The History and Future of Rare Earth Elements

What Are the Rare Earth Elements, and Where Do They Come From?

The rare earths are 17 metallic elements, located in the middle of the periodic table (atomic numbers 21, 39, and 57–71). These metals have unusual fluorescent, conductive, and magnetic properties—which make them very useful when alloyed, or mixed, in small quantities with more common metals such as iron.

Geologically speaking, the rare earth elements are not especially rare. Deposits of these metals are found in many places around the globe, with some elements in about the same abundance in the earth’s crust as copper or tin. But rare earths are never found in very high concentrations and are usually found mixed together with one another or with radioactive elements, such as uranium and thorium.

The chemical properties of the rare earth elements make them difficult to separate from surrounding materials and from one another. These qualities also make them difficult to purify. Current production methods require a lot of ore and generate a great deal of harmful waste to extract just small amounts of rare earth metals. Waste from the processing methods include radioactive water, toxic fluorine, and acids.

Video: What are some common misconceptions about rare earth elements? (see transcript below)

Our increased understanding of the unique properties of rare earth elements has generated their expanded use in contemporary society. Rare earths are components in many familiar technologies, including smartphones, LED lights, and hybrid cars. A few rare earth elements are used in oil refining and nuclear power; others are important for wind turbines and electric vehicles; and more specialized uses occur in medicine and manufacturing. The rare earths have become crucial to modern life, but our dependence on them is mostly invisible to American consumers.

The Discovery and Commercialization of the Rare Earth Elements
The term rare earth was coined when an unusual black rock was unearthed by a miner in Ytterby, Sweden, in 1788. The ore was called “rare” because it had never been seen before and “earth” because that was the 18th-century geological term for rocks that could be dissolved in acid. In 1794 the chemist Johan Gadolin named this previously unknown “earth” yttria, after the town where it was discovered. Over time the mines around Ytterby extracted rocks that yielded four elements named for the town (yttrium, ytterbium, terbium, and erbium).

Identifying new elements was a prestigious but contentious activity for European chemists during the 19th century. Jöns Jacob Berzelius isolated and named cerium in 1803 and thorium in 1828. In 1839 the Swedish chemist Carl Gustaf Mosander began to systematically analyze the mixed rare earths, discovering and naming lanthanum, erbium, and terbium. In the second half of the 19th century, chemists Gustav Kirchhoff and Robert Bunsen developed spectroscopy as a technique for identifying elements by examining light spectra. The great challenge in rare earth chemistry—both then and now—was finding ways to separate them.

Carl Auer von Welsbach was a student of Robert Bunsen—the inventor of the Bunsen burner—at the University of Heidelberg in Germany in 1880. While there, Welsbach began to work with the rare earth elements. As a skilled laboratory chemist he showed that didymium, then thought to be an element, was in fact an alloy of two rare earth elements, which he named neodymium and praseodymium. As Welsbach turned his attention to industrial concerns, he became the first person to develop a commercial use for the rare earth elements.

He recognized that the incandescent properties of the rare earth elements might be useful. (“Incandescence” describes the glow of visible light given off when a material is heated.) Welsbach developed a gas mantle (lamp) using an incandescent material that produced a bright light and could be mass-produced. By 1935, more than five billion mantles had been produced, but this invention posed problems: the lamps were hard to light, and the piles of rare earth waste left over after production were prone to catching fire. Welsbach found a way to alloy, or mix, these rare earth wastes with iron, creating a “flint stone” that sparked when struck, which he named ferrocerium. This material was widely used in cigarette lighters, as well as ignition devices in automobiles. The ore to supply these rare earth elements came largely from Brazil, India, and North Carolina, thus creating the first international trade in rare earth elements. 
The rare earth elements took on a new scientific and then geopolitical importance with advances in atomic physics during the 20th century.

The challenge of separating the rare earth elements from ore and from one another made it unclear just how many rare earth elements there might be. In 1913, the British physicist Henry Moseley determined there were 15 elements in the lanthanide series (atomic numbers 57 through 71) using X-ray spectroscopy.

**Rare Earth Elements Periodic Table**

The rare earth elements are sometimes also referred to as the lanthanides—referring specifically to the series of 15 elements running from lanthanum (La) to lutetium (Lu).

Illustration by Claud Li

Rare earths acquired a new status in 1939, after Otto Hahn, Lise Meitner, and Fritz Strassmann discovered nuclear fission of uranium—an insight leading to the atomic bomb—and identified rare earth elements in fission products. In the United States the plan to build an atomic bomb, code-named the Manhattan Project, drew on the expertise of the leading American rare earth chemist, Frank Spedding, to solve a key problem. The rare earth elements were impurities that prevented a nuclear chain reaction by absorbing neutrons. The rare earths needed to be separated and removed in the process of purifying uranium. Out of Spedding’s wartime work was born the Ames Laboratory at
Iowa State University, now the U.S. government’s premier rare earth elements research facility.

Learning to Use the Rare Earth Elements

The quest to find sources of uranium in the United States led to the development of the Mountain Pass Mine in California’s Mojave Desert near the Nevada border. While the mine’s uranium and thorium deposits did not prove useful, its deposits of the rare earth elements did. In the early 1950s the mine and separations plant extracted europium, which was used to produce red phosphors for the newly developed color television technology. Later production expanded to include cerium, lanthanum, neodymium, and praseodymium. This mine, owned by the Molybdenum Corporation of America, or Molycorp, dominated world rare earth production and exports from about 1960 until 2000.

The arms race between the United States and the Soviet Union during the Cold War (1945 to 1991) led to huge increases in government-funded research and development in many areas, including the rare earth elements. U.S. Air Force researchers developed samarium-cobalt magnets in the 1960s. This material retained its powerful magnetic properties even when very hot, thus making possible more powerful radar instruments. Soviet metallurgists used scandium to make aluminum stronger and lighter in the 1980s, which increased the performance of MiG-29 fighter planes. Laser research led to the development of yttrium-aluminum-garnet lasers used for laser rangefinders or target designators for guided weapons.

Corporate and industrial research generated new products for consumers that used the rare earth elements. Battery research in the 1970s and 1980s led to the development of the nickel–metal hydride battery, which used lanthanum and neodymium. These batteries could be recharged repeatedly while holding a lot of energy relative to their volume (size). They became popular for use in portable electronics, such as video cameras in the 1990s, and were widely used in hybrid cars, such as the Toyota Prius, released in 2001. Researchers at General Motors patented neodymium-iron-boron magnets in the 1980s and created a company, Magnequench, that produced the lightweight, powerful, permanent magnets used in power windows and door locks, windshield wiper motors, and electric engine starters. Magnequench soon found a valuable market in selling tiny magnets for computer hard drives, as personal computers became widespread in American homes and offices during the 1990s.

Use of rare earth elements in electronics expanded through the 1990s and the 2000s. In the early 1990s Bell Labs developed the erbium-doped fiber amplifier to boost the signal in fiber-optic cables. These small devices made possible a global network of long fiber-optic cables that reduced the price of long-distance telephone calls and now carry internet data around the world. The release of the first iPhone in 2008 showed how far
advances in rare earth metallurgy and applications had developed. Smartphones use lanthanum to reduce distortion in their tiny glass camera lenses, neodymium magnets to improve sound from tiny speakers, and yttrium and erbium phosphors to make bright colors in an energy-efficient screen.

**Changes in Global Trade**

At the same time that new applications of the rare earth elements were being developed, changes in the global economy caused shifts in the locations of rare earth production and high-tech manufacturing. The United States was the world’s leading exporter of manufactured goods throughout much of the 20th century. In the decades after World War II, U.S. government officials promoted international trade agreements to open foreign markets for U.S. manufacturers.

As governments around the world reduced restrictions on trade and as global shipping and communications costs decreased, manufacturing companies began to set up factories wherever goods could be produced most cheaply. Beginning in the 1980s and accelerating through the 1990s, many American firms relocated their manufacturing to countries that paid much lower wages and had fewer health and safety protections for workers and less stringent environmental regulations. These actions reduced the price of goods for American consumers but led to the closing of factories and loss of jobs in the United States.

Outside of the United States other governments sought to increase trade and manufacturing to advance their nations. In Asia the governments of Japan and the so-called Asian Tigers (Hong Kong, Singapore, Taiwan, and South Korea), which had few natural mineral or energy resources, promoted import of raw materials from around the world in order to manufacture products for global export. In Europe leaders worked to integrate national economies, harmonizing employment and environmental regulations and encouraging easy migration for citizens among the European countries. This was reflected most significantly in the establishment of the European Union in 1993.

**China Develops Its Rare Earth Elements Industry**

By the late 1970s the Communist government of China began to develop its manufacturing and global trade capabilities as a way to secure political stability, establish domestic prosperity, and overcome the catastrophic events of 20th-century history. In 1976 Deng Xiaoping became the leader of the Chinese Communist Party. He sought to restore the nation’s prosperity through carefully controlled market and economic reforms without reducing the Communist Party’s political control. The development of China’s rare earth elements industry is closely connected to China’s
reentry into global trade after 1978 and its government’s successful efforts to make the country a global manufacturing power.

A very brief history of 20th-century China:

Through the 19th and early 20th centuries, the weakening Qing dynasty left China increasingly vulnerable to exploitation by European colonial powers. A revolt in 1911 led to two decades of warlord rule and instability, until China was largely reunified under the rule of the Kuomintang party in 1928. The Communist Party of China resisted the Kuomintang until Japan invaded China in 1937. Between 15 million and 20 million people died in China during World War II, with more killed when the civil war resumed after 1945. The Communist Party triumphed in 1949, under the leadership of Mao Zedong. Mao sought to transform China and secure his own political position through two totalitarian movements. The Great Leap Forward, from 1958 to 1962, sought to collectivize agriculture and build heavy industry in China. But the social and agricultural displacement it created led to devastating famine that killed tens of millions of people. Mao’s power diminished after the failure of the Great Leap Forward but was restored in 1966 through the Cultural Revolution, a deep purge of political rivals and alternate sources of authority in Chinese society. Academics, scientists, and engineers were sent to rural reeducation camps to labor with peasants. This history created a deep concern for order and security in Chinese society, which was amplified by government propaganda and education.

Between 1978 and 1995 China’s annual production of rare earth elements increased by an average of 40% per year. During the 1990s its exports of rare earth elements also increased rapidly, causing prices for these metals around the world to decline sharply. As prices dropped, competing producers either went out of business or steeply reduced their production, unable to meet the so-called China price.

Beginning in the 1990s companies owned by the Chinese government sought to buy controlling shares in rare earth companies located in other countries. In 1995 two Chinese firms joined with American investors to buy Magnequench. This kind of foreign investment needed to be approved by American government regulators: they allowed the purchase but required the company to keep its operations in the United States for at least five years. Five years and one day later the factory was moved to China.
More recently, Chinese companies proposed buying controlling interests in rare earth mines in both the United States (Molycorp’s Mountain Pass Mine in 2005) and Australia (Lynas Corporation’s Mount Weld Mine in 2009). These proposals were rejected by the foreign investment regulators in both nations.

The 2010 Rare Earths Crisis

In the fall of 2010 it looked as though China might exert geopolitical leverage by restricting the export of rare earths. An international incident between China and Japan in disputed waters touched off a trade embargo with unforeseen consequences. A Chinese fisherman was detained by the Japanese Coast Guard. News of his arrest led Chinese customs agents to hold up a number of shipments destined for Japan. Little did they know that in those shipments were rare earth oxides crucial for Japanese high-tech manufacturing. Before long, the price of rare earth metals spiked—going up several hundred percent in some cases.

Suddenly many people and companies realized that the rare earths had become pervasive and essential. Governments began to worry about the materials their nations needed for weapons and other important technologies. The high prices of rare earths—and the fear of not having them—made bold solutions seem reasonable. Some people demanded opening up the Amazon rainforest to mining or exploiting resources in Greenland. Other entrepreneurs proposed extracting rare earths from the sea floor or raking them off the Moon. After investing $500 million on new pollution controls for its processing operations, Molycorp reopened the Mountain Pass Mine in California in 2012.

But the boom produced by high prices proved short lived. In 2012 a World Trade Organization grievance brought by the United States, Japan, and the European Union resulted in a loosening of Chinese export quotas, opening the flood gates and lowering prices to near 2009 levels. By 2015 it was once again difficult for anybody but the Chinese producers to make money producing rare earths. The bold plans for obtaining rare earths from around the world were mostly abandoned. Molycorp went bankrupt, and the firm that bought the Mountain Pass Mine now sends its semi-processed ore to China for final processing.

Video: What are the real-world consequences of mining and producing rare earth elements? (see transcript below)

The Future of Rare Earth Elements

Rare earth elements are likely to remain an important part of our future—from quantum computing and material sciences, to medical applications and advances in green technology. They are essential in efforts to reduce greenhouse-gas emissions enough to avoid the most devastating consequences of climate collapse. The growth of wind farms
will continue to drive demand for **neodymium** and **dysprosium** used in wind turbine motors. Ongoing moves away from internal combustion cars to electric vehicles will also increase demand for rare earth magnets and batteries.

To meet future demand, mining companies have proposed opening new mines and building new processing plants in many parts of the world. Some plans sound like science fiction, such as deep-sea mining or extracting rare earths from the acidic wastewater draining from abandoned mines. But these production techniques might become economically viable if a large increase in demand drives up prices or if governments decide to subsidize the costs of production.

Another idea is to better design our technologies so we can reduce or more easily reuse the rare earth metals inside of them. In the wake of the 2010 crisis, car makers redesigned vehicles to use smaller amounts of rare earth metals. Consumer electronics could be designed to be more easily repaired and upgraded rather than simply discarded. Research into new methods to recover rare earths from electronic waste, for instance, could reduce the amount of metals that need to be produced by mining and refining. Governments, activist groups, and companies could also collaborate to collect wastes containing the rare earths to enable more economically viable recycling programs.

One looming question focuses on what decisions the Chinese government and Chinese producers will make. Planning documents show the Chinese government is interested in reducing the local pollution and harms caused by manufacturing rare earth elements. China may use its investments across the rare earth industry to move the dirtiest parts of production to locations outside of China but still under Chinese financial control, thus relocating the pollution to poorer countries.

Sustainable and socially fair production of the rare earth metals ultimately depends on the willingness of consumers and manufacturers to pay more for materials that are produced ethically. In addition mechanisms both inside and outside of governments must ensure that sustainable production methods are actually implemented.

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**Video Transcripts**

**What are some common misconceptions about rare earth elements?**

**Rare earth elements aren’t so rare.**

*Julie Klinger* (Associate Director, Land Use and Livelihoods Initiative, Global Development Policy Center):
The first misconception about rare earths is it’s actually in the name, and I don’t blame people for being confused. Rare earths are not rare. They’re in fact quite common. The ones that we use the most are as common as copper or lead, and in fact you can find them on every continent, and on the ocean floor, and they’re also in our technologies around us. That’s the first misconception. I would say the second one in these times is that China currently produces most rare earth elements, but that’s not because China has most rare earth elements. There are over 800 potentially minable deposits around the world, and they’re scattered evenly throughout the earth’s crust more or less. But a lot of people tend to think that China supplies most of the rare earth elements because they have the most. And that’s another big misconception.

**Rare earth elements aren’t radioactive.**

*Eric Schelter (Director, Center for the Sustainable Separations of Metals):*

I think the second one [question] that people often ask me is are rare earths radioactive because there just isn’t very much that’s commonly known about these weird elements at the bottom of the periodic table. And so the answer is no. By and large, rare earths are not radioactive. There’s one example, promethium, which is, but it doesn’t occur in any significant abundance in the earth’s crust. And the majority of the others don’t possess any significant radioactivity. So they’re just as safe and benign as copper and nickel for that matter.

**Rare earth elements make clean tech possible—and less clean.**

*Gwen Bailey (Researcher, KU Leuven):*

Yeah, I think one of the—again, back to your question about what is the surprising thing to learn about your research—is that these clean tech materials aren’t so clean, and people don’t realize that. Almost everyone who thinks that they drive an electric vehicle thinks it’s always more sustainable than a combustion engine vehicle. And research has shown that that’s not always 100% of the case. It is sometimes the case but not always the case.

Credits: The Rare Earth Elements Project is made possible by a generous grant from Roy Eddleman, founder of Spectrum LifeSciences. Illustrations and animations: Claud Li  
Music: "Leafeaters" by Podington Bear  
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What are the real-world consequences of mining and producing rare earth elements?

Julie Klinger (Associate Director, Land Use and Livelihoods Initiative, Global Development Policy Center):

One of the things that was most impactful to me when I was doing field work in Inner Mongolia—so this is a place that’s been mining and refining rare earth elements for 40-odd years. You know, effectively the city was built around the rare earth mining and processing industry.

One of the things that happened after my first couple of visits there—and I wouldn’t just go for a couple of days, I would go for at least a couple of weeks, sometimes six, eight, or ten—is that I noticed that I was developing these sores on my skin and I didn’t really know what they were. And so I asked a local friend, and they said, “Oh, that’s just from the water. We all get those.” I said, “Well, what do you mean? Is it the water that I take a shower in, or is it the water that I drink, or what is it?” And they said, “Well, it’s both actually,” and then they kind of gave me a funny look, and they said, “Haven’t you noticed that a lot of people here have, they look like maybe cuts or scrapes or lesions on their face or on their skin?” And there’s a lot of people that in more severe cases actually have bone deformities and things like that. And I asked what it was from, and they said, “Oh, it’s from the mining. It’s from the chemicals that come up, that are used in mining, but also the pollutants that are brought up with the rare earth elements and not properly controlled.” And so I looked a little bit more into this, and it turns out there’s a lot of research that’s been done in China to understand the scope of the problem. And it turns out that the pollution from the mining industry has led to a cancer mortality rate of one in seven adults in some villages, cancers that are directly related to lifelong exposure to pollution from the mining industry. Also this pollution really affects children, and there’s been robust studies that have also shown that the cognitive development of about 40% of the children in the region—and this is a region that has a population of about 6 million people—has been impacted from exposure to certain chemical pollutants. And after a while I realized that I could tell who was a local and who was visiting or who was there for a shorter term just by looking at their skin, their teeth, and things like that. And for me to learn this and then to use my laptop, to use my cell phone, it was very eye-opening for me. And that helped me realize that we can do things in a much better way. We don’t have to create immense human suffering in order to have our laptops and our iPhones. We can do better.

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Illustrations and animations: Claud Li
Music: "The Hump" by Podington Bear
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An industrial plant in Baotou, Inner Mongolia. (ebenart)
Farmers affected by a dumping ground for rare earth elements waste, which poisoned the water supply and land around Baotou city in Inner Mongolia. (Frederic J. Brown/AFP via Getty Images)