysprosium content, they often substitute some terbium to maintain coercivity, so Tb demand can increase as a result of Dy thrifting strategies. Some reports indicate that next-generation magnets might rely more on Tb because each percent of Tb can replace a couple percent of Dy. In the EV/wind boom, this could cause terbium usage in magnets to climb significantly (albeit from a low base). On the phosphor side, the phase-out of fluorescent lamps (due to LED adoption) has reduced terbium demand for lighting compared to its peak in the 2000s. However, LED phosphors still require some terbium and europium, and the overall growth of LED and laser markets partly offsets the decline in fluorescent lamps. Additionally, new mini-LED and micro-LED display technologies continue to use phosphor layers that include Tb for green pixels. The net effect is that **magnet demand is now the dominant driver for terbium**, and it is expected to more than double Tb consumption over the next decade. Precise figures are hard to come by (analyst forecasts for Tb often are rolled into Dy/Tb together), but we know that current global terbium oxide production is extremely limited – on the order of only ~300–400 tonnes per year or less. Adamas has noted that terbium, like dysprosium, faces looming shortages without new supply. One forecast by the U.S. DOE indicated Tb demand for magnets in a clean technology scenario could increase 4-6× by 2040 (similar in scale to Dy increases). Because terbium is so scarce, any growth in demand puts immediate strain on the market. Already, terbium oxide prices are among the highest of the rare earths, reflecting a tight market. In 2022–2023, Tb oxide traded in the range of \$1,500+ per kg in China, and spikes have occurred on news of export controls. With China's recent curbs on heavy REEs, terbium prices and availability outside China have been volatile. Overall, **terbium demand growth is strong but may be constrained by supply** – it's one of those elements where, if supply cannot rise, it could limit how much terbium companies can actually use (potentially forcing further innovation to avoid Tb).

Geologic Occurrence: Terbium generally occurs together with dysprosium and other heavy REEs in the same geological settings. The **ion-adsorption clays** of southern China and Myanmar are the primary source, containing terbium in the absorbed REE ion mixture. In these clays, typically Dy is about 1–2% of the total rare earth oxide and Tb is 0.2–0.5% (ratios vary). So Tb is present at roughly one-fifth to one-quarter the level of Dy in typical ionic clay ores. **Xenotime** (YPO_4) also carries terbium in small quantities, as do other heavy-rich minerals like **gadolinite** or **euxenite**, but none are mined specifically for Tb. Some advanced projects (e.g. Browns Range in Australia) list a Tb oxide output target of a few tens of tonnes per year, indicating how small the volumes are. For instance, Browns Range aims for ~110 tonnes of Tb_4O_7 and ~650 tonnes of Dy_2O_3 annually at full scale – highlighting that Tb is about one-sixth of Dy in that deposit's output, consistent with typical ratios. **No independent Tb deposits** are known; it is always a by-product of heavy rare earth extraction. One noteworthy point: because Tb is chemically similar to Gd and Dy, certain unique deposits like **Deep-sea muds** in the Pacific have been found to contain elevated heavy REEs including Tb (Japan has researched extracting REEs from deep ocean sediments near Minamitorishima). Those could in theory be a future Tb source, but that technology is nascent. On land, **phosphate rock** (as in fertilizer mines) contains tiny amounts of REEs including Tb, but not economically recoverable yet. In summary, terbium's geology ties it inseparably to dysprosium and the heavy REEs in clay or phosphate deposits, with ionic clays being the practical source for the foreseeable future.

Major Producers & Regions: Because terbium is extracted alongside dysprosium, **the same regional production applies**: China (including material sourced from Myanmar) produces the vast majority of the world's terbium. China's export quotas and production figures usually lump Dy and Tb (and sometimes all HREEs) together, but industry experts estimate that China produces on the order of 50–100 tonnes of terbium oxide annually. This comes from the ionic clay refining in Jiangxi/Guangdong and from processing of imported Myanmar clays. **Myanmar**'s share is significant; as noted earlier, 70% of China's heavy RE feedstock is imported from Myanmar, and those clays contain Tb. When Myanmar's supply was disrupted in late 2024 by conflict, terbium prices in China reportedly climbed, indicating how dependent China is on that source. **Thailand** might also now be contributing some heavy REE output (if their rapid production increase involves heavy-rich clays, some Tb is likely included). Outside of Asia, **no meaningful terbium production** exists yet. **Australia's** Browns Range project, if it comes online by late 2020s, could become the first Western Tb source, albeit small. **Nigeria** appeared as a surprise entrant in 2024 with 13,000 t REO production – the details are unclear, but if real, Nigeria may have tapped monazite or xenotime-rich sands (which could contain a bit of Tb). However, monazite sands are LREE-dominant, so any Tb from there would be minor. **Madagascar** had a project in the past (Tantalus) to extract heavy REEs from clays, but it stalled; if revived, it could produce Tb. **Vietnam** has large heavy REE reserves in pegmatite/aplite deposits, but again, development is uncertain. So, China remains the hub: it controls the separation facilities for Tb (which is challenging to separate from adjacent REEs). Also notable, **Estonia's Neo Performance Materials plant** (Silmet) processes some REE feedstock – historically they processed loparite from Russia and could produce some HREEs as a byproduct, but likely minimal Tb.

Supply Chain & Outlook: Terbium has gained notoriety as one of the scarcest of the critical minerals. The recent Chinese export policy changes implicitly target terbium: the April 2025 controls listed **gallium, germanium (semiconductor metals) and heavy rare earths including terbium** as restricted. Terbium metal and oxide now likely require export licenses, making it harder for non-Chinese companies to directly obtain. This has pushed companies to search for **terbium alternatives or recycling**. In magnets, if terbium is unavailable, manufacturers might have to use more dysprosium (which itself is limited) – not a great solution. Alternatively, they might accept lower performance or design motors to run cooler. Some magnet R&D has looked at using **cerium** as a partial substitute in magnets (cerium is abundant and cheap) – one Japanese project developed a Ce-based magnet material, but its magnetic strength is lower, making it unsuitable for traction motors without redesign. Thus, no trivial swap exists for Tb in magnets. On the phosphor side, LED manufacturers have largely optimized to minimize Tb usage. The shift from fluorescent tubes (which needed relatively large amounts of terbium in phosphor coatings) to LEDs (which use tiny phosphor amounts per diode) has actually *reduced* Tb consumption for lighting per lumen produced. So phosphor demand for Tb is not growing and in fact helped free up some supply for magnets. The **circular economy** potential for terbium comes mainly from recycling fluorescent lamp phosphors and magnet scrap. Lamp phosphor recycling was pioneered by companies like Solvay in the 2010s: they would dissolve spent phosphor powder from CFL bulbs and precipitate rare earth oxides, recovering Tb and Eu. This is technically feasible and was done at scale in Europe until fluorescent lamp usage started declining. There is still stock of old phosphor waste that could be processed for Tb if economics permit. For magnets, as mentioned, end-of-life EV motors in the 2030s will be rich sources. However, collecting and processing those will take time to ramp up.

In terms of *innovation*, an intriguing development in 2025 was that magnet makers started experimenting with **holmium (Ho)** as a partial substitute for Dy/Tb – because holmium is also a heavy REE with similar effects and was not initially restricted. However, in a twist, China's November 2025 expanded controls **added holmium** to the restricted list, specifically because some firms had pivoted to Ho in response to Dy/Tb controls. This cat-and-mouse shows how strategic these elements are. It also means terbium, dysprosium, **and** holmium are all tightly controlled now, leaving Western manufacturers limited options within the heavy RE family.

The endgame to reduce terbium dependency might be **new magnet materials altogether** – e.g., iron-nitride magnets, alnico or ferrite magnets with improved properties, or even entirely new magnetic compounds that don't require rare earths. Research is active in these areas (for example, $Fe_{16}N_2$ iron nitride was touted as a possible high-Ms magnet, and some theoretical work on samarium-iron-nitrogen compounds, etc.). But none are commercially on par with NdFeB yet for most applications. Until such breakthroughs occur, **terbium will remain a critical ingredient for the strongest magnets**.

In conclusion, terbium's next decade will be marked by *persistent tight supply*. Its demand is set by high-end magnets and efficient lighting/display technology – both likely to grow. Supply chain diversification for Tb is even more challenging than for Dy, given Tb's smaller volumes and fewer deposits. Any new heavy RE mining outside China will help, but ramping up from tens to hundreds of tonnes of Tb output is a big ask. Much like dysprosium, terbium underscores the need for **recycling and substitution innovations** in the rare earth world. Policymakers are well aware that Tb (and Dy) shortages could bottleneck green tech, so expect continued strategic stockpiling and R&D efforts surrounding this metal.

Yttrium (Y) – Phosphor and Alloy Workhorse Among Rare Earths

Industrial Applications: Yttrium is often grouped with the heavy rare earths (though it is not a lanthanide, it behaves like one chemically). It is a versatile metal used in a variety of high-tech applications, *especially in phosphors, ceramics, and alloys*. Perhaps the most well-known use of Y is in **phosphor powders** for lighting and displays. Yttrium oxide doped with europium (Y_2O_3:Eu^{3+}) produces a brilliant red phosphor that was critical for color televisions and CRT displays, and is still used in some LED phosphor mixes. Similarly, yttrium is part of "YAG:Ce" (yttrium-aluminum-garnet doped with cerium) phosphor, which is used to convert blue LED light into white light in most modern white LEDs. This *yellow-emitting YAG:Ce phosphor* is a backbone of LED lighting technology. Yttrium is also key in **yttrium iron garnets (YIG)** and **yttrium orthoferrite** materials used in microwave filters and transducers (e.g. in cellular communications). Another huge application is **advanced ceramics**: Yttria-stabilized zirconia (YSZ) is a ceramic where Y_2O_3 is added to ZrO_2 to stabilize its cubic phase; YSZ is used as the electrolyte in solid oxide fuel cells, in oxygen sensors (like those in car engines), and as a thermal barrier coating in jet engines. Yttrium oxide itself is a high-temperature ceramic used in gas turbine engine coatings and crucibles. In metallurgy, small additions of yttrium improve alloys: for example, adding Y to steel or chromium alloys helps grain refinement and reduces oxidation (it's a deoxidizer). Some magnesium and aluminum alloys meant for aerospace include yttrium for strength. Yttrium is also used in **lasers**: the host crystal in many solid-state lasers is yttrium aluminum garnet; when doped with neodymium you get the ubiquitous **Nd:YAG laser**, and when doped with erbium or others you get different laser wavelengths. This makes Y the backbone for many industrial, medical, and military lasers. Additionally, **medical uses**: Yttrium-90 is a radioisotope used in cancer therapy (radioembolization for liver cancer). Yttrium's spectrum of uses is broad – from color TVs and LED lamps to superconductors (the first high-Tc superconductor was $YBa_2Cu_3O_7$, "yttrium barium copper oxide") to electronics. Because of this, even though Y is not in magnets, it is considered strategically important for *electronics, lighting, and green energy tech* (fuel cells, lasers for manufacturing, etc.).

Demand Trends: Yttrium demand has evolved over time. It boomed in the late 20th century with color TVs (each CRT TV had grams of Y in the red phosphor) and stayed high with fluorescent lamp production. In recent years, as LEDs took over lighting, some traditional Y phosphor demand declined, but the **LED industry still relies on YAG phosphors** heavily. The net effect is that phosphor demand for Y has probably leveled off or slightly decreased from its peak (fewer fluorescent lamps, more efficient LEDs requiring less phosphor per lumen). However, new demand drivers are emerging: *clean energy and AI-related sectors* are increasing usage of yttrium-bearing materials. For example, **solid oxide fuel cells (SOFCs)** for stationary power or perhaps future hydrogen vehicles use YSZ electrolytes – if hydrogen economy efforts grow, Y demand for fuel cells could rise. **5G and next-gen telecommunications** use YIG filters in microwave circuits, potentially boosting Y consumption in electronics. The high-temperature ceramic applications in aircraft and turbines (which improve efficiency and thus reduce emissions) may also consume more Y as those industries adopt new materials. The mention of AI hardware might refer to the need for powerful lasers (for manufacturing chips or in LiDAR sensors for autonomous vehicles) – many of which are Nd:YAG or Yb:YAG lasers, again implicating Y. Also, data centers and quantum computing sometimes use YBCO high-temperature superconducting materials (still experimental for power cables, but could scale in the future). It's reasonable to say **yttrium demand will experience moderate growth** (not as explosive as Nd or Dy) but steady, diversified across sectors. According to Canada's NRCan, China produced ~240,000 tonnes of REO in 2023 of which a significant fraction is yttrium from ionic clays. Yttrium is relatively abundant in those clays, so supply has generally kept pace. One concern is that if ionic clay mining is curtailed (due to environmental or geopolitical reasons), Y supply would tighten. But at present, there is often a slight oversupply of light/heavy-medium REEs like yttrium and cerium because they are produced as byproducts of efforts to get Nd, Dy, etc. Prices for yttrium have been relatively stable and lower than those of Tb or Dy. The *value proposition* of recycling is also notable: significant Y (and Eu) can be reclaimed from fluorescent lamp waste, which could provide a secondary supply cushion. As of 2025, the *IEA* does not flag yttrium as in as critical shortage as magnet REEs, but it is still considered a **critical material** by many countries (USA, EU) due to its importance in defense (lasers, optics) and energy tech. The AI revolution's impact on Y may be indirect – more data centers and telecom = more YIG filters and possibly more laser-based manufacturing, but these are niche. Overall, expect yttrium usage to **grow modestly** in LEDs, lasers, and ceramics, maintaining it as one of the higher-volume REEs (by mass, Y oxide output is often second only to Ce and La in some Chinese REE operations, because those clays yield a lot of Y).

Geologic Occurrence: Yttrium is found in most rare earth deposits, typically following the heavy REEs. In fact, in many **ion-adsorption clays**, Y is the single most abundant REE present (even more than Dy or Nd), because Y is often about 2/3 of the "REO" content of those clays by weight. It is also a major component of **xenotime** (YPO_4) and **monazite** (which often has a yttrium component). The **primary sources** of yttrium today are the same ionic clay deposits in China/Myanmar that provide Dy/Tb. These clays yield a mixed rare earth carbonate that, when separated, produces substantial yttrium oxide. Historically, **monazite sand processing** (in places like India, Brazil) for thorium used to result in yttrium-rich residues (since Y and heavy REEs concentrate in the later fractions or in xenotime separated from monazite). In the mid-20th century, some yttrium was also extracted from **uranium ore tailings** – certain uranium deposits have rare earths, including Y. **Xenotime placers** in Malaysia and Indonesia (byproducts of tin mining) were a notable source of yttrium and heavy REEs in the 1980s. For instance, Malaysia's **Bukit Merah** facility extracted Y, Eu, Tb from tin tailings (that operation was controversial and closed in 1990s). **Hard rock deposits** such as *eudialyte-bearing* alkaline complexes (e.g. in Greenland, or Dubbo zirconia project in Australia) also contain yttrium, but none have been fully developed. Yttrium tends to be **geologically associated with heavy REEs** because of similar ionic size for Y^{3+} and Ho^{3+}, Er^{3+} etc., so minerals that incorporate heavy REEs often accept Y. Examples: **gadolinite** ($Y_2FeBe_2Si_2O_{10}$) in some pegmatites contains Y; **samarskite, fergusonite, bastnäsite** can have Y as minor substituent. But the economically dominant ones remain clays and xenotime. Yttrium is actually more abundant in the Earth's crust (~31 ppm) than lead, but it's so dispersed that concentrated deposits are uncommon. It typically piggybacks on other rare earth mining rather than being mined for itself.

Major Producers & Regions: China produces the lion's share of yttrium. The ionic clay belt in southern China (and the imported clays from Myanmar) feed refineries that produce yttrium oxide in large quantities. China's published export numbers for "yttrium oxide" have historically been substantial – for example, a decade ago China exported several hundred tonnes of Y_2O_3 annually. China's dominance in processing (over 90% for all REEs) means it also dominates Y refining. **Other current sources:** *Japan* and *Estonia* both import REE concentrates (from China or elsewhere) and can separate some yttrium – for instance, Neo Performance Materials' plant in Estonia might produce some Y compounds from whatever feed they use. *India* has sizable yttrium in its monazite stockpiles, and Indian Rare Earths Ltd (IREL) could potentially extract Y if demand rises, though currently India's output is modest. *Malaysia* houses Lynas's processing plant, which handles Mt. Weld LREE concentrate – that concentrate has little Y (Mt. Weld is LREE-rich, Y <1%), so Lynas's operation doesn't yield much Y. However, Malaysia's history with RE processing (the old Asian Rare Earth plant) means legacy wastes containing Y exist. *Russia* might have some Y production from its Lovozero loparite mine (loparite ore contains ~1% Y), but the scale is small (~2,000 t REO/year total from Lovozero, mostly Ce, Nb, etc.). *Australia* will produce some Y as byproduct in certain new projects (e.g., Nolans in NT is mostly NdPr but has some Y in its monazite component; if processed fully, it could yield a couple hundred tonnes of Y_2O_3 per year). *Kazakhstan* and *Uzbekistan* have uranium processing that occasionally recovers Y (a historic note: they had Y-rich ion exchange liquors from uranium mines, but not sure if currently exploited). As of 2025, China's near-monopoly on heavy REE separation means **most of the world's purified yttrium oxide comes from Chinese facilities**, even if some raw material originated in Myanmar or elsewhere. Notably, **yttrium is one of the materials that can be recycled relatively economically** from phosphor waste, and some countries have stockpiled it. The United States has some strategic stockpile of yttrium oxide from past purchases.

Supply Chain & Recent Developments: Yttrium hasn't been in the headlines as much as Nd or Dy, but it is subject to the same supply chain consolidation. If China were to restrict yttrium exports, industries reliant on certain phosphors or specialty ceramics would feel the pinch. So far, China's 2025 export controls mentioned did not single out yttrium in the initial lists (they focused on medium/heavy RE like Dy, Tb, plus added Ho, Eu, etc.). Interestingly, **yttrium was not explicitly named** in the October 2025 expansion (Eu and Yb were named, but not Y). This could be because yttrium was perhaps covered under some other category or simply not targeted (perhaps China feels Y is abundant enough). Nonetheless, being grouped as a heavy rare earth, any broad actions on HREEs would involve Y. The global push for **supply chain diversification** includes yttrium – e.g., the EU's recycling programs recovered notable quantities of Y from lamps (Philips and Osram had programs to recycle fluorescent powders for Y and Eu). With fluorescent lamps being phased out in many countries by 2023–2025, companies have been stockpiling old phosphor or shifting those recycling efforts toward LED phosphor waste (which is trickier due to lower concentrations). On the **technological innovation** front, some lighting manufacturers are moving to **phosphor-free LED technologies** (like quantum dot LEDs or novel perovskite emitters) which could reduce reliance on rare-earth phosphors (and thus Y and Eu). However, those are not yet mainstream in general lighting. In metallurgy, one trend is more **use of yttrium in high-temperature alloys** for clean power plants and efficient engines; these uses require only small amounts but could increase if adopted widely.

Given yttrium's moderate risk level, efforts such as the U.S.-led **Minerals Security Partnership** have listed yttrium among target elements for collaboration. Countries like **Australia and Canada** (which have critical mineral agreements with the U.S.) are looking at whether their REE projects can produce Y. For instance, Canada's Nechalacho deposit has some heavy-enriched zones that could yield Y concentrate; a Saskatchewan separation plant is being built which could potentially separate Y if feedstock is provided.

Recycling remains a key part of the yttrium story. The Foresight Group report highlights that while consumer electronics recycling yields <5% of contained rare earths, the magnets and phosphors in big clean-tech equipment will be easier to collect. Yttrium from lighting is a case in point – many countries have recycling programs for fluorescent tubes (due to mercury content) and thereby recover the phosphor powder with REEs. As LED fixtures eventually need recycling, there might be a push to recover the small amounts of Y and other REEs in them too, though it's more challenging.

In conclusion, **yttrium's supply chain is somewhat more diversified** than those of Dy/Tb in the sense that it is produced in larger volumes and was not hit as directly by export curbs yet. But it is still predominantly controlled by China. The next decade likely sees stable to growing demand for Y in energy-efficient lighting, electronics, and ceramics. Yttrium doesn't face the dramatic shortfall projections that Nd or Dy do, yet any general rare earth supply crunch will affect it as well. It remains a *critical element* for which secure supply and recycling will play important roles. If solid oxide fuel cells or other Y-intensive technologies take off (for example, if every data center starts using YBCO superconducting cables for efficiency – a hypothetical scenario), then Y demand could spike more than currently anticipated. Policymakers thus include Y in critical mineral lists to ensure *this often-overlooked rare earth* is not neglected in the broader push to bolster supply chains.

Supply Chain Challenges and Innovations (2023–2025)

In reviewing these key rare earth elements – Nd, Pr, Dy, Tb, and Y – several common themes emerge regarding supply and recent developments:

- **China's Dominance and Geopolitics:** The supply chain for rare earths, especially processing and magnet manufacturing, is one of the most concentrated of all critical minerals. As of 2024, China mined ~60% and refined ~90% of the world's REEs used in magnets. Moreover, China produces **94% of the world's NdFeB magnets**, giving it immense leverage over downstream industries. This concentration became a geopolitical tool in 2025 when China imposed **new export controls**. In April 2025, Beijing restricted exports of several heavy rare earth compounds and magnet alloys (affecting Dy, Tb and others), causing disruption for magnet buyers globally. By late 2025, the controls were expanded: foreign companies now need licenses to export any products containing Chinese-sourced REEs, and additional elements like europium, holmium, erbium, thulium, ytterbium were added to the restricted list. These moves sent a wake-up call that **supply concentration has become a real vulnerability, not just a theoretical risk**. Prices for rare earths outside China surged (magnets in Europe saw up to 6× price jumps vs. inside China during mid-2025). Industries from automotive to defense scrambled for contingency plans. The situation underscored that **energy security now interlinks with critical mineral security** – securing rare earth supply is essential for securing the energy transition.

- **Diversification Efforts:** In response, many countries have accelerated plans to develop their own rare earth sources and value chains. The U.S., EU, Japan, and Australia are investing heavily in rare earth projects. For example, the U.S. Department of Energy and Department of Defense provided funding to Lynas (Australia) to build a heavy RE separation facility in Texas and to MP Materials to establish domestic magnet manufacturing. The EU announced the Critical Raw Materials Act with targets for internal supply and recycling of REEs by 2030. Alliances like the **Minerals Security Partnership (MSP)** – which includes the U.S., EU, Japan, Australia, Canada, and recently India – are coordinating to finance critical mineral projects (including rare earth mines in Africa, Australia, and the Americas). **New mines** under development across the globe (from Tanzania to Sweden to Brazil) aim to come online in the late 2020s, potentially chipping away at Chinese dominance. However, as reports note, even aggressive new projects might only reduce China's share of mining to ~50% by 2035 (from 60%+) – still leaving a very concentrated scene. And in heavy REEs, China (plus its neighbors like Myanmar) could still control 60%+ of production and an even larger share of processing through 2035. Thus, diversification is a slow, challenging process.

- **Recycling and Circular Economy:** Recycling is increasingly seen as an *essential complement* to mining for rare earths. Given the long lead times and environmental hurdles for new mines, many countries are trying to "close the loop" on materials like REEs. As mentioned, the IEA projects significant contributions from recycling by 2040–2050 for magnets. Already, numerous recycling initiatives have been launched (2023–2025): The EU has projects in France and Germany to recycle magnet scrap; the US has funded a consortium for rare earth magnet recycling and recovery of REEs from coal by-products; Japan, which started recycling after the 2010 crisis, continues to refine its processes. By 2026, publicly announced recycling facilities worldwide aim to process about **30,000 tonnes of magnet scrap annually, yielding roughly 8,000 tonnes of REEs** (about 7% of projected demand in 2026). This includes both production scrap (pre-consumer, from magnet manufacturing) and end-of-life scrap. Recycling manufacturing scrap is low-hanging fruit since it's clean and concentrated – and because most magnet making happens in China, Chinese firms are actually leaders in recycling their own scrap (with high recovery rates) [2]. The harder part is collecting and processing *post-consumer* scrap, like magnets embedded in electronics or vehicles. For that, better dismantling technologies are needed. There's promising research on using automation (robots to identify and extract magnets from e-waste) and on novel extraction methods (electrochemical, vapor-phase extraction of REEs from shredded motors, etc.). Recyclers are also working on direct re-use approaches – e.g., re-magnetizing old magnets, or blending scrap alloy with virgin material to make new magnets (reducing the need for separated oxides). These approaches could simplify the loop.

Importantly, while recycling can **supplement** supply, it cannot fully replace mining in the near term. Given the demand growth, even a perfect recycling system would lag because much of the rare earths being used today won't reach end-of-life for 10-20 years (e.g., EVs sold in 2025 might not be scrapped until 2035–2040).

Thus, primary production must still increase to meet the surging demand in the 2020s and 2030s. But over a longer timeframe, a circular rare earth economy could stabilize the supply.

- **Technological Innovations and Substitution:** Facing potential shortages, researchers and companies are innovating to **thrift or substitute rare earths** in applications. As discussed in each section, notable trends include:
- *Motor designs that avoid RE magnets:* Several automakers now offer or plan EV models with **induction motors or separately excited motors** that use no rare earths. Nissan's Ariya and Renault's Zoe use magnet-free drivetrains; BMW's iX3 uses an electric motor with no permanent magnets. Tesla initially used induction, then shifted to a hybrid approach (one magnet motor, one induction motor in dual-motor models). Mercedes/Daimler has stated plans to eliminate rare earths in the medium term. These moves show a willingness to trade off some efficiency to reduce critical dependency. However, permanent magnet motors remain the most efficient and power-dense solution, so most high-performance EVs still stick with them for primary drive units.
- *Reduced heavy REE content:* For those still using magnets, material scientists have found ways to use **less Dy/Tb**. Grain boundary diffusion (GBD) and other metallurgy tricks can cut heavy REE usage by ~30-50% without performance loss. Toyota's aforementioned magnet manages up to 50% Nd reduction by adding La/Ce and requires *zero dysprosium/terbium*. Volkswagen also touts magnets with "less terbium and dysprosium" in its designs [3]. These incremental improvements across the industry significantly reduce per-unit REE content (and thus exposure to heavy RE supply risk). If every magnet producer implements such measures, the effective demand for Dy/Tb per kW of motor power goes down, helping stretch supply.
- *Alternate magnet chemistries:* Beyond NdFeB, other magnet types are being refined. **Samarium-cobalt magnets (SmCo)**, which need no Dy/Tb and can operate at very high temperatures, are seeing renewed interest for aerospace and defense use (where cost is less an issue). They have slightly lower maximum energy than NdFeB but much better intrinsic high-temp performance. Using SmCo in certain EV applications could alleviate Dy needs (though SmCo contains cobalt, another critical element). Meanwhile, research continues on completely new magnets: e.g., iron-based magnets like Fe-N nitrides or Fe-Co alloys with novel structures. A promising one is the tetragonal Fe–Ni alloy mimicking meteorite minerals (tetrataenite) – scientists have found ways to stabilize it in labs; if it can be made in bulk with slight RE doping, it could be a rare-earth-light magnet alternative. Additionally, **cerium** (the most abundant REE) is being tried as a substitute in magnets – a cerium-based magnet developed by Oak Ridge NatLab achieved reasonably high performance by using Ce to replace some Nd (with a trade-off in Curie temperature). All these are in R&D or early commercialization and not yet able to replace NdFeB widely. But success in any one of them could dramatically reshape REE demand (for example, if Ce could replace Nd in many magnets, Nd demand would drop and Ce demand rise – which would be easier since Ce is oversupplied).
- *Phosphor and lighting tech:* LED technology has reduced reliance on europium and terbium for lighting compared to fluorescent lamps. Further, **quantum dot LEDs** and **laser-based headlights** (as seen in some new cars) can reduce the need for traditional phosphors. If quantum dot displays (using semiconductor nanocrystals) become mainstream, they might cut rare earth usage in displays (no phosphor needed for colors). On the other hand, some new display tech like **Mini-LED backlights** actually use more LEDs (thus more phosphor) to achieve high brightness, potentially increasing Y/Eu use again. The overall trend in lighting/display is toward *more efficient use* of rare earth phosphors – meaning demand for Eu, Y, Tb in this sector is not growing like magnets, and might even shrink. This frees up capacity for other uses or reduces criticality of these particular REEs (Eu, for instance, is less talked about now than a decade ago when it was critical for CFL bulbs).

- *Lasers and optical fibers:* Yttrium-based lasers (like Nd:YAG) remain standard, but competition from fiber lasers (which often use erbium or thulium dopants in fiber) and other sources means there are options. In communications, *erbium-doped fiber amplifiers (EDFAs)* are essential (erbium is another heavy REE) – the AI/data boom means more fiber optic infrastructure, which uses Er (and Ytterbium to pump the Er). Erbium hasn't been in short supply but is now part of China's export curb list. If that became an issue, companies might look at alternative amplifier tech (like Raman amplification which needs no rare earth, or semiconductor optical amplifiers). Still, these are specialized considerations.

- **Environmental and Social Factors:** Rare earth mining and processing have significant environmental footprints – from radioactive waste (monazite contains thorium) to chemical pollution (ionic clay mining historically involved ammonia and ammonium sulfate leaching that contaminated water). China's past dominance partly came from tolerating environmental costs that others avoided. Now China itself is tightening regulations, closing illegal mines, and implementing traceability for REE production. New projects worldwide must meet high environmental standards. There's also community resistance in some locales (as seen in Madagascar and Sweden's recent deposit announcement met with cautious responses about environmental impact). This can slow or block projects, further complicating supply expansion. However, there are **technological improvements** on this front too: companies are developing **greener extraction methods** (e.g., using ionic liquids or bio-leaching for REEs, instead of harsh acids; or selective adsorption resins that reduce waste). The U.S. and EU are funding research into **recycling coal mine waste and acid mine drainage** as alternative REE sources – potentially extracting REEs (especially Y and Nd) from what's currently pollution. This could solve two problems at once (cleaning waste and sourcing critical minerals). If successful, it may add small supplemental sources.

In summary, the period 2023–2025 has seen **significant shifts** in the rare earth landscape: a surge in demand from clean tech, sharper supply chain risks due to geopolitics, and a concerted global effort to innovate and diversify. The *green transition and AI revolution are firmly intertwined with these materials*. Each of the key REEs – neodymium, praseodymium, dysprosium, terbium, and yttrium – plays a non-fungible role in modern technology, and securing their supply will be pivotal. Progress is being made through recycling initiatives, new mining projects, and material science breakthroughs, but the next decade will likely feature continued tight markets and the need for coordinated strategy to ensure that rare earth elements enable, rather than hinder, our global technology and climate goals.

Sources:

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8. SAM (Stanford Advanced Materials) Blog. *Praseodymium: Element Properties and Uses.* (Pr used in high-strength alloys, permanent magnets, specialty glass and ceramics, catalysts).

9. SAM Blog. *Main Applications of Yttrium in Alloys and Phosphors.* (Y widely used in phosphors for TV tubes, efficient lighting, fuel cells, metallurgy, ceramics, superconductors; sources of Y include xenotime, monazite, bastnaesite).

10. McKinsey Global Materials Perspective 2024 (cited in source 2 and 5). (China >60% of mined supply, >80% of refined supply in 2023; heavy REEs likely mined in Asia-Pac and processed in China through 2035).

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