Rare earth elements as a key element of the future

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Abstract: Rare earth elements (REEs) are a group of chemical elements with similar physicochemical properties that play a crucial role in the development of modern technologies. This article examines their structural characteristics, natural occurrence, and extraction methods. Particular attention is given to the application of REEs in high-tech industries, including electronics, energy, magnet production, and environmentally friendly technologies. The article also analyzes the economic and geopolitical aspects associated with the limited availability of these resources and the concentration of their production in specific regions of the world. The conclusion discusses future prospects for the rare earth elements market and highlights the need for more sustainable and efficient methods of their use and recycling.

Key words: Rare earth elements, REEs, lanthanides, critical materials, mineral resources, extraction methods, electronics, renewable energy, permanent magnets, sustainability, geopolitics, supply chain

Rare earth elements (REEs) constitute a specific group of chemical elements that play a fundamental role in modern geology, technology, and the global economy. This group includes scandium, yttrium, and fifteen lanthanides from lanthanum to lutetium. From a geological perspective, rare earth elements are not truly rare in terms of their average abundance in the Earth's crust; many of them are more common than metals such as gold, platinum, or silver. Their perceived rarity is instead обусловлена the fact that they seldom form highly concentrated ore bodies and are usually dispersed within complex mineral assemblages, which significantly complicates their extraction and processing.

The geochemical behavior of rare earth elements is largely controlled by their similar ionic radii and predominantly trivalent oxidation state. These characteristics cause REEs to substitute for one another within crystal lattices and to accumulate together during magmatic differentiation and hydrothermal processes. As a result, rare earth elements typically occur in specific minerals such as monazite, bastnäsite, xenotime, loparite, and ion-adsorption clays. The formation of economically viable REE deposits is commonly associated with alkaline and carbonatite magmatism, late-stage magmatic fluids, as well as prolonged weathering in tropical climates, where secondary enrichment can occur.

The largest known resources are associated with a limited number of countries, which creates both economic opportunities and geopolitical vulnerabilities. Large carbonatite-related deposits, such as those found in East Asia, represent some of the most significant accumulations of light rare earth elements. Heavy rare earth elements, which are particularly valuable for advanced technologies, are often concentrated in ion-adsorption clay deposits formed by intense chemical weathering of granitic rocks. Although global geological resources of rare earth elements are sufficient to meet long-term demand, the challenge lies not in their absolute quantity but in the technical and environmental feasibility of their extraction.

From the standpoint of Earth resources, rare earth elements are widely distributed across the planet, but their economically recoverable reserves are unevenly concentrated. The table of global REE reserve distribution shows that Asia, particularly East Asia, contains the greatest share of known reserves, followed by regions in South America, North America, Africa, and Australia. In rough proportion, approximately **45 - 50%** of known REE reserves are located in East Asia, with significant contributions from Brazil, Russia, India, and Australia.

The following table describes **major REE deposits worldwide** along with host lithology and dominant element types:

Approximate table of major rare earth element deposits

Deposit / Region	**Country**	**Host Rock Type**	**Dominant REE Category**	**Notes**
Bayan Obo	China	Carbonatite / Hydrothermal	Light REEs	Largest known REE deposit
Mount Weld	Australia	Carbonatite	Light REEs, some HREE	High-grade resource
Ion-adsorption Clays	South China	Weathered Granite	Heavy REEs	High extraction potential

Khibiny–Lovozero	Russia	Alkaline Complex	Mixed REE suite	Large resource, geologically unique
Araxá	Brazil	Carbonatite	Light + Medium REEs	Historically significant
Strange Lake	Canada	Peralkaline Granite	HREE-rich	Complex geology, rare HREE

The technological importance of rare earth elements is exceptionally high. Their unique magnetic, optical, electronic, and catalytic properties make them indispensable in modern industry. The next list summarizes some of the **most critical REEs, core applications, and indicative price categories** (note: prices vary over time and with purity):

Representative REE Applications and Indicative Relative Prices

- **Neodymium (Nd):** Highest demand for high-performance permanent magnets used in electric motors, wind turbines, and robotics. Price tier: *high–very high*.
- **Dysprosium (Dy):** Enhances magnet performance at high temperatures; critical for EVs and aerospace. Price tier: *very high*.
- **Terbium (Tb):** Used in green phosphors and magnet alloys. Price tier: *very high*.

- **Europium (Eu):** Essential in red phosphors for display technologies. Price tier: *high*.
- **Yttrium (Y):** Used in LED phosphors, advanced ceramics, and superconductors. Price tier: *moderate–high*.
- **Cerium (Ce) & Lanthanum (La):** Common in catalysts and glass polishing; price tier: *lower relative to HREEs*.

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The technological importance of rare earth elements is exceptionally high. Their unique magnetic, optical, electronic, and catalytic properties make them indispensable in modern industry. Neodymium, praseodymium, and dysprosium are critical components of high-performance permanent magnets used in electric vehicles, wind turbines, and industrial motors. Europium, terbium, and yttrium are essential for phosphors in lighting, displays, and laser systems. Cerium and lanthanum are widely used in catalysts for petroleum refining and environmental protection technologies. Without rare earth elements, many key sectors of the high-tech economy, including renewable energy, electronics, aerospace, and defense industries, would face severe limitations.

The mining and processing of rare earth elements represent one of the most technologically complex segments of the mineral industry. Ore grades are often low, and the minerals containing REEs are chemically resistant, requiring energy-intensive beneficiation and sophisticated chemical separation techniques. After mining and physical concentration, rare earth ores undergo hydrometallurgical processing involving acid leaching, solvent extraction, or ion-exchange methods to separate individual elements from one another. This stage is particularly challenging because of the chemical similarity of REEs, which necessitates multi-stage separation processes and generates large volumes of waste.

Economic factors strongly influence the development of rare earth projects. The cost of production is high, capital investment requirements are substantial, and market prices are volatile. Individual rare earth elements differ greatly in value, depending on their scarcity, demand, and technological relevance. Heavy rare earth elements generally command significantly higher prices than light rare earths due to their limited supply and critical applications. Market dynamics are further complicated by the concentration of processing and refining capacity in a small number of countries, which can lead to supply disruptions and price fluctuations.

Environmental considerations are inseparable from the geology and economics of rare earth elements. Many REE-bearing minerals contain radioactive elements such as thorium and uranium, which require careful handling and long-term waste management. Chemical processing can result in soil, water, and air contamination if not properly controlled. Consequently, the sustainable development of rare earth resources demands strict environmental regulations, improved processing technologies, recycling of end-of-life products, and the search for alternative materials where possible.

In conclusion, rare earth elements represent a paradox of modern geology: they are relatively abundant in the Earth's crust, yet difficult to concentrate, extract, and process in an economically and environmentally acceptable manner. Their importance for advanced technologies and the global transition to low-carbon energy systems makes them strategically critical resources of the twenty-first century. Future progress in the rare earth sector will depend on integrated geological exploration, technological innovation in extraction and separation, diversification of supply chains, and the development of sustainable approaches that balance economic demand with environmental responsibility.

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