Geopolitics of Technology

Rare Earth Elements

Micro-Market with Macro-Impact

Prithwis Mukerjee, PhD

Contents

Where does India fit into this story?

1. Overview - What are Rare Earth Elements and where are they used?
2. Geography - Where are they found ?
3. Technology - What are the challenges associated with the extraction and refining process ?
4. Geopolitics - What is the economic impact of this technology
5. Closing Thoughts

Rare Earth Elements

Seventeen elements are classified as Rare Earth Elements (REEs), a group of similar metals critical for many advanced technologies.

They include the 15 lanthanide elements plus Scandium and Yttrium.

Six key elements

- Magnet Trio - Neodymium (Nd) Praseodymium (Pr) Dysprosium (Dy)
- Industrial Trio - Terbium (Tb), Lanthanum (La), Cerium (Ce):

Despite their name, REEs are relatively abundant in the Earth's crust, but rarely found in economically exploitable concentrations.

They play a critical role in energy, defense, and digital applications, particularly in permanent magnets used in electric vehicles (EVs) and wind turbines, as well as in catalysts, fiber optics, and high-precision electronics.

Six Rare Earth Elements

The Magnet Trio

- Neodymium - Nd
- Praseodymium - Pr

The "Workhorses." Essential for high-strength permanent magnets in EV motors and wind turbines.

- Dysprosium - Dy

The "Heat Shield." Added to magnets so they don't lose power in high-heat environments (fighter jets, industrial robots).

Nd & Pr – The "Power Pair" (Light Rare Earths)

The Engine of Electrification.

Neodymium (Nd) and Praseodymium (Pr) are typically produced together as a combined oxide (NdPr).

They are the primary ingredients in NdFeB (Neodymium-Iron-Boron) magnets, the strongest permanent magnets in existence.

Because Nd and Pr are "Light" rare earths, they are more abundant globally than the "Heavy" ones. However, the metal-making process (turning oxide into metal) remains a Chinese-dominated chokepoint.

They allow for incredibly powerful magnetic fields in small volumes. This allows motors to be smaller, lighter, and more efficient.

- EV Traction Motors: Provides the torque needed for rapid acceleration.
- Direct-Drive Wind Turbines: Eliminates the need for heavy, high-maintenance gearboxes, making offshore wind viable.

Dy – The "Heat Shield" (Heavy Rare Earth)

High-Performance Survivability.

Standard NdFeB magnets have a weakness. Once a standard magnet exceeds 80°C, it begins to lose its magnetic alignment.

Dysprosium is added to the alloy (replacing some Neodymium atoms) to increase Coercivity—the magnet's ability to resist demagnetization under stress.

Geopolitical Fact: Dy is a "Heavy" rare earth, found almost exclusively in the ionic clays of South China and Myanmar. This makes it the ultimate strategic bottleneck.

Adding just 2-5% Dysprosium allows magnets to operate reliably at temperatures exceeding 200°C.

Mission-Critical Applications:

- Fighter Jets: Flight control actuators operate in extreme heat near engines. Industrial
- Robotics: Precision motors running 24/7 in hot factory environments.
- High-Speed Rail: Heavy loads generate massive friction-heat in the motors.

The Technical Synergy & Chokepoints

The "Rare Earth Recipe" as a Strategic Lever.

A high-performance magnet isn't just "Rare Earth"; it's a specific chemical recipe: $(Nd, Pr, Dy)_2Fe_{14}B$.

Praseodymium (Pr) can substitute for Neodymium to lower costs, but it is slightly less powerful.

Terbium (Tb) can substitute for Dysprosium—it's even better at heat resistance but is 3x more expensive and even rarer.

To build an EV motor, you need all three. If a nation controls only the Nd (Light) but not the Dy (Heavy), they cannot build a high-performance EV motor independently.

This is why China's 2025 export controls on Heavy Rare Earths (Dy/Tb) are more damaging than controls on Light ones; you can't just "mine" your way out of a Heavy REE shortage quickly.

The Industrial Trio

- Terbium - Tb
- Lanthanum - La
- Cerium - Ce

The "Industrial Trio" (Tb, La, Ce) provides a perfect case study for the Balance Problem and the Abundance vs. Criticality paradox. While Neodymium makes the headlines, these three elements are the quiet enablers of global energy, vision, and compute.

Terbium (Tb) – The "Green Light" & Navy's Ears
High-Frequency Precision and Defense.

Terbium is a "Heavy" rare earth (HREE) known for its vibrant green luminescence and extreme magnetostriction (the ability to change shape in a magnetic field).

Terbium is one of the rarest and most expensive REEs (~$400/kg). Found primarily in the ionic clays of South China and Myanmar, it is a high-risk "single-source" dependency for the global defense industry.

Advanced Sonar (Terfenol-D)

Used in naval sonar transducers to convert electrical signals into underwater sound. It allows submarines to "see" at greater depths and with higher resolution than traditional materials.

Green Phosphors

Essential for the "Green" in RGB screens (LEDs, OLEDs) and energy-efficient trichromatic lighting. Without Tb, your smartphone screen would be dim and color-inaccurate.

Lanthanum (La) – The "Catalytic Guard"

Fuel Security and Optical Clarity.

Lanthanum is a "Light" rare earth (LREE) used primarily as a chemical catalyst and an optical additive.

While La is abundant, its role in fuel refining makes it a "National Security" metal. If the supply of La were cut, global petroleum production would drop, and fuel prices would spike instantly.

Petroleum Refining (FCC):

90% of global petroleum is produced using Fluid Catalytic Cracking catalysts. Lanthanum makes these catalysts stable at high temperatures, increasing fuel yield by up to 10%. A modern refinery consumes 200-500 tons of La-based catalyst annually.

High-Index Optics:

Added to glass to create lenses with high refractive indices but low dispersion. This allows for thinner, clearer lenses in telescopes, microscopes, and high-end camera lenses (like those on iPhones)

Cerium (Ce) – The "Abundant Polisher"

The Semiconductor Manufacturing Bottleneck.

The most abundant REE (more common in the crust than copper). It is a "Light" rare earth (LREE) with a unique ability to switch between oxidation states (+3 and +4), making it a powerful abrasive and decolorizer.

Because we mine REEs together, we produce an oversupply of Cerium just to get enough Neodymium. This keeps Cerium prices low (~$8/kg), but its role as a "gatekeeper" for the semiconductor industry gives it massive hidden geopolitical leverage.

Semiconductor Polishing (CMP):

Cerium oxide is the "gold standard" for Chemical Mechanical Planarization (CMP). It is used to polish silicon wafers to atomic-level flatness between layers of transistors. Without Ce-slurries, modern sub-7nm chips (AI chips, GPUs) could not be manufactured.

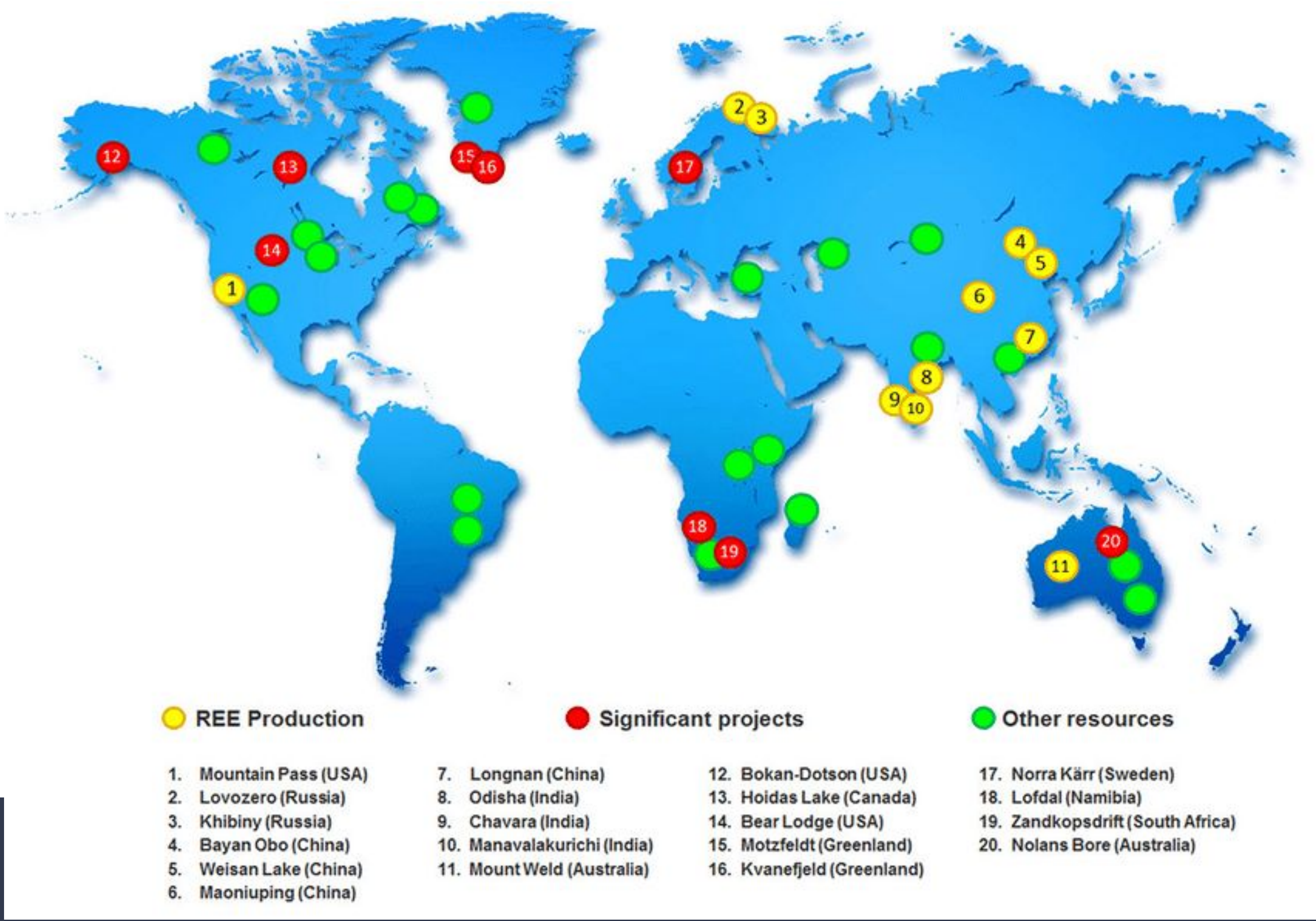
Environmental Protection:

Used in automotive catalytic converters to store and release oxygen, reducing toxic NOx emissions from internal combustion engines.

Geography

- Mines
- Refining

An outlook on the rare earth elements mining industry - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Map-showing-the-global-distribution-of-REE-deposits-and-mines_fig1_303140029 [accessed 31 Jan 2026]



Challenge

RARE EARTHs: CHINA's POSITION Travail réalisé par - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/World-map-showing-reserves-of-rare-earth-metals-vital-to-the-production-of-hightech_fig1_344560698 [accessed 31 Jan 2026]

Illusion of Global Mining

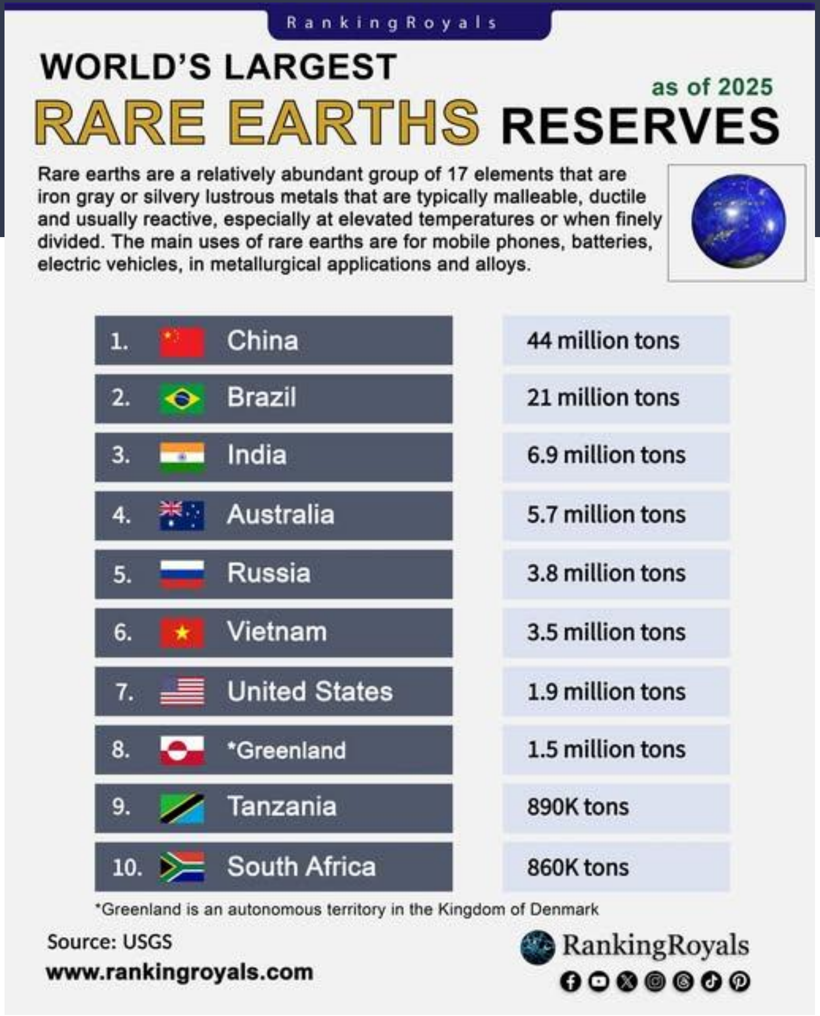
Many mine, but few control the value

The "Mine-to-Metal" Gap

Minerals like those from the US (Mountain Pass) or Myanmar are often shipped as concentrate back to China for final processing.

The Indian Paradox

India has the world's 5th largest reserves but currently contributes <1% to global refined supply.

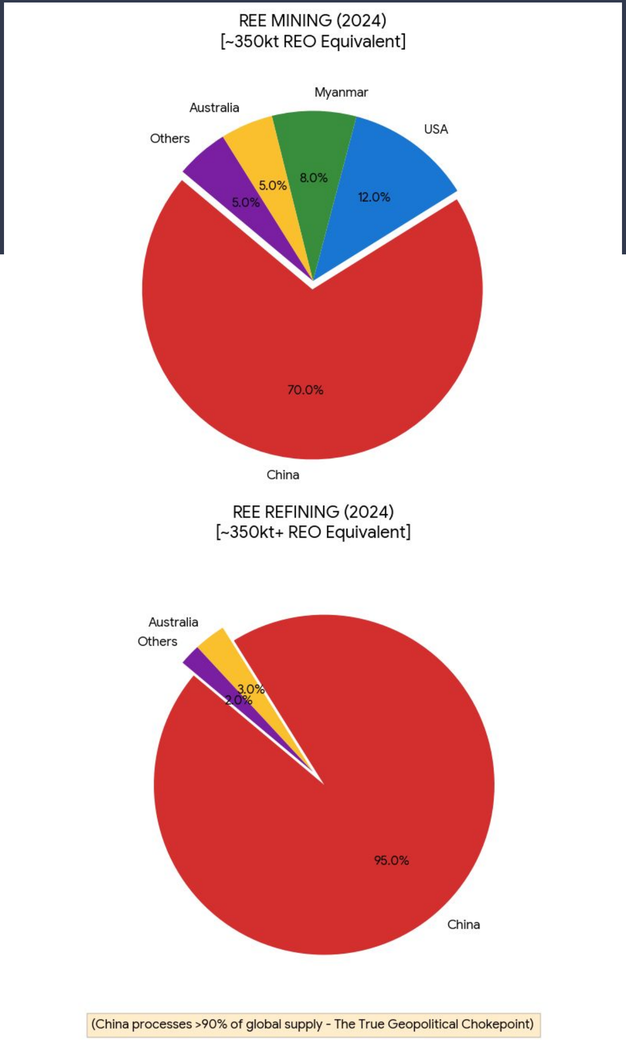


The 90% Chokepoint
Refining vs. Mining

Mining: China controls ~60-70% of global mining.

Separation/Refining: China controls 90%+ of global capacity.

The Conclusion: Owning the mine is useless if you don’t own the "Chemical Kitchen" required to cook the ore.



The Refining Choke

The West’s struggle for "Strategic Autonomy."

- Mountain Pass (MP Materials): The only US site; relies on China for refining until very recently.
- Lynas (Mt Weld): The only major non-Chinese refiner (processing in Malaysia).

Myanmar – The "Hidden" Supplier

- Myanmar is the world’s 3rd largest producer, providing high-value Heavy REEs (Dy/Tb).
- Geopolitical Shadow - Most Myanmar mines are controlled by militias and feed directly into Chinese supply chains.

India – The "Sleeping Giant" of Monazite

The Resource Base (Monazite Sands):

- India possesses over 12 million tonnes of Monazite. Unlike the "hard rock" mines in the US or China, India's rare earths are found in heavy mineral beach sands along the coasts of Odisha, Tamil Nadu, and Kerala

Abundance and Accessibility

- Unlike deep-rock mining, these are surface deposits that are relatively easier to harvest.

The Thorium Dilemma:

- Indian Monazite is high-quality but contains significant Thorium (a radioactive element).

The Chokepoint:

- Extracting rare earths from Monazite requires "cracking" the mineral, which creates radioactive waste. Handling this waste is technically complex and strictly regulated by the Department of Atomic Energy (DAE), limiting rapid private sector entry.

Why Monazite ?

Primary Source of the "Magnet Trio":

- Monazite is rich in Neodymium (Nd) and Praseodymium (Pr). These are the "workhorse" elements required for high-strength permanent magnets in EV motors and wind turbines.

High Neodymium Content:

- Compared to other ores like Bastnäsite (found in the US), Monazite often has a higher percentage of Neodymium, making it more valuable for the "green energy" transition.

Source of the "Industrial Trio":

- It contains significant amounts of Lanthanum (La) and Cerium (Ce), which are essential for petroleum refining and semiconductor polishing.

Trace Heavy Rare Earths:

- Monazite also contains small but vital amounts of Dysprosium (Dy) and Terbium (Tb), the "heat shields" for high-performance magnets used in defense and aerospace.

Praxis Business School
CELEBRATE YOUR WORTH

Technology Challenges

Solvent Extraction (SX) - Chemical Marathon

The chokepoint isn't the mine; it's the "Chemical Kitchen."

SX is a liquid-liquid separation process that relies on "Differential Solubility."

The Ingredients:

- Aqueous Phase (Acid): A "soup" of mixed rare earth elements dissolved in strong acid (usually Hydrochloric or Nitric acid).
- Organic Phase (Oil): A carrier (typically kerosene) mixed with a specialized extractant (the "chemical claw") designed to grab specific elements.

It has taken China nearly 30 years to master this process

The Process:

- When these two immiscible liquids are mixed, the extractant "claws" out the desired element from the acid and pulls it into the oil. Because they don't mix, the oil floats to the top, carrying the specific rare earth with it.

Why it's Hard:

- Rare earths are "chemical twins." Their atomic properties are so similar that an extractant might accidentally grab 51% of Neodymium and 49% of Praseodymium. This leads to the need for the "Cascade."

The "Cascade" – Why Purity Takes Hundreds of Steps

The Single Stage Failure:

A single mixing event only provides a "rough" separation. To reach the 99.9% purity required for an EV magnet or a fighter jet sensor, you must repeat the process.

- 100+ Stages: Industrial plants use long "batteries" of mixer-settler tanks. The liquids flow in opposite directions (Counter-Current).
- The Loop: In each tank, the rare earth becomes slightly purer. By the time it reaches the 50th or 100th tank, it has finally been "filtered" of its siblings.
- Scale: A single industrial separation line can be longer than a football field, containing hundreds of thousands of liters of volatile chemicals.

Extraction Challenge

The Acid Wash

Chemical Consumption: Requires massive amounts of Sulfuric, Hydrochloric, and Nitric acids.

Infrastructure: Requires thousands of meters of corrosion-resistant piping and settling tanks.

The Energy/Waste Burden

Energy Intensity: The refining process is highly energy-dependent, adding to the carbon footprint.

Wastewater: Produces "Ammonia-Nitrogen" waste and acidic tailings that must be managed to avoid "Red Lakes".

The Thorium Barrier – A Regulatory Chokepoint

The Radioactive Reality

- Many high-value rare earth ores (like Monazite) naturally contain Thorium and Uranium.

The 1990s Collapse

- In the 1980s and 90s, the US (specifically the Molycorp mine) faced increasingly stringent environmental regulations regarding radioactive waste.

The "Externalization" of Cost

- China capitalized on this by offering low-cost refining with significantly lower environmental and radioactive waste oversight.
- Western companies, unable to compete with China's "subsidized" environmental costs, shuttered their refineries.

The Result: The US went from being self-sufficient in the 1960s to exporting 95% of its mined ore to China for processing today, simply because it lacks the domestic radioactive waste infrastructure.

Acid Lakes & "Red Mud" — The Case of Baotou

The Baotou Tailings Pond

- Located in Inner Mongolia, this is one of the largest man-made "toxic lakes" in the world (~11 sq km).

The "Toxic Cocktail"

Stores over 180 million tonnes of waste

- Acidic Wastewater: Millions of cubic meters of sulfuric and nitric acid used in the "solvent extraction" marathon.

- Radioactive Seepage: High concentrations of Thorium have contaminated local aquifers, moving toward the Yellow River at a rate of 20-30 meters per year.

A Cautionary Tale of ESG

Agricultural Destruction

Over 60,000 mu* (~ 10000 acres or 40 sq km) of farmland have been rendered unusable or poisoned.

Strategic Lesson

China’s dominance was built on a trade-off: Global market control in exchange for local ecological devastation. As China now implements its own "Green" regulations in 2025-2026, the global price of rare earths is rising to reflect these "true" costs.

* mu is the Chinese unit of land measurement = 0.667 sq metres ~ 1/15 hectares

Geopolitics

Detailed Report

Basic Economics

Value Table – Projected 2026 Prices

Terbium (Tb): ~$3,800–$4,000/kg (Critical for Navy Sonar/Screens).

Dysprosium (Dy): ~$900–$950/kg (High-heat magnets).

Neodymium (Nd): ~$120–$150/kg (Mainstream magnets).

Lanthanum/Cerium: ~$5–$10/kg (Abundant, often oversupplied).

"Balance Problem" – Miner’s Nightmare Key

Geological Reality - To get 1kg of high-value Terbium, a mine might have to produce 100kg of nearly worthless Cerium.

Economic Impact - The oversupply of Cerium/Lanthanum crashes their prices, making it hard for new Western mines to be profitable.

Solution - Developing new uses for Cerium (like semiconductor polishing) is a strategic priority.

All prices and control measures shown are indicative, subject to volatility, scope interpretation, and selective enforcement.

REE Market – Small Dollars, Massive Leverage

Micro-Market with Macro-Impact.

The Market Valuation (2025-2026)

- The Mineral Market: The global rare earth elements (REE) market is valued at approximately USD 5.14 to 5.73 billion in 2025.
- The Magnet Multiplier: The real value is unlocked in the Rare Earth Magnets market, which is nearly 4x larger, valued at approximately USD 22 billion.
- Projected Growth: The REE market is expected to surge to USD 10-12 billion by 2030-2035, driven by the "Green Transition" (EVs and Wind).

The "Value vs. Volume" Paradox

- Volume Leader: Cerium accounts for ~38% of volume but only a tiny fraction of total revenue due to its low price ($5-10/kg).
- Value Leader: Neodymium and Praseodymium (NdPr) dominate the revenue share (up to 40% of market value) because they are essential for magnets.

Geopolitical Significance

Small but Vital

For perspective, the global smartphone market is worth ~$500 billion, yet it depends entirely on this $5 billion rare earth market.

The Leverage Ratio

China uses its 90% control of a relatively "cheap" $5 billion industry to influence $trillions in downstream technology, from defense to clean energy.

India’s Domestic Opportunity

India's REE market is currently a "Sleeping Giant," valued at only USD 80 million in 2026. However, India’s Rare Earth Magnet market is projected to hit USD 3.7 billion by 2032, showing where the "value-add" priority lies.

China’s 2025 "Waves" – The Licensing Trap

Export controls have moved from raw ore to "Dual-Use" technology.

The April & October Waves

- In 2025, China introduced two massive waves of export restrictions targeting Neodymium (Nd), Dysprosium (Dy), and Terbium (Tb).

Beyond the Mineral

- For the first time, Beijing asserted Extraterritorial Reach.
- Any foreign-made product (like an iPhone or a Tesla motor) containing even 0.1% Chinese rare earths now technically requires a Chinese export license.

The Intelligence Gap

- The licensing process is intentionally "opaque and selective." By approving licenses for some companies but delaying them for others, China can effectively decide which Western car or defense manufacturers "survive" a quarter.

Targeting the Defense Sector

- As of late 2025, export licenses for rare earths used in military applications are being automatically rejected for "unfriendly" nations.

The "November 2026" Cliff – A Tactical Pause

The South Korea Détente:

Following a high-stakes meeting between Presidents Trump and Xi in late 2025, China announced a temporary suspension of its most aggressive controls.

The "Cliff" Date:

Most of these suspensions expire on November 10, 2026.

Why it's a "Ticking Clock"

- It is a "Tactical Pause," not a policy shift. Beijing is using this window to observe Western reactions. For manufacturers, this is a reprieve, not a solution. It takes 5–10 years to build a new refinery, but only 1 year remains before the "Cliff".

The Leverage

- Beijing preserves its long-term leverage; if trade relations sour in early 2026, the "Cliff" can be moved forward at any time.

Case Study – How Japan Broke the Chokehold

The 2010 Wake-Up Call

After a maritime clash near the Senkaku (Diaoyu) Islands, China abruptly halted rare earth exports to Japan.Prices for magnets spiked 10x within a year, threatening the entire Japanese automotive (Toyota/Honda) and electronics sectors.

The "Japan-Australia-Malaysia" Axis

- The Funding: Japan’s state-backed JOGMEC and trading house Sojitz provided a $250M lifeline to a then-struggling Australian miner, Lynas, in 2011.

The Structure

- Ore is mined at Mt Weld (Australia) >> Shipped to Kuantan (Malaysia) for refining >> Exported to Japan for magnet manufacturing.

Strategic Payoff

Reducing Dependency

Japan successfully lowered its reliance on Chinese rare earths from 90% in 2010 to roughly 60% today.

Heavy REE Breakthrough

In May 2025, the Lynas Malaysia plant produced the first commercial Dysprosium outside of China—neutralizing Beijing's strongest "trump card" in high-temp magnets.

The Price of Autonomy

Japanese companies pay ~50% more for Lynas material than Chinese material, viewing the premium as an "insurance policy" against geopolitical blackmail.

Government as an Anchor

Without JOGMEC’s patient, state-backed capital, Lynas would likely have failed or been bought by Chinese state-owned firms.

Japan did not defeat China on cost; it defeated China on continuity, coordination, and state patience.

India Story

The "Midstream" Gap:

- Current State: India primarily exports low-value beach sand minerals or mixed concentrates rather than high-value refined metals or magnets.

Strategic Horizon:

- Under the National Critical Minerals Mission, India is now racing to build domestic "Value-Added" refineries to bypass the Chinese "Chemical Kitchen".

Strategic Autonomy

- Mastering the extraction of rare earths from Monazite is a pillar of the National Critical Minerals Mission. It allows India to move from being a "resource exporter" to a "value-added refiner," reducing dependence on Chinese supply chains.

Industrial Convergence

- India's ability to process its Monazite sands is a key point of interest for the India-EU industrial convergence, as Europe seeks alternative sources for permanent magnets.

India’s "Magnet Sovereignty"
The 2047 Horizon

The IREL Pivot

- India’s state-owned IREL (India) Ltd. has launched a landmark ₹7,280 crore scheme to build an integrated Rare Earth Permanent Magnet (REPM) ecosystem.

The 6,000 MTPA Goal

- India aims to produce 6,000 Metric Tons per Annum of finished magnets by 2030, covering the full value chain from Oxide → Metal → Alloy → Magnet.

Strategic Autonomy

- The Vizag Plant: A new facility in Visakhapatnam is utilizing indigenous technology to produce magnets specifically for India’s defense and EV sectors.

The Challenge: While India has the ore, it still lacks commercial-scale "Metallurgical Expertise." The next 24 months are a race to master the Sintering process required to make magnets that can compete with Chinese quality.

The Summing Up

- In the 21st century, sovereignty is no longer decided by oil or data alone, but by who controls the chemistry that turns minerals into machines.
- Rare earths are not rare because of geology; they are rare because mastery of their chemistry is.
- India’s strategic choice is no longer whether it has rare earths, but whether it chooses to master what comes after the mine.
- A nation that controls mines may bargain; a nation that controls refining decides.

Prithwis Mukerjee, PhD

This deck is dedicated to my father Sri Subhrendu Mukerjee, who as a student of Chemistry had created a small collection of Monazite sands in 1950. Unfortunately, his collection is now lost

रूपान्तरण -प्रभुत्वं सार्वभौम्यम्।

Rūpāntaraṇa-prabhutvaṁ sārvabhaumyam

“Sovereignty lies in mastery of transformation”