BMAC Battery Metals Association of Canada

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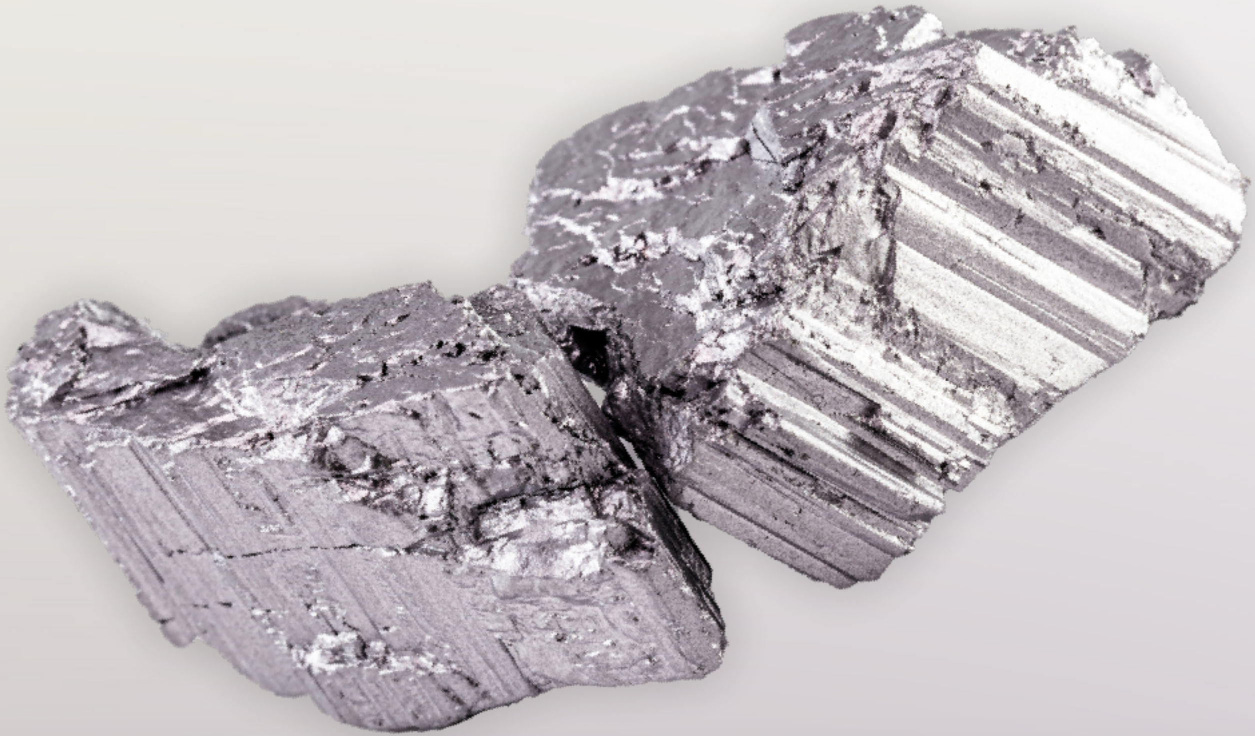
FOCUS ON

RARE EARTHS



FROM

ROCKS
TO
POWER

Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, & Beyond

August 2025 | V1.0

From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond

Focus on Rare Earths

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About Us

BMAC | Battery Metals Association of Canada

The Battery Metals Association of Canada (BMAC) is a national non-profit association of industry participants and champions from across all segments of the battery metals value chain. From mining to specialty chemical refining, manufacturing, end use and recycling, BMAC is focused on coordinating and connecting the segments of this value chain, ensuring Canada captures the economic potential of the sector and is able to attain its electrification targets. Together, our members collaborate to accelerate the development of the battery metals ecosystem in Canada.

The Transition Accelerator | L'Accélérateur de transition

The Transition Accelerator drives projects, partnerships, and strategies to ensure Canada is competitive in a carbon-neutral world. We're harnessing the global shift towards clean growth to secure permanent jobs, abundant energy, and strong regional economies across the country. We work with 300+ partner organizations to build out pathways to a prosperous low-carbon economy and avoid costly dead-ends along the way. By connecting systems-level thinking with real-world analysis, we're enabling a more affordable, competitive, and resilient future for all Canadians.

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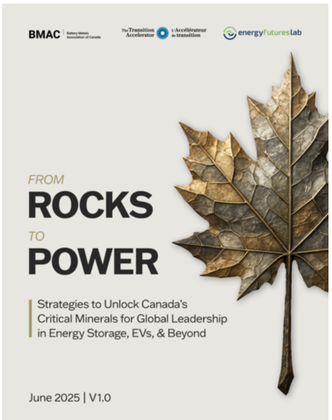
The Energy Futures Lab is an award-winning, Alberta-based not-for-profit that brings together a diverse network of innovators, influencers, and system actors from across Canada's energy landscape. Established in 2015, the Lab was created to address growing polarization around Canada's energy transition and respond to its most pressing challenges.

Through trusted leadership and creating non-partisan spaces for collaboration, the Lab convenes stakeholders and Rights and Title Holders to generate and test innovative, enduring solutions to complex, system-level issues. By empowering communities and change-makers to work across divides, the Lab fosters the conditions for meaningful progress toward a shared vision of a resilient and sustainable energy future.

About This Report



This chapter is part of a larger report, *From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond*. The full report identifies clear, investable priorities in eight minerals, each of them critical to building resilient EV and energy storage value chains. By looking at specific opportunities and providing detailed justifications for its recommendations, *From Rocks to Power* offers a way out of our perpetual planning cycle and towards a new momentum for Canada's critical minerals sector—and our future economic prosperity.

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Additional chapters are available for download below:

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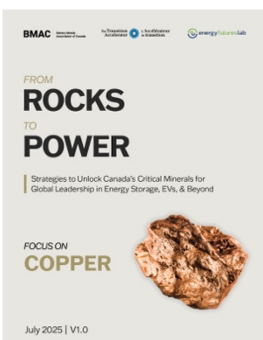

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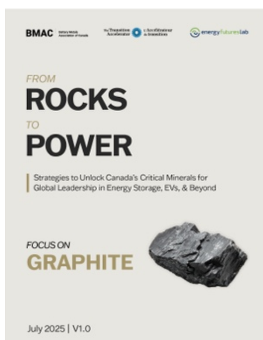

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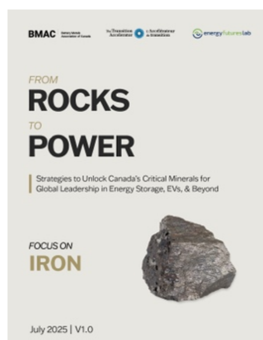

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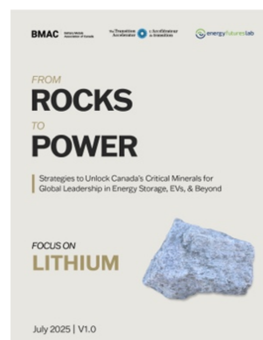

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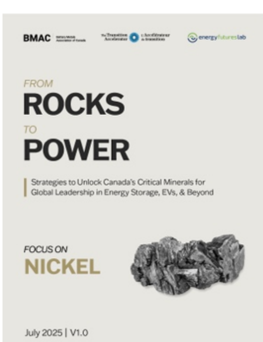

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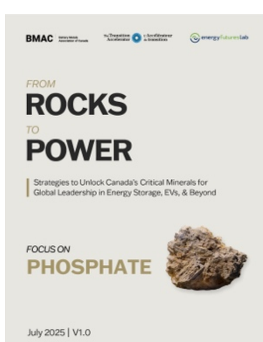

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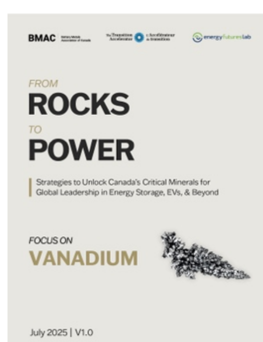

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The Rare Earths

1 The Canadian Rare Earth Strategy

1.1 Rare Earths in Canada

Table 1 Non-exhaustive selection of current and future REE extraction, processing and recycling projects in Canada

Selection of Future REE Extraction Projects				
Site Name	**Company**	**Province**	**Type**	**Status**
Nechalacho/Tardiff	Vital Metals	NT	bastnäsite	Scoping study
Wicheeda Rare Earth	Defense Metals	BC	bastnäsite	PFS 2025
Bear Lake Project	Searchlight Resources	SK	possibly monazite	Exploration
Alces Lake	Appia Rare Earths & Uranium Corp.	SK	monazite	Exploration
Elliot Lake	Appia Rare Earths & Uranium Corp.	ON	uranium, monazite	Exploration
Eco Ridge Mine	Radio Fuels Corp.	ON	uranium, monazite	Exploration
Strange Lake	Torngat Metals	QC	gerenite, gagarinite, kainosite, other	PFS projected in 2025
Ashram	Commerce Resources	QC	monazite, bastnäsite, xenotime	Advancing Updated PEA
Kwyjibo	SOQUEM	QC	apatite, britholite, allanite, kainosite	PEA 2018
Kipawa- Zeus	Québec Precious Metals, Investissement Québec	QC	eudialyte, mosandrite, britholite	FS 2013
Foxtrot	Search Minerals	NL	HREE	PEA 2022

Selection of Operational & Future REE Processing Facilities				
Project Name	**Company**	**Province**	**Product Type**	**Status**
Saskatoon Processing Facility	Vital Metals	SK	Mixed Rare Earth Carbonate	Cancelled
SRC Rare Earth Processing Facility	SRC	SK	Mixed Rare Earth Carbonate, Separated REO, separated metals and alloy	Operational
Sept-Iles Separation Facility	Torngat Metals	QC	Separated REO	2028+
Hub100 Demonstration Plant	Cyclic Materials	ON	recycled mixed REO	Operational
Commercialization & Demonstration Facility	Ucore	ON	Separated REO	Operational
Saint-Hubert Demonstration Plant	Geomega	QC	Separated REO	Construction

1.1.1 Summary

Despite ranking 10th in REE reserves globally in 2024, Canada did not mine or process REEs at scale in 2023. Active mining projects can be found in the Northwest Territories, BC, Saskatchewan, Quebec, Ontario, and Labrador. In contrast, a processing plant, going from digestion to separation and metallization, is projected in Saskatchewan, and Geomega plans to build a magnet recycling demonstration plant in Quebec.

1.1.2 Upstream

Torngat Metals is a Quebec-based company focused on developing the Strange Lake Project, located in Nunavik at the Labrador-Quebec border. This deposit has a high proportion of HREEs. A PFS is expected to be completed by 2025, and production is targeted to begin in 2028. A separation facility is also projected in the Sept-Îles Industrial Park.

Vital Metals, an Australian rare earth company, was the first to initiate rare earth mining in Canada through its Nechalacho project in the Northwest Territories, a bastnäsite-rich deposit. The extracted ore was to be processed into a concentrate and further refined at Vital's rare earth processing facility in Saskatoon, Saskatchewan. Due to financial difficulties, the project was paused or scaled down, and the processing facility project has been cancelled. The financial situation preceded a 9.9% stake in Chinese purchase by Shenghe Resources in 2023. Vital Metals had planned to sell Shenghe its bastnäsite stockpile but finally sold it to the SRC for $3.3 million after the federal government's involvement.[1]

A longer list of REE mining projects is available in Table 1.

1.1.3 Midstream & Downstream

Additionally, two Canadian-based companies hold expertise along the midstream and downstream of the REE magnet value chain: Ucore Rare Metals and Neo Performance Materials. The Saskatchewan Research Council has launched a midstream facility in Saskatoon, and Cyclic Materials is a new company in Ontario focusing on REE recycling.

Ucore, a Nova Scotia-based mineral processing company, is proprietary of a novel solvent extraction method for REE separation enhanced by computerized column technology, able to separate LREE & HREE with the same equipment. An 80 tpa commercial and demonstration plant operates in Kingston, Ontario, while the Strategic Metal Complex production plant is commissioned in Alexandria, Louisiana, for 2025. It is projected to reach a capacity of 7,500 tpa in 2026. Ucore has received support from a $5M incentive from the state of Louisiana, a $360,000 grant from the Greater Alexandria Economic Development Authority, and a $4M OTA from the U.S. DoD. Additionally, Ucore received $4.3 M from the government of Canada to produce NdPr, Pr and Nd over 6 months from 13–15 tonnes of Canadian and US feedstock sources in Canada.

Neo Performance Materials, a Toronto-based firm, has numerous activities in mainland China but also operates LREE separation in Narva, Estonia, while projecting to manufacture sintered NdFeB magnets there, in addition to already active operations in Thailand and the U.K. The company owns three business units: Neo Magnequench, focusing on downstream REE magnetic powders and bonded/sintered magnets; Neo Chemicals & Oxides, which deals with midstream REE separation, mixed oxides and catalysts; and Neo Rare Metals, which targets hafnium and gallium recycling as well as tantalum metal. The company is uniquely positioned to be fully integrated from REE separation to metals & alloys to magnet making and recycling. The Narva sintered magnet plant is forecasted to produce 2,000 tpa of magnets, reaching 5,000 tpa in the second phase.

The SRC Rare Earth Processing Facility is unique in Canada because it is a publicly funded company operating in the REE midstream segment on Canadian territory. With this venture, the Saskatchewan Research Council has shown a strong will to develop and derisk the REE industry in Canada. The Saskatoon facility focuses on monazite as a feedstock and its hydrometallurgical processing, separation, and metallization. The SRC also has proprietary technology for automated solvent extraction cells and metal smelting. The facility can produce medium/heavy mixed REE carbonate, La/Ce mixed REE Carbonate, NdPr metal alloy, and HREEs in the form of dysprosium oxide and terbium oxide. The smelting unit will be capable of producing neodymium, praseodymium and didymium mix as ingots. The SRC recently announced that the facility had produced REE metals commercially in the summer of 2024 and will be fully operational by 2025 to produce 400 tpa of NdPr metals.[2] Prairies Canada announced in August 2024 a $16 million support for the SRC Rare Earth Processing Facility to develop processing capacity for the bastnäsite ore acquired from Vital Metals. This funding comes after an earlier support of $13.5 million from NRCan and Prairies Canada to establish the SRC processing centre.[3]

Cyclic Materials, founded in 2021 and based in Kingston, Ontario, specializes in recycling REEs from end-of-life products such as electric vehicle motors, wind turbines, MRI machines, and data centre electronic waste. Copper scrap will also be recycled and sent to the Horne smelter. Their proprietary technology enables the process of waste through a hydrometallurgical process to recover recycled mixed rare earth oxide (rMREO). They opened their Hub100 commercial demonstration plant in 2024,[4] and have secured collaborations with Glencore, Vacuumschmelze, Solvay, Ucore, SYNETIQ, Polestar, *etc.*

1.2 Scenario Outline

Canada should strengthen a domestic REE processing and magnet manufacturing hub in Saskatchewan, anchored in the already operational SRC REE Processing facility, before opening several rare earth mines in western provinces and territories. Collaborating with off-takers such as material manufacturers and EV motor producers is crucial to meet their requirements.

- **In the Short Term, Secure a Strong Midstream REE Processing:**
  - **Establish a Strong Centralized REE Processing Hub:** Bolster the Canadian monazite processing capacity by importing monazite concentrates first and waste materials as feedstock to maximize the production of individual Rare Earth oxides and metals. Ensure an optimal production of heavy rare earth products when possible. Leverage the already existing Canadian refining facilities and IPs, such as the Saskatchewan Research Council processing plant, Ucore, and Cyclic Materials. In parallel, a bastnäsite processing pathway and importing concentrates should be developed as a later priority.
  - **Manufacture Magnets:** Use the processed REOs, metals and alloys from the to processing hub to make sintered permanent magnets in magnet or magnetic powder plants. Secure partnerships with major material companies, EV motor producers, and OEMs to build a customer-driven, reliable chain.

        - **Foster REE Process Optimization:** Develop 'test kitchen' pre-production hubs, gathering talents and resources to optimize a Canadian REE value chain and improve processes.
    - **In the Medium Term:**
        - **Develop Mining Capacity:** Ramp up mining capacities in the Northwest Territories, Quebec, Saskatchewan and British Columbia to feed the processing hub with high-grade concentrates of monazite and bastnäsite.

1.3 Signature Projects

- 3–4 REE mines (Such as Nechalacho, Wicheeda, Alces Lake, Strange Lake, *etc.*)
- One centralized processing hub, anchored in the SRC plant in Saskatoon
- One permanent magnet plant

1.4 Strategic Priorities

- **Establishing Midstream REE Processing Hub:**
    - **Support a Centralized Hub:** Develop a hub-and-spoke model to streamline the REE supply chain's chemical processing, separation, and refining stages. This hub will produce individual rare earth oxides or metals critical for downstream applications.
    - **Anchor the Hub in Existing Facilities**, such as the Saskatchewan Research Council (SRC) in Saskatoon, which already produces REE metals from monazite concentrate. Supporting the viability, development and expansion of this facility should be pursued.
    - **Leverage existing Canadian intellectual property:** Such as Ucore for REE separation or Cyclic Materials for REE recycling from old magnets and waste. Both companies have a footprint in Kingston, Ontario, and have attracted funding and partnerships.
    - **Feedstock Diversification:** Start with reliable monazite feeds, which is the first feedstock used by the SRC, then expand capabilities for bastnäsite and ionic clays as processes mature. Recycled mixed rare earth oxide should also be considered as an alternative feedstock that advances circularity. Start processing with the import of foreign concentrates, then use domestic ones when the mine come online.
    - **Magnet Manufacturing Integration:** Co-locate a permanent magnet manufacturing facility with the processing hub to develop the downstream segment of the supply chain. Secure partnership with Original Equipment Manufacturers (OEMs) and EV motor producers to ensure demand and reliability. Encourage e-waste recycling as a supplemental material source for magnet manufacturing

        - A magnet production hub will benefit from being located near clients (OEMs, Tier 1 suppliers, EV motor manufacturers, *etc.*). However, this could prove difficult for the colocation of a magnet plant in Saskatchewan. In this case, locating the plant in Ontario and/or securing strong partnerships with domestic or international off-takers is necessary.
    - **Pre-Commercial Test Hub:** Create a 'test kitchen' pre-production hub to optimize processes, explore commercialization strategies.
    - **Develop Processing Expertise Abroad and Export IP and Engineering Services:** A secondary strategy for the midstream is to gain experience in optimizing processes abroad and establish credibility internationally. An example of this would be the partnership between the SRC, Hatch and Aclara, a South American junior miner projecting to develop a heavy rare earth separating facility in the U.S.
- **Ramp Up Domestic Mining Capacities:**
    - In the medium term, and parallel to the development of the processing hub, mining operations in the Northwest Territories, Quebec, Saskatchewan, and British Columbia should be advanced to feed the processing hub with high-grade concentrates. Lessons should be learned from the recent Vital Metals situation to increase viability and investor confidence.
- **Access to Energy, Chemicals, Infrastructure and Talent:**
    - **Energy Access:** Ensure clean, affordable energy to support energy-intensive refining processes.
    - **Chemical Supply:** Guarantee reliable access to essential reagents such as acids and sodium hydroxide.
    - **Infrastructure Integration**: Build the supply chain around robust transport networks, including road and rail. Access to REE deposits in the northern territories or northern Quebec necessitates infrastructure investment.
    - **Talent Development:** Facilitate access to global expertise while fostering domestic education and training programs.
- **Develop Synergies:**
    - **Coordination with the Nuclear Industry**: Collaborate with the nuclear industry (*e.g.* AECL, OPG, Cameco, Orano) and standards (CNSC) to manage and monetize uranium and thorium waste from monazite processing. This collaboration could reduce regulatory barriers and unlock REE mining potential.
    - **Phosphate Co-Production:** Leverage opportunities to produce phosphate as a byproduct of monazite processing.
    - **REE Co-production from Sedimentary-Based Phosphogypsum**: Conversely, recovering REEs from sedimentary apatite deposits in

Western Canada, or from phosphogypsum made by a future phosphoric acid plant could be an interesting venue to explore. South African company Rainbow Rare Earths is investigating operations in South Africa, Brazil, and Morocco.

- **Research & Development:**
  - **Secure Long-Term Investments** for an R&D strategy based on developing extraction, refining and scaling processes specific to Canadian feeds and off-takers.
  - **Optimize the Process for Different Feedstock:** Address the issue of feedstock and concentrate diversity by building a robust processing method which can be customized for monazite and bastnäsite first, then for recycled mixed rare earth oxide concentrates, and eventually for clays.
  - **Heavy REE Production:** optimize the separation of HREE from standard monazite and bastnäsite feedstock, and later on from clays, as to maximize the output of HREE.
  - **Beneficiation:** optimize the beneficiation processes on mining sites to obtain higher-grade rare-earth oxide concentrates.
  - **A Magnet Production Focused on EVs and High Performance:** For permanent magnet production, focus on optimizing grain boundary diffusion processes to decrease the reliance on HREEs and prioritize the production of sintered magnets over bonded magnets.
- **Material Standards:**
  - **Harmonize the EV Supply Chain** by issuing standards and specifications for REE feedstocks, intermediates, and magnets. Initiatives such as the Product Category Rules (PCR) developed by the Rare Earth Industry Association (REIA) and their collaborators help define common, consistent guidelines to perform LCA on the REE supply chain.[5] Similar international initiatives based on this work should be supported.
- **Protection from Price Volatility:**
  - **Market Stability Mechanisms:** Facilitate stability and certainty through government procurement, contract for differences, government-guaranteed future purchase of locally sourced critical minerals, or buffer stock mechanisms.[6]
  - **Ex-China Economics:** Develop and understand the economics for specific pricing for the ex-China REE industry.
- **Meeting the Off-takers' Requirements**:
  - **Collaborate with Off Takers Down the Supply Chain:** REE miners and processors should collaborate with the off-takers (magnet manufacturers, EV motors manufacturers, OEMs) to understand and identify their material standards requirements and perspectives
  - **Design Flowsheets that Make Sense:** Work backward from those off-takers to design a customer-driven REE flowsheet.

    - **Involve Major Material Producing Companies:** Favour the involvement of major material producers in investing in the REE mining and processing steps to ensure long-term reliability.
- **Encourage Circularity:**
    - **E-Waste Integration:** Encourage rare-earth recycling by processing waste materials (E-waste, old magnets, waste from the REE processing supply chain, *etc.*) on top of primary feedstocks.
    - **Remove Barriers** to the import of electronic waste.
    - **Unified Industry Effort:** Foster collaboration throughout the supply chain to ensure a cohesive REE circularity strategy. Co-locate or integrate rare earth recycling when possible where the REE processing and magnet manufacturing operations are to maximize efficiency and sustainability.

2 Rare Earths: An Inseparable Set of Elements Attractive for Magnets

2.1 General Properties

Rare Earth Elements (REE) are 17 metallic elements, including the 15 lanthanides associated with scandium and yttrium. Due to physicochemical and commercial properties, they can be split into the more abundant light rare earth elements (LREEs – La to Sm or Eu) and heavy rare earth elements (HREEs – Eu or Gd to Lu, and Y), while scandium is often left out. Didymium is the specific name given to the mixture of neodymium and praseodymium. REEs find applications in high-strength permanent magnets in wind turbines and EV motors. REEs like cerium and lanthanum are used in automotive catalytic converters, industrial fluidized cracking catalysts and polishing powders for glass and ceramics.[7,8] REEs are also critical in optics and display (*e.g.*, phosphors for LEDs or LCD and fluorescent lamps) and medical imaging. Certain REEs are also used in water treatment, as they can selectively bind to phosphate ions in water, making them helpful water treatment additives for preventing algal blooms or phosphate overconcentration.

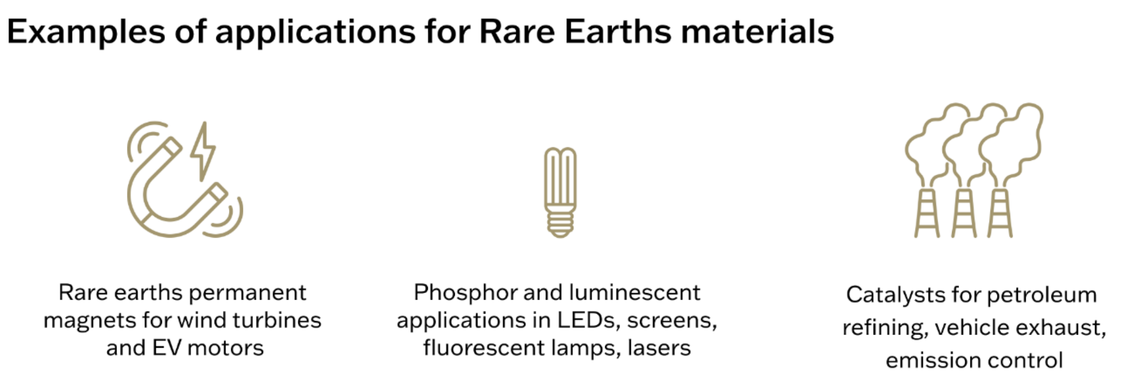

Figure 1 Examples of applications for rare earths materials

Historically, the early development of the rare earth industry started in the late 19th century and continued until 1930, with the development of incandescent gas mantles using thorium and cerium oxide. *Mischmetal*, a mixture of lanthanides and iron, was also used for flints and metallurgy. This was the initial development of REE alloys together with a specific focus on cerium oxide for lighting purposes. Then, until the 1960s, REEs gained importance in various industries, using cerium oxide in polishing powders, ceramic glazes and as an additive for optical glass. Military research also drove the advancement of REE separation techniques during WWII. Lanthanide luminescence was discovered in 1942, leading to optical applications as phosphors; by 1965, europium-based red phosphors also revolutionized colour television technology. The development of SmCo magnets and later NdFeB magnets in 1983 significantly diversified the applications for REE and allowed vital advancements to our use of permanent magnets. Other applications, such as superconductors or catalytic converters, were also implemented. Lanthanum also became critical for nickel-metal hydride (NiMH) batteries, which were widely used before being gradually supplanted by lithium-ion batteries. Since the 1990s, China has dominated the mining, separation, processing, refining and manufacturing of REE materials. Modern applications have expanded to include advanced magnets for electric vehicles and wind turbines, magnetocaloric materials for refrigeration, energy-efficient lighting (LEDs), and water purification technologies. High-tech innovations now drive the demand for REEs, and their strategic importance arose as their vulnerabilities in global supply chains developed.

Thus, the U.S. Department of Energy considers Neodymium and Dysprosium critical elements in the short term and praseodymium in the medium term.[9] At the same time, NRCan labels all REEs as Critical Minerals.[10]

2.2 Role in Clean Technologies

Rare-earth magnets are considered strategic materials because they are difficult to replace without a significant loss of performance. In 2021, they accounted for 43% of the total REE demand. They excel compared to other permanent magnets in applications where weight, size, and efficiency are critical.

In EVs, REE magnets are primarily used in electric motors, specifically **permanent magnet synchronous motors** (PMSMs). These motors rely on the strong magnetic properties of NdFeB magnets to achieve high efficiency, compact size, and superior power density compared to other motor designs. REE magnets can also be found in regenerative braking systems, where kinetic energy can be converted back into electricity, in powertrain components such as cooling fans and electric drive units, and in accessory systems such as sensors and actuators. Aside from EVs, REE permanent magnets can be found in direct-drive wind turbines to convert wind energy into electricity or in consumer electronics such as smartphones, laptops, speakers, microphones and hard disk drives. Precision aerospace, defence, and robotic applications such as guidance systems, precision motors, actuators, and radar also use those types of magnets, and medical devices such as MRI machines need a strong permanent magnet to generate a magnetic field.

The REE-based permanent magnets rely mainly on LREEs such as **neodymium** for $Nd_2Fe_{14}B$ magnets (NdFeB), which are often partially substituted by **praseodymium**, another light element, enhancing cost-efficiency while maintaining performance. Cerium can also substitute neodymium or praseodymium, as it is cheaper and more abundant, but can lead to lower performances. Adding a small amount of HREEs like **dysprosium** or

terbium is critical for improving the thermal stability of these magnets, especially in high-temperature applications like electric vehicle motors and wind turbines. Indeed, magnets tend to lose magnetic strength at elevated temperatures, and adding HREEs increases the Curie temperature, the temperature above which a material loses its magnetic properties. Coercivity, the measure of a material's resistance to losing its magnetization when exposed to an opposing magnetic field, is also improved by HREE addition. Finally, **Samarium** is used separately for $SmCo_5$ magnets and has found its niche as they are stable under extreme conditions.

The evolution of rare earth magnets reflects technological leaps, starting with samarium-cobalt (SmCo) magnets in the 1970s. These magnets displayed high coercivity but were limited by the scarcity and cost of samarium and cobalt. In 1984, Masato Sagawa at Sumitomo Special Metals and John Croat at General Motors independently discovered neodymium-iron-boron (NdFeB) magnets, revolutionizing the industry by offering magnets 2.5 times stronger than $SmCo_5$ at a lower cost.[11]

As HREEs are rarer, expensive, and extracted almost solely in China and Myanmar, the trend toward minimizing HREEs such as dysprosium and terbium in magnet production has significantly impacted the REE value chain. Techniques like Grain Boundary Diffusion (GDB) have reduced HREE content in magnets without compromising magnetic performances. GDB enhances the coercivity by concentrating HREE at the grain boundaries, and this targeted approach allows for a significant reduction in the overall HREE content, from almost 10% to a couple of percent, lowering costs and increasing sustainability. However, while this trend is expected to continue, there is likely a physical limit to how far HREE reduction can go without compromising magnet performance.

Finally, there are two broad types of NdFeB magnets: bonded and sintered. **Bonded magnets** are created by combining magnetic powders with a binding agent, allowing the production of complex shapes with tight tolerances. They typically exhibit lower magnetic strength than sintered magnets but offer advantages in design flexibility and resistance to cracking. They are used for small electric motors and electronics. On the other hand, **sintered magnets** are formed by compressing and heating magnetic powders without a binder, leading to higher magnetic performance but less flexibility in shaping and a greater susceptibility to brittleness. They can be used in EV motors and wind turbines. Most sintered magnets are also manufactured in China. Outside of China, and before the future advent of the new Neo Performance Materials plant in Estonia, the e-VAC plant in South Carolina or the new plant from South Korean Star Group company, there are only two large sintered magnet plants in Japan, with smaller capacities in other countries.[12]

2.3 Substitutes

Other motor designs can be used: Permanent magnets are not necessary for all electric motors, as only **permanent magnet synchronous motors** (PMSM) rely on them. Other designs, such as induction motors, electrically excited synchronous motors (EESM, also known as wound synchronous motors), and synchronous reluctance motors (SynRM), operate without permanent magnets. While PMSMs are highly efficient and boast superior power density compared to these alternatives, they come at a higher cost, largely due to their reliance on REEs.

Induction motors operate using electromagnetic induction and do not require permanent magnets. Tesla initially used induction motors for its EVs before transitioning to PMSMs for better efficiency. They are proven, cost-effective technology, but they are less efficient and bulkier than PMSMs.

Electrically Excited Synchronous Motors (EESMs) use an external electrical current to generate the magnetic field, eliminating the need for permanent magnets. Due to additional components, the trade-off is slightly lower efficiency and a higher fabrication complexity.

Synchronous reluctance motors (SynRM) operate based on the principle of magnetic reluctance, with torque generated as the rotor aligns with the stator's magnetic field. Unlike PMSMs, SynRMs do not require permanent magnets and instead rely on rotor designs with specific air gaps and iron segments. They can have comparable efficiency to PMSMs at higher operating speeds, and their simplified rotor design and absence of expensive magnets reduce manufacturing costs. However, they suffer from a lower torque density than PMSMs, meaning they would require larger motors for a similar performance; they can also suffer from higher losses at lower speeds and thermal challenges, and they are still not widely adopted.

Another viable solution to switching motor design is substituting NdFeB magnets for REE-free permanent magnets. Ferrite magnets are widely available and significantly cheaper than REE-based magnets. They consist of mostly iron oxide and other metal oxides and are typically used in low-cost and low-power applications. However, they exhibit a much weaker magnetic strength compared to NdFeB magnets, thus limiting their use in high-performance applications.

Iron-nitride magnets have shown promise for high-performance applications without the need for REEs. Companies focusing on this solution, such as Niron Magnetics, have received ARPA-E awards and attracted private investments from GM, Stellantis, Samsung Ventures, and Tier 1 automotive suppliers such as Allison Transmission and Magna.[13,14]

AlNiCo (Aluminum-Nickel-Cobalt) is a mature permanent magnet with excellent thermal resistance. However, it has a much lower magnetic strength than NdFeB or SmCo magnets, making it unsuitable for EV applications.

While still an REE-based magnet using samarium, SmCo is highly resistant to demagnetization, has great thermal stability, and has good magnetic strength, although lower than NdFeB. However, being based on samarium, another heavy rare earth, it suffers from the same supply chain vulnerabilities as NdFeB. The cobalt supply chain it relies on is also controversial and highly concentrated in specific countries such as the DRC and China. These factors also explain the high cost of SmCo magnets.

2.4 Supply and Demand

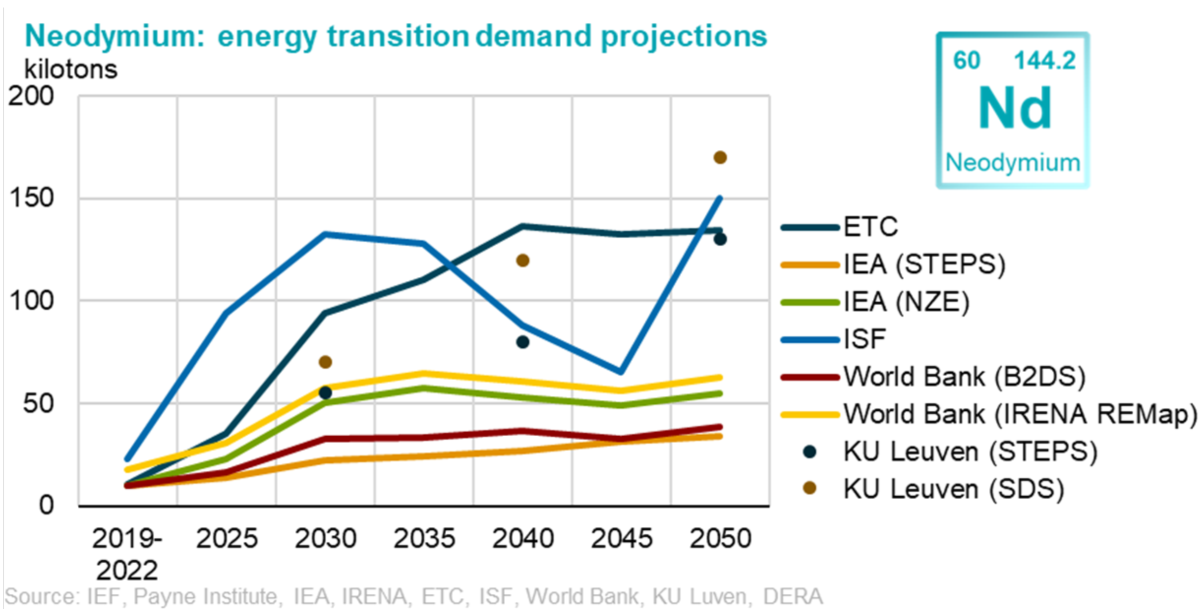

Figure 2 Neodymium demand projections to 2050 according to various energy transition scenarios[12]

The price of REE has been particularly volatile and is based on non-transparent markets. The rare earth crisis of 2010–2011 highlighted the vulnerabilities of global supply chains dominated by China.[15] By the early 2000s, China controlled approximately 95% of global rare earth production. Concerns over environmental degradation, illegal mining, and resource depletion led China to impose export and production quotas, export taxes, and investment restrictions starting in 2006. In 2010, a 37% reduction in China's export quota caused rare earth oxide prices to surge, exacerbated by reports of interrupted shipments to Japan during a maritime dispute.

This price spike triggered significant shifts in the rare earth market. Recycling, substitution, trade deflection, and opening new mines allowed a relative alleviation of demand and supply constraints, leading to price stabilization by 2012. Subsequently, the

World Trade Organization finally ruled against China's export restrictions in 2014. This followed a formal complaint by Japan, the U.S., and the EU, requiring China to lift these restriction measures. This historical crisis highlights the need for more diversified rare earth supply chains and the development of alternative sources.

Between 2017 and 2022, the REE market has multiplied by 2.5, driven mainly by rising clean tech and EV demand. The IEA accounts for a 2023 demand of 93 kt of REE, driven primarily by EV sales and wind turbines, growing the share of clean technologies applications for REE from 8% in 2015 to 18% in 2023. The announced pledge scenario projects a total demand of 131 kt by 2030 and 181 kt in 2050, while the net zero emission by 2050 scenario (NZE) forecasts a demand of 146 kt for 2030 to 200 kt in 2050.[16]

According to Adamas Intelligence, the magnet market is projected to grow by a factor of 4 by 2040. Three main avenues will cause magnet growth: the adoption of EV motors, the potential advent of advanced air mobility such as eVTOL and air taxis, and robotics. An additional production of 400 to 600 ktpa of LREO will be needed by then to meet this demand. According to their analysis, the REE market is projected to be balanced until 2030 but not after, which is why there is a case for an alternative supply chain of rare earth magnets outside of China

3 The Rare Earth Flowsheet: From Rocks and Ionic Clays to Permanent Magnets

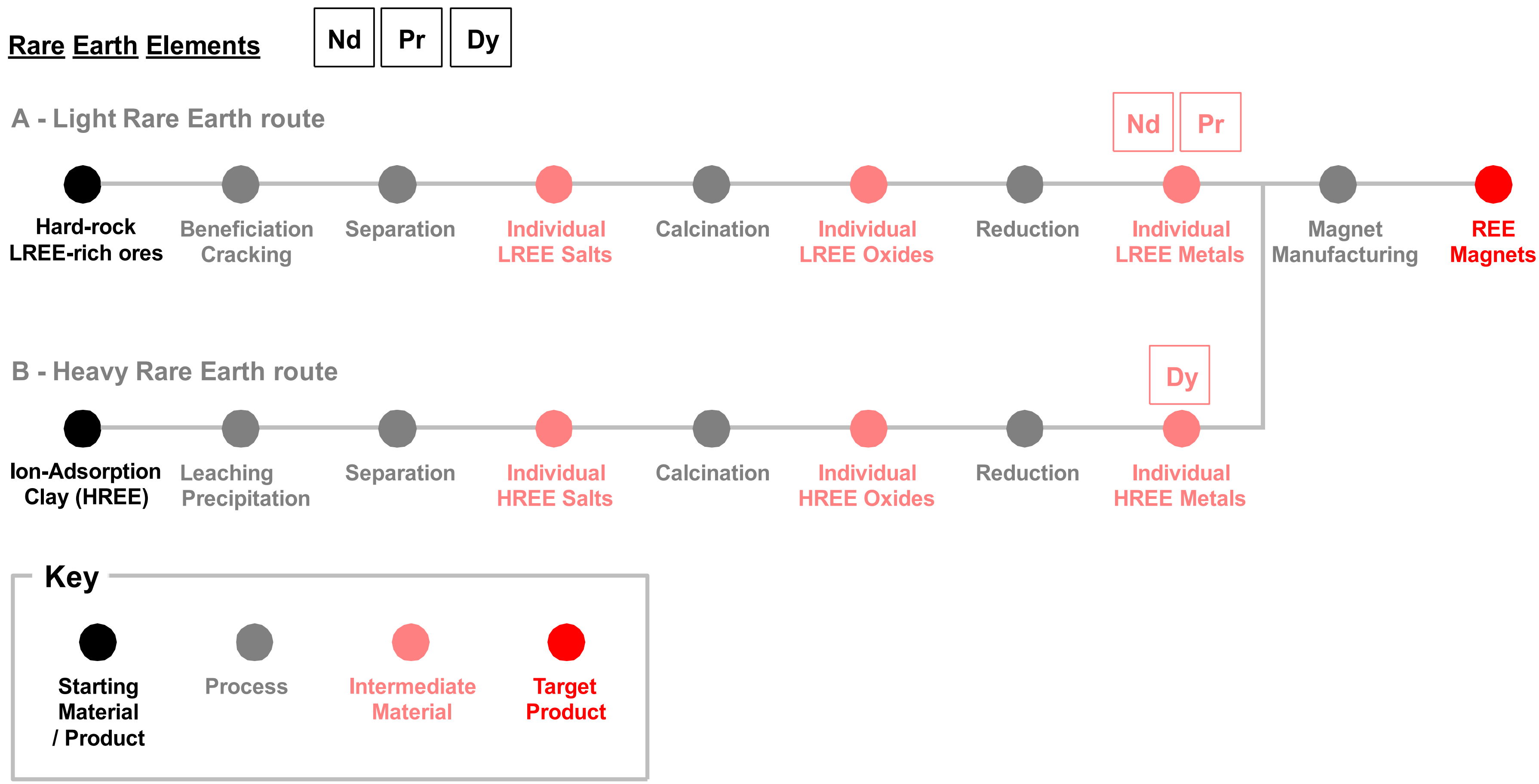

Figure 3 Simplified flowsheet of rare earth elements

3.1 Ores, Reserves & Production

The extraction of REEs originates mainly from hard-rock minerals such as **bastnäsite**, **monazite** and **xenotime**, or soft **ion adsorption clays**, especially in the case of HREE production in Southern China.

Bastnäsite, or bastnaesite, (La,Ce,Y)CO_3F is a rare earth carbonate mineral predominantly enriched with light rare earth elements (LREEs) like cerium, lanthanum, and neodymium. It is often found in carbonatite deposits such as Mountain Pass in the United States and Bayan Obo in China. Bastnäsite typically contains up to 75% REO (rare earth oxide) content, making it a high-grade source. These deposits are often associated with minerals like magnetite, hematite, and fluorite, influencing mining and beneficiation processes. Bastnäsite's high-grade composition and relatively straightforward processing make it a cornerstone of global REE production.

Monazite, (Ce,La,Th)PO4, is a phosphate mineral that contains light and heavy rare earth elements, as well as notable amounts of thorium. It is primarily found in secondary deposits like beach sands in countries such as Australia, Brazil, and India, often as a byproduct of heavy mineral sands mining for rutile, ilmenite, and zircon. Bayan Obo in China also holds a lesser amount of monazite. Monazite's REO content typically ranges between 55% and 70%. While monazite's thorium content can pose challenges due to its inherent radioactivity, many advancements in processing technologies have allowed it to remain one of the primary resources for REEs. However, outside of China, only a few countries possess the infrastructure, social mandate, and commitment to effectively manage and store radioactive by-products.[16]

Ion-adsorption clays (IACs), sometimes called ionic adsorption deposits (IADs), are unique, low-grade rare earth deposits in southern China, Myanmar, and Laos. Unlike other minerals, these clays are enriched in HREEs, which are weakly adsorbed onto the clay particles. This property allows for simple and cost-effective extraction using salt solutions at ambient temperatures, eliminating the need for complex chemical digestion. IAC typically contain less than 0.5% REO. These clays are known for their ease of processing and their cost-efficiency, thus making them critical resources for heavy rare earth production. Additionally, IAC projects show a lower capital intensity, minimal radioactive waste and reduced carbon emissions, which is why those projects are increasingly drawing attention.

The economic viability of IAC projects is increasingly recognized due to their lower capital intensity, ease of processing, reduced carbon emissions, and minimal radioactive waste.

Xenotime YPO_4 is another phosphate mineral predominantly composed of HREEs, including yttrium, dysprosium, and terbium. It is typically found in alluvial and pegmatite deposits and contains up to 62% rare earth oxide (REO). The processing of xenotime is more challenging than monazite due to its resistance to acid digestion. Despite these technical complexities, xenotime is potentially a highly valuable resource due to its high HREE content.

Table 2 Estimated reserves & production of rare-earth oxide equivalent by country

Country	REE Estimated Production in 2023[a] (in tonnes)	Country	REE Reserves in 2024[a] (tonnes x 10^3)
Canada	**/**	Burma	NA
Greenland	/	Madagascar	NA
South Africa	/	Malaysia	NA
Tanzania	/	Thailand	4,500
Brazil	80	South Africa	790,000
Malaysia	80	**Canada**	**830,000**
Vietnam	600	Tanzania	890,000
Madagascar	960	Greenland	1,500,000
Russia	2,600	United States	1,800,000
India	2,900	Australia	5,700,000
Thailand	7,100	India	6,900,000
Australia	18,000	Russia	10,000,000
Burma	38,000	Brazil	21,000,000
United States	43,000	Vietnam	22,000,000
China	240,000	China	44,000,000
World Total	350,000	**World Total**	110,000,000

[a]Data from the 2024 U.S. Geological Survey in tonnes of rare-earth-oxide equivalent.[17]

World REE extraction is highly concentrated, with China dominating both mining and processing. In 2023, China accounted for 62% of global REE mining, according to the IEA,[16] and 68% according to the U.S. Geological Survey.[17] Beyond China, other contributors include the United States, Myanmar, and Australia, but their collective output remains relatively small. While most of China's extraction production focuses on light rare earth elements (LREEs), it also produces almost all of the world's heavy rare earth elements (HREEs), sourced from ion-adsorption clays in southern China and Myanmar. By 2030, the dominance of the top three mining countries is projected to decline modestly, with their combined share falling from 85% to around 81%.

Refining operations are even more geographically concentrated than mining. Although small quantities of LREEs are processed in Malaysia and Estonia, China dominates refining capacity for both LREEs and HREEs, with an overwhelming 92% share of global refined output, cementing China's position as the world's largest producer and processor of rare earth elements. Similarly, by 2030, the top three refining nations are expected to maintain a high share of output, though China's share of refined REEs is anticipated to drop to 77%. This concentration level makes REE production one of the least diversified supply chains among key energy transition materials, surpassing even cobalt and natural graphite regarding geographical dependency.

Regarding downstream industries, China also leads in NdFeB magnet production, accounting for approximately 80-90% of global output. Japan represents around 7% of global magnet manufacturing capacity, with smaller contributions from Vietnam and Germany.

3.2 Regional Outlook

Myanmar, a fragile global leader in HREEs: Myanmar plays a critical role in the worldwide supply of heavy rare earth elements (HREEs), accounting for 57% of dysprosium and terbium global mined supply in 2023.[18] Most of Myanmar's rare earth extraction occurs in Kachin State, near the Chinese border. This proximity allows for the swift transport of rare earth concentrates across the border for processing. However, tracing these materials can become challenging. Moreover, the region's mining operations are also under significant geopolitical, environmental, and social tensions. This problematic situation introduces uncertainty into an already concentrated global HREE supply chain. The escalating conflict between Myanmar's military junta and rebel groups, including the Kachin Independence Army (KIA), has disrupted rare earth mining and trade routes in Kachin State, particularly in the Panwa region, a key mining hub. The Kachin Independence Organization (KIO) suspended rare earth mining in September 2023 due to environmental damage and protests. This suspension caused a prolonged operational halt and added uncertainty for local workers.[16] These disruptions have threatened China's rare earth supply, which heavily depends on Myanmar's feedstock to meet magnet manufacturing demands. While low prices and rising production have overshadowed important environmental and social issues, the recent events exposed the fragility of this supply chain, thus emphasizing the urgency of diversifying and securing sustainable, ethical alternatives for HREE production.

The U.S. restores its domestic REE supply chain by reopening Mountain Pass: The Mountain Pass Rare Earth Mine, located in California's Mojave Desert, has played a pivotal role in the global REE industry. Discovered in 1949, the site revealed significant bastnäsite ore deposits, leading to the commencement of mining operations in 1952 by the Molybdenum Corporation of America. From the 1960s through the mid-1990s, Mountain Pass was the world's leading supplier of REEs. At the time, it was also essential for various high-tech applications. However, a toxic spill raised environmental concerns, and the increased competition from China led to a decline in production, culminating in a shutdown in 2002. The mine experienced a brief revival between 2007 and 2015 but faced financial challenges, resulting in bankruptcy. In 2017, MP Materials acquired the facility, resuming operations in 2018. The U.S. Department of Defense has actively supported this operation through grants. The IEA estimates that the share of global REE mining output rose from 1% in 2015 to 9% in 2023.[16] Although the concentrates were initially shipped to China for refining, MP Materials started in 2023 the production of separated rare earth products (NdPR oxide, but also Ce chloride, La carbonate and HREE concentrates) on top of the original mixed rare earth concentrate production. So far, the NdPr oxide has been sold to Japanese and Korean magnet manufacturers and automakers. This separation and processing facility in California is completed by the project to open a magnet factory in Fort Worth, Texas, which is planned to produce NdPr metal and NdFeB alloy and magnets. MP Materials has also agreed with GM to provide permanent magnets for their EV engines. In July 2025, a groundbreaking public-private partnership between the U.S. Department of Defense and MP Materials was announced, with a 15% equity participation from the DoD, a cost-plus manufacturing offtake of magnets production from a newly planned 10X Facility, planned to be operational in 2028, and a modified contract for difference guaranteeing a price floor of $110/kg of NdPr products. The DoD will cover any gap between market price and the $110 strike price, while capturing 30% of additional revenue if market prices exceed this threshold.[19] The same month, Apple also disclosed a $500 million partnership with MP Materials to produce magnets from recycled materials, processing waste at the Mountain Pass site, and manufacturing magnets at the Fort Worth plant.[20]

Lynas, mining in Australia, and expanding separation operations in Malaysia and the U.S.: Together with MP Materials, Lynas is a major REE miner outside of China, with an integrated production from mining to separated REE salts. The mining and concentrating occur at Mount Weld in Australia, a large, high-grade deposit of monazite containing both LREE and HREE. The mining operation began in 2007 and has produced mixed REE concentrates since then. The Japanese government notably supported Lynas by providing strategic financing and securing long-term supply agreements with Japanese magnet manufacturers. Lynas opened a processing facility in Kuantan, Malaysia, in 2012 to crack & leach Mount Weld concentrates through an acid, which is then separated through solvent extraction and precipitated to individual REE carbonate or oxalate salts. Calcination to NdPr oxide is also possible, and other products of this facility include HREE SEG oxide (Samarium Europium Gadolinium).[21] The company also projects to separate HREEs such as Dy and Tb in Kuantan in 2025. A new processing facility was opened in Kalgoorlie, Western Australia, to crack and leach mixed REE concentrates to mixed REE carbonate products domestically, thus slowly replacing a step previously undertaken in Malaysia.[22] The mixed carbonate salt can be sold to customers, separated in Kuantan, or, in the future, separated in the U.S. Indeed, the US government granted Lynas $30.4 million USD in 2021 to build an LREE separation plant in Seadrift, Texas, and a further $120 million USD in 2022 to build an HREE facility.[23] More support from the DoD followed, and the Texas separation plant is projected to come online by 2025-2026.

3.3 Processing

3.3.1 Bastnäsite and Monazite for LREE

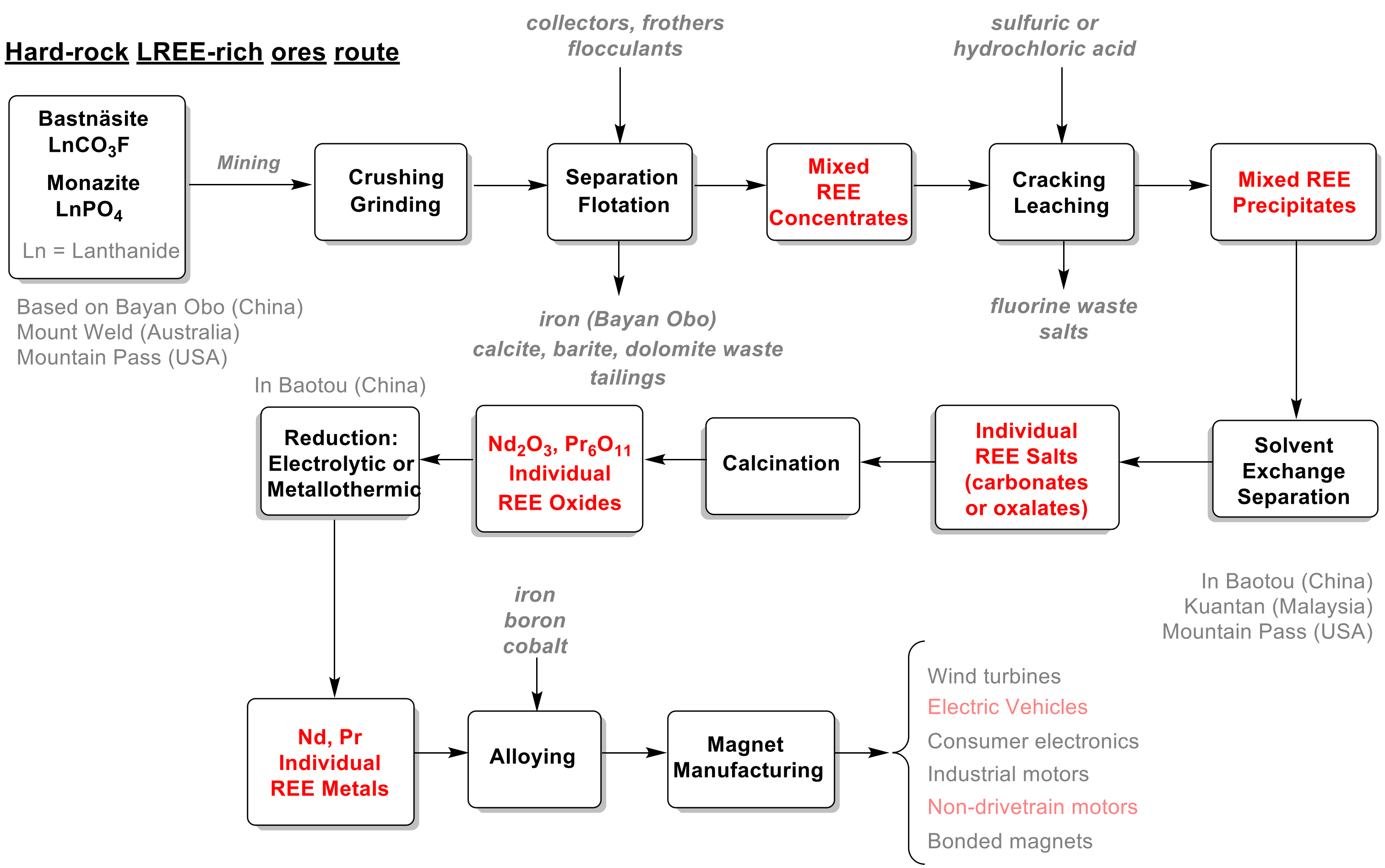

Figure 4 Flowsheet from hard-rock REE ores to magnets

Bastnäsite ore, mostly from either the Bayan Obo mine in Inner Mongolia, China or the Mountain Pass Mine in California, U.S., is first **beneficiated** through crushing and grinding to fine particles, before undergoing flotation processes. A concentrate is obtained, with 68% REO content at Mountain Pass, or 56% for bastnäsite and 34% for monazite from Chinese operations at Bayan Obo/Baotou. In the Chinese case, an iron concentrate is also produced. In Mount Weld, a 37% REO concentrate is obtained after beneficiation, flotation and filtering.[24]

The following step is the **digestion** of the concentrates to obtain soluble REE ions and precipitate them. It is also called **cracking and leaching**. Bastnäsite concentrate can be leached with acid, followed by calcination. The previous Molycorp process used heating in the presence of air at 620°C, obtaining CeO_2 solid concentrate and dissolved REE chloride salts in the solution.[8] Other processes use calcination to decompose carbonate salts and sulfuric acid to dissolve REE as sulfate ions. The calcination or heated acid-leaching steps then emit CO_2, SO_2, and HF. The use of nitric acid after calcination, or even the alkali digestion at 200°C to form REE hydroxides has been reported.[7] In the case of monazite, its reaction with concentrated sodium hydroxide at high temperatures also yields rare earth hydroxides. They can be separated through treatment with hot water, while the trisodium phosphate byproduct can be sold. The hydroxide salts can be dissolved in hydrochloric or nitric acid. Sulfuric acid digestion of monazite has also been reported and yields rare earth sulfate salts, which can be dissolved in water. Conditions must be controlled adequately to separate thorium selectively. For Bayan Obo and Mount Weld, roasting in a rotary kiln with sulfuric acid seems to be the preferred digestion pathway. Depending on the following treatments, mixed REE chloride or carbonate salts are often the products.

Those mixed REE precipitates must now be individually purified through a **separation** process, often through complex solvent extraction processes. The challenge resides in that REE bears similar chemical properties and has typically low separation factors, making this step difficult. Small differences in acidity, salt solubility, cation hydrolysis, and complexation with other chemicals can be exploited. An initial group separation, such as LREEs from HREEs, is often carried out before refining individual elements. In general, two main methods exist, with solid-liquid systems such as ion exchange or fractional crystallization, which are suitable for high-purity and small quantities; while the main industrial process remains liquid-liquid systems based on solvent extraction principles. The latter category can operate continuously and at high capacity. Depending on the system, several specialty chemicals called extractants might be necessary, such as tri-n-butyl phosphate (TBP), di-(2-ethylhexyl) phosphoric acid DEHPA, carboxylic acids or ammonium salts are used to bind individual rare earths selectively. A detailed description of the separation processes is available in the literature.[7,8] After the process, further treatment of individually separated REE salts with oxalic acid yields individual REE oxalate salts, a marketable product. Carbonate, hydroxide, fluoride or chloride salts are also available. After 900°C calcination of those salts, individual rare earth oxide can be obtained.

3.3.2 Ionic Clays for HREE

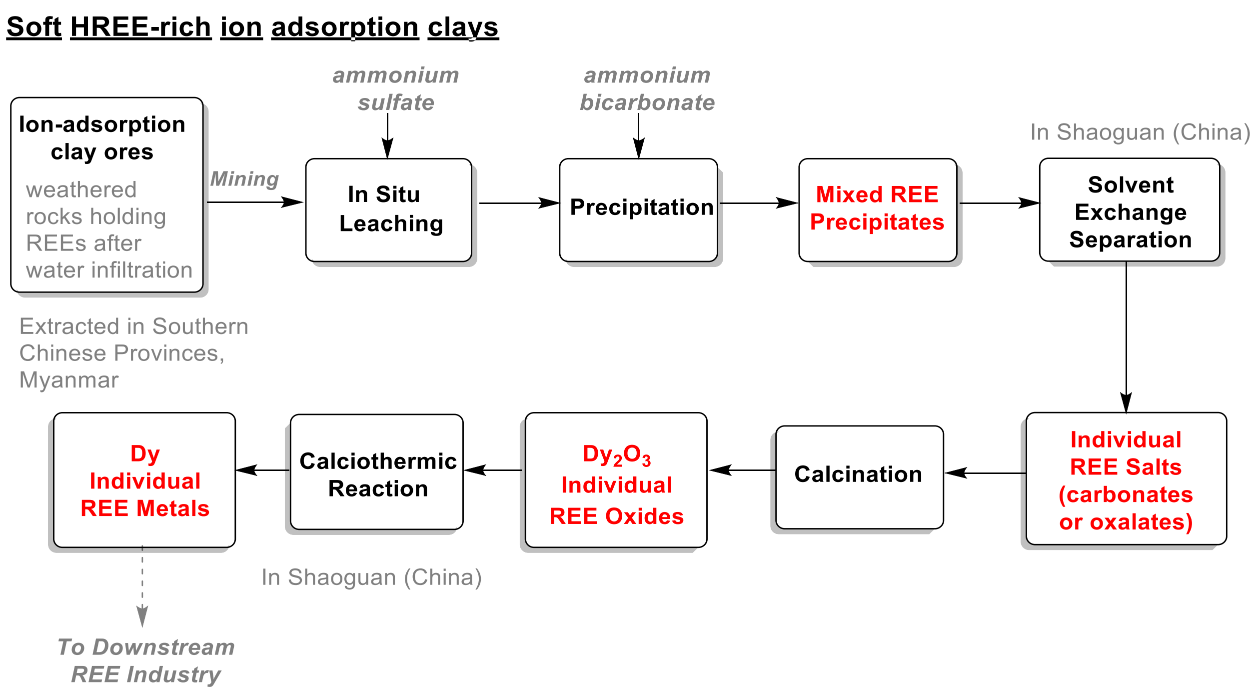

Figure 5 Flowsheet from Ion Adsorption Clay to HREE metals

Heavy rare earth elements (HREEs) are primarily extracted from ionic adsorption clays (IACs) in China, Myanmar, and Laos.[16] IAC deposits are also common in Brazil, Madagascar and Chile. These deposits involve shallow mining (top 20 meters), minimal crushing, and straightforward leaching processes such as heap or vat leaching under atmospheric conditions. Weakly acidic electrolytes such as ammonium sulfate can readily exchange REE ions in IACs, even in dilute solutions, without beneficiation.[25] Precipitation with ammonium bicarbonate and subsequent solvent extraction will yield salts.

Compared to hard rock mining, which requires deep excavation, intensive crushing, high-temperature roasting, and complex acid leaching, IAC mining is less capital-intensive and has a smaller environmental footprint. Clay waste from IACs can be backfilled, avoiding the need for tailings dams. They also exhibit lower radioactivity than monazite or bastnäsite operations. Most IAC leaching products are separated into individual REE precipitates/salts in China, similar to the monazite or bastnäsite products, with the notable difference in yielding additional HREE salts.

The economic appeal of IAC projects lies in their lower processing costs, reduced carbon emissions, and minimal radioactive waste. However, they face limitations, including low recovery rates (30–40%) and environmental concerns from leaching agents like ammonium sulfate. Indeed, ammonium sulfate remaining in the environment can favour eutrophication and algae bloom. A large number of IACs are also mined illegally.[26] New IAC discoveries in Australia, Brazil, and Uganda offer the potential to diversify supply chains, though scaling these operations remains a challenge.

3.3.2.1 Reduction to Metal, Alloys & Magnet

Two main processes for reducing REE oxides, chlorides, or fluorides to metal exist: fused-oxide or salt electrolysis and the metallothermic method. These processes are sometimes called **metallization**. Metallization is considered an energy-demanding but low-margin step, but future automation might optimize the processes.

The **fused-salt electrolysis** method is suitable for LREEs such as La, Ce, Pr and Nd as the melting point for heavier elements is too high, and this would reach the temperature limit of electrodes and containers. First, adding another salt (mostly alkali metal and alkaline earth salts) to the electrolytic bath mixture is necessary to optimize the conductivity and lower the melting point, then a strong current is passed through electrodes in the bath, reducing the RE oxide or salt to their metallic form at the cathode.[7] Mixtures such as didymium or mischmetal can also be produced. Most electrolysis takes place in China.

The **metallothermic method** necessitates alkali metals, alkaline-earth metals or aluminum as reducing agents. Lithium and calcium are often employed, which is called **calciothermic reduction** in the latter case. It is also suitable for REE oxides, chlorides and fluorides and can produce high-purity metallic HREEs, particularly Gd to Lu and Y. For La, Ce, Pr and Nd, rare earth chloride reagents are preferred, and they are heated at temperatures up to 1,100°C with a reducing agent such as lithium with MgO in crucibles.[7] For HREEs with higher melting points, such as Y, Gd-Er, Lu, and Sc, the RE fluorides, prepared from oxides, are preferred starting materials. They are treated with calcium at 1,500–1,600°C in tantalum crucibles.

After reduction, REE metals can be purified through melting and distillation under an inert atmosphere or vacuum.

REE-based permanent magnets necessitate specific alloys. The calciothermic reduction can also produce alloys directly, a feature that can be used to manufacture $SmCo_5$ magnet alloy. In the case of the NdFeB alloy, the specific quantity of Nd, Fe, and B is added to an induction furnace, thus yielding the 'Neo' alloy.

After strip casting, further hydrogen decrepitation breaks down 'Neo' ingots, and a jet-milled inert atmosphere pulverizes the alloy into fine powders. Magnets can then be manufactured by pressing this powder in a magnetic field.[8] Before final inspection, several steps including sintering, grinding, slicing, electroplating, and magnetization to saturation are performed.[24]

3.3.3 Examples of Companies in the Midstream & Downstream Magnet Segments

Most of the steps, from metallization to alloy-making and magnet manufacturing, are mainly occurring in China, except for several players. Shin-Etsu Chemicals and Hitachi perform metal-making in Japan, while Less Common Metals operates in the UK, and Neo Performance Material is active in Estonia. As for magnet manufacturing, TDK, Proterial, and Shin-Etsu Chemicals are active in Japan, Star Group is in South Korea, the Vacuumschmelze group is based in Germany, and Noveon is a U.S.-based company producing sintered magnets from recycled end-of-life products such as electric motors, medical devices and data storage units.[27]

Neo Performance Materials is a company headquartered in Canada that operates inside and outside China. It is currently building a sintered NdFeB magnet plant in Narva, Estonia, specifically for EVs and wind turbine applications. Neo Performance Materials' previous expertise relied on bonded magnets, and this is their first expansion outside of China aimed at more robust and EV-compatible sintered magnets. The company is also unique in being present in any segments of the value chain: REE separation, metallization and alloys, magnet manufacturing and recycling.

Vacuumschmelze is constructing a sintered NdFeB magnet plant in South Carolina to supply GM's EV motors with the support of the U.S. government through tax credits.[28,29] As mentioned above, MP Materials is also constructing a magnet plant in Fort Worth, Texas, with off-take agreements with GM. Commercial production is aimed to start in 2025.[30]

The Australian company Australian Strategic Minerals has also projected to venture into downstream metal reduction in Korea while developing its domestic Dubbo mining in New South Wales.

3.3.4 Circularity

The end-of-life recycling rate for REEs is very low and expected to be around 1%.[31] However, recycling R&D was accelerated in 2011 within the context of the Rare-Earth crisis and price spikes. So far, the lack of collection systems and high costs have hindered the development of large-scale REE recycling solutions. Solvay previously developed a recycling unit with Umicore in La Rochelle, France, specializing in reprocessing and separating LREEs from fluorescent batteries, but the operations lasted from 2012 to 2016 when REE prices were too low to justify recycling.[23] More recent developments have shown that Solvay is now interested again in expanding its REE separation capacity at La Rochelle.[32] They have also signed an MOU with Cyclic Materials, where Cyclic agrees to supply Solvay with recycled rare earth oxides for further separation.[33] Cyclic Materials itself is an Ontario-based company specializing in recycling REE from end-of-life products such as electronic waste and old motors. Noveon, as mentioned above, also recycles e-waste to produce REE magnets.

3.3.4.1 Comparison of Processing Pathways and Environmental Impacts

The impacts of REE production can pose significant environmental challenges, with implications varying wildly across production pathways and geographical regions.

Life Cycle Assessments (LCAs) highlight that most REE production is concentrated in China, where inefficient processes, high chemical consumption, and coal-heavy energy use exacerbate environmental footprints. A comparative LCA from 2018 indicates that the Bayan Obo mine in China exhibits the highest environmental impacts, driven by poor recovery rates and outdated infrastructure, including a 50-year-old tailing pond, which contributes to higher leakage and ecological damage. In contrast, Mountain Pass benefits from cleaner processes, such as the absence of acid roasting, reliance on natural gas-fired power, and recycling saline wastewater, which collectively reduce its footprint. Mount Weld performs moderately, with impacts partly mitigated by using magnesium oxide instead of ammonium bicarbonate in precipitation, lowering eutrophication. However, its particulate matter emissions remain high due to mining and grinding requirements. It should be noted that this particular LCA analysis did not consider the newly opened separation facility in Mountain Pass or the Kalgoorlie processing plant from Lynas.[24]

Another 2018 LCA analyzed magnet-to-magnet recycling and found that virgin production, which relies heavily on fresh REEs, has a significantly higher environmental impact than magnet-to-magnet recycling.[34] Recycling undoubtedly reduces reliance on mining and decreases fresh REE consumption by approximately 99.9%. It also slashed overall impacts by 64–96%. However, the recycling process heavily relies on electricity and nickel for coating, which accounts for most of its footprint. Transitioning to renewable energy sources, such as wind or hydroelectric power, could reduce recycling impacts by up to 93%, thus highlighting the importance of the electricity grid footprint.

A cradle-to-gate LCA from 2013 analyzed the cradle-to-gate production of the 14 REE metals, choosing Bayan Obo as the processing site with both mass-based and price-based allocation of GHG emissions.[35] The mass-based method allocates emissions proportionally to the abundance of elements, emphasizing energy and material inputs and extractable REE mass. This approach shows that elements like scandium (Sc) and yttrium (Y) have higher impacts due to their lower extractable masses and energy-intensive processing. The price-based method incorporates economic factors, highlighting the high impacts of expensive and less abundant REEs such as scandium, europium, terbium, and dysprosium. Indeed, these elements require more energy and materials for separation as well as reduction, owing to their lower concentrations and extractable masses. Price fluctuations influence this method, amplifying the impact of high-priced REEs. Additionally, the environmental impact of processing waste, especially tailings containing radionuclides from bastnäsite and monazite, poses long-term risks to ecosystems and human health.

Addressing waste management and exploring low-impact recycling and production technologies are critical for sustainable REE supply chain development. This point is also supported by another 2022 study, which also emphasized the need for better emission treatment, chemical recycling, closing illegal mines and raising environmental standards.[26]

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