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# How rare earths metals power our future - and the risks we must consider

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**ABSTRACT**

Rare earth elements (REEs) are indispensable to modern technology, driving advances in renewable energy, consumer electronics, and medical imaging through their unique magnetic, light-emitting, and catalytic properties. From the rare earths in wind turbine magnets to those in the phosphors that give LED displays their vivid colors, these 17 metals underpin critical sectors of the global economy. You might never notice them, yet they are present in almost every device around you. Their story, however, is not without complications: extraction and processing can cause deforestation, soil and water contamination, and in some regions are tied to human rights abuses. Meeting these challenges will require better recycling, greener processing, and alternative materials, which is a task that grows more urgent as demand soars. Ultimately, understanding the science, applications, and policy of REEs is key to ensuring a sustainable and equitable supply for the technological transition of the 21st century.

**KEYWORDS:** Rare Earth Elements, Renewable Energy Technologies, Sustainability, Materials, Technology

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## How rare earths metals power our future — and the risks we must consider

There is something incredibly small inside your laptop, your smartphone, and even the MRI machine at your local hospital that makes it all work. It's not just silicon or iron, but the rare earth elements. These metals, with bizarre names such as gadolinium (Gd), dysprosium (Dy), lanthanum (La), and lutetium (Lu), unknown to most people, are behind the operation of modern digital technologies and at the core of the renewable energy transition. From the magnets in wind turbines and electric vehicles to battery materials made with lanthanum, rare earth elements (REEs) are essential to many technologies we rely on every day.

But what exactly are rare earth elements, and why are they considered so essential to the scientific and economic landscape of the 21st century? Rare earth elements (REEs) are a group of 17 chemically similar metals: the 15 lanthanides, plus scandium and yttrium [1]. Despite their name, most are relatively abundant in Earth's crust [2]. For instance, cerium, the most abundant rare earth element, is more common than copper. They are called 'rare' because they are rarely found in concentrated deposits. Instead, they occur in small amounts around the world, mixed with other minerals, and must be chemically separated before they can be of any technological use.

From the powerful magnets in wind turbines and electric car motors to the glowing red phosphors in LED screens, rare earth elements can be combined with other materials to create compounds with magnetic, light-emitting, and catalytic properties (which help chemical reactions happen faster) that are extremely hard to reproduce [3]. Because of these unique properties, REEs have become critical components in high-performance materials used across a wide range of industries, enabling improvements in efficiency, durability, and the miniaturization of electronic components.

Most rare earth elements possess electronic properties that make them excellent candidates for strong, permanent magnets. For instance, neodymium (Nd), dysprosium (Dy), and praseodymium (Pr) are commonly used to create high-performance magnets [4,5,6], which are essential in wind turbines, electric vehicle motors, computer hard drives, and even in the tiny speakers of your earbuds [7]. Among them, neodymium is perhaps the best known due to its role in the strongest commercial magnets available today. While pure neodymium is only magnetic at very low temperatures it becomes technologically useful when combined with iron and boron to form the compound Nd2Fe14B. This material exhibits the highest known magnetic energy density, with neodymium magnets storing up to 18 times more magnetic energy than iron magnets of the same volume [8].

This remarkable performance illustrates a key point: it is not rare earth elements alone that give rise to desirable properties, but rather their combination in small, tailored amounts with other elements. When engineered into compounds like Nd2Fe14B, rare earths unlock entirely new functionalities making them indispensable to modern technology. The applications of these “super magnets” are broad, spanning industries from automotive, where they enable smaller and lighter motors, to clean energy, where wind turbines use them to generate a magnetic field without an external power source. Although rare earth materials make up only a small fraction of a device’s weight or volume, they are often essential to its function. For instance, rare earth-based magnets may constitute only a minor fraction of a laptop’s total mass, but they are critical for components such as the spindle of a disk drive, which is necessary for data storage. Without them, many core components of modern electronics would be significantly bulkier, less efficient, or simply not work at all.

Beyond magnetism, other rare earth elements play crucial roles in optical components and in catalytic applications, where they help chemical reactions occur faster or more efficiently.

Europium (Eu), terbium (Tb), and yttrium (Y) are used in phosphors that produce the vivid colors seen in LED displays and energy-efficient lighting [9]. Cerium (Ce) is essential in catalytic converters for reducing vehicle emissions and in high-efficiency glass polishing [10, 11]. The list could go on, making it clear how these elements are ubiquitous in today's technology: from the screens we look at, to the cars we drive, to the tools we use to make science.

Despite their critical role, rare earth elements are associated with several challenges, not least of which are environmental, geopolitical, and ethical concerns. In some countries, weak environmental regulations in mining practices have led to deforestation, pollution, and human rights abuses; mining and refining rare earths can produce radioactive waste and cause soil and water contamination if not properly managed. For example, in China's Jiangxi province, extraction has caused

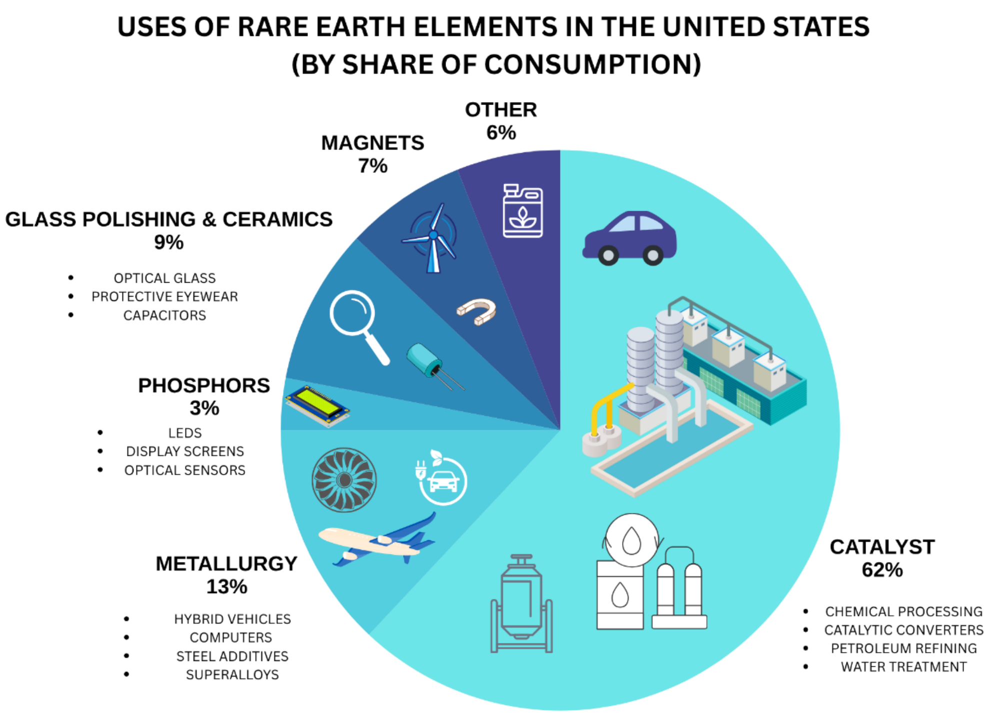


*Figure 1: Distribution of rare earth element (REE) use in the United States by application, including catalysts, metallurgy, magnets, glass and ceramics, phosphors. Percentages are based on the 2022 U.S. Geological Survey data [22].*

severe deforestation, with satellite images revealing vegetation loss over tens of square kilometers, and in some cases the release of thorium-containing waste into local waterways [12]. Chinese officials have reported excessive levels of ammonia and nitrogen compounds in groundwater near mining sites, while other pollutants such as cadmium and lead accumulate in soils [13], with long-term exposure to these metals being linked to kidney and neurological damage [14].

In Myanmar, unregulated rare earth mining in Kachin State, often under militia control, has been associated with human rights abuses, including forced labor and displacement of local communities [15].

The global supply chain is also heavily concentrated: China accounts for over 70% of global annual rare earth mine production, estimated at 210,000 tonnes in 2022 [16], raising concerns about supply security, trade dependence, and potential market manipulation. This dominance has geopolitical implications, and these risks are not just abstract economic terms, but can directly affect the cost and availability of everyday products. In 2010, a dispute between Japan and China, triggered by a naval collision between a Chinese fishing boat and the Japanese coast guard, led China to halt rare earth exports to Japan [17]. The move sent the Japanese tech and automotive industries into panic, with the price of some elements surging more than tenfold in a matter of months. Trade dependence means that if one country dominates supply, others have little leverage to secure fair prices or stable deliveries. More recently, in the summer of 2023, China announced new controls on exports of germanium and gallium, two metals critical for semiconductor manufacturing [18]. This was widely seen as the latest act in an intensifying global contest over access to materials needed for high-tech microchips, showing us clearly how resource supply can quickly become a geopolitical weapon.

As technology advances, rare earth elements will continue to play a critical role, especially in sustainable energy and high-tech devices. However, concerns about the availability and sustainable recovery of these materials have grown, leading to their classification by the European Commission as critical raw materials for the European Union due to their supply risk [19]. These concerns call for innovative solutions that reduce dependence on primary mining, such as improved recycling techniques and the development of alternative materials. Another promising area is improving environmentally friendly separation techniques of rare-earth metals, such as chemical leaching [20] and advanced solvent extraction [21], which could make their processing less harmful.

Rare earth elements might not be the first materials we think of when considering what our economies rely on, but they are central to many of the most critical technological transformations of our time. When studying these materials with an eye toward their industrial applications, understanding the science and policy behind rare earth elements must be seen as more than an academic exercise. It is a critical consideration, because ensuring a resilient, responsible, and equitable supply of these elements will be essential to advancing a more sustainable future.

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