For instructors:

This document contains brief descriptions of the REE technologies mentioned in the PowerPoint and student activity sheet, suggestions for group discussion topics, and other resources.

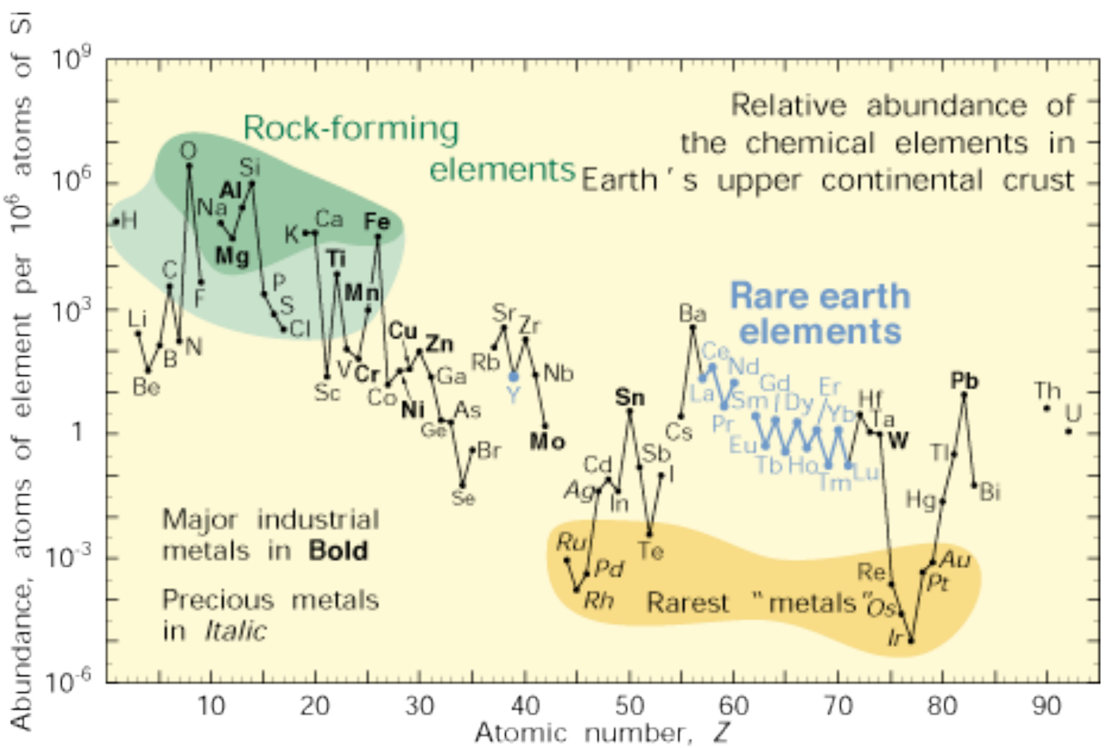
For a historical perspective of rare earth elements, accounts of their discovery, naming, and uses:

1787 –1987 Two Hundred years of Rare Earth, edited by K. A. Gschneidner Jr. and J. Capellen, Rare-earth Information Center, Institute of Physical Research and Technology, Iowa State University https://www.ameslab.gov/files/TwoHundredYearsRE.pdf.

A brief discussion regarding China's monopoly of REEs (This might be useful for questions 4, 5, and 6):

Extraction of any economic reserve materials depend on four factors: (a) abundance of the material in the crust, (b) tendency of the material to form economic reserves, (c) ease of mining or ability to mine at a profit, and (d) ease of processing to extract the desired material from the ore.

Abundance of REEs in the crust: Despite being called "rare" earth elements, these elements are actually more abundant in earth's crust than gold and silver, as shown in the graph below from USGS fact sheet 087-02. Therefore, China's monopoly on REEs is not due to the scarcity of REEs elsewhere in the world.



USGS Fact Sheet 087-02 http://pubs.usgs.gov/fs/2002/fs087-02/

Economic reserves of REEs: The current USGS estimate for worldwide REE reserves indicates that more than enough REE reserves exist globally to meet current and expected future demand. According to the

USGS, about 12% of global REE reserves exist in the United States in 2013. Clearly, more than enough REE deposits exist outside China to adequately meet global demand.

Ease of mining or ability to mine REEs at a profit: This depends on the "ore grade," or the concentration of the valuable material in the ore. A higher grade ore generates higher profit. The average REE ore grade for Mountain Pass deposit in California is 9.2% (see Table 2-4 in "Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues" (December 2012), http://nepis.epa.gov/Adobe/PDF/P100EUBC.pdf. Considering the fact that copper, a relatively cheap ore, can be profitably mined at a grade of 0.5% even when the cost of processing technologies vary, there is no question that REEs can be mined at a considerable profit without having to depend on China as the sole supplier.

However, common REE ores like monazite contain radioactive elements like thorium. Safely disposing of thorium-rich mine waste is a *huge* challenge for REE mining in the United States.

Ease of processing: This is the biggest hurdle in the path of REE production. The fifteen rare earth elements that naturally occur together in the ore have very similar chemical properties. Separating them out from each other is therefore technologically challenging, cost and energy intensive, and time consuming. Different REE ores, such as monazite and bastnäsite, require different processing methods. The lack of a single standardized processing method adds to the cost of processing and remains a technical challenge. Safely extracting and removing radioactive byproducts also adds to the overall challenge. As of right now, most commercially viable REE processing plants are located in China. Until other countries are economically able to separate the different REEs from the ore, China will remain the sole supplier of REEs in the global market.

In recent years China has reduced the REE export quota, claiming that they should meet the demands of Chinese industries before supplying global demand. As of 2010, China consumes almost 70% of their own REE production. China also claims to have tightened their mining regulations to minimize the environmental impacts of REE mining, resulting in lower REE production. The reduction of REE supply in the face of increased demand has driven up REE prices worldwide.

More information about the economics of REEs (useful for questions 4–6):

"China's Continuing Monopoly Over Rare Earth Minerals," by Jeff Nesbit. *U.S. News & World Report.* April 2, 2013: http://www.usnews.com/news/blogs/at-the-edge/2013/04/02/chinas-continuing-monopoly-over-rare-earth-minerals.

"Are We Losing the Race for Rare Earths?" by Eric Hannis. *U.S. News & World Report.* November 20, 2012: http://www.usnews.com/opinion/blogs/world-report/2012/11/20/the-us-needs-rare-earth-independence-from-china.

"The Statistics of the Rare Earths Industry," by Mark Tyrer and John P. Sykes. *Significance Magazine* 10, no. 2 (April 25, 2013).

http://www.significancemagazine.org/details/magazine/4705901/The-statistics-of-the-rare-earths-industry.html.

"China's Rare-Earth Industry," by Pui-Kwan Tse. USGS Open File Report 2011-1042: http://pubs.er.usgs.gov/publication/ofr20111042.

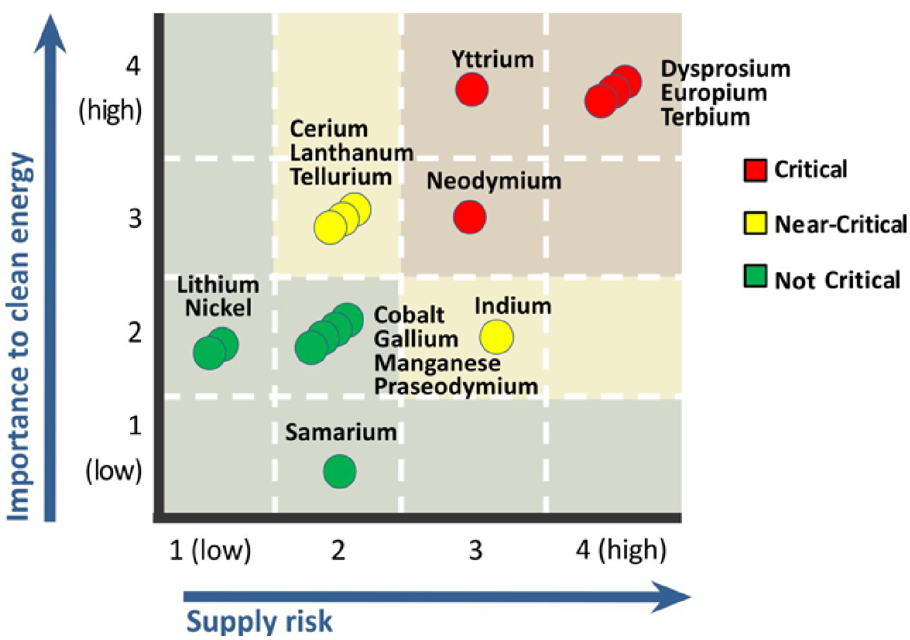
"Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues" (December 2012), http://nepis.epa.gov/Adobe/PDF/P100EUBC.pdf.

For up-to-date REE statistics and information:

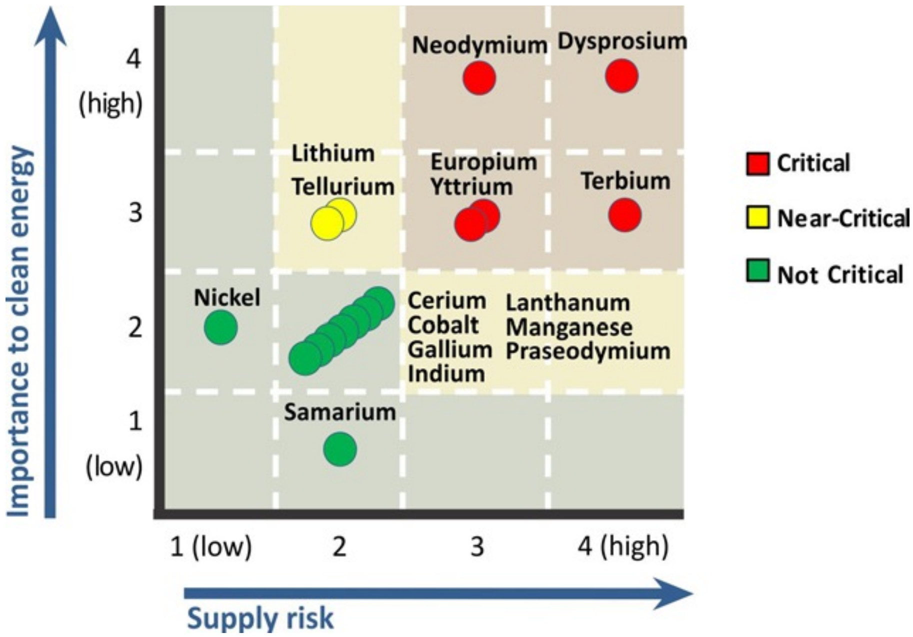
http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/

More about uses of REEs in clean energy technology (especially if question 6 is expanded to a group discussion format):

REEs as "Critical Elements": The Department of Energy (DOE) assesses the criticality of REE by plotting the importance of specific rare earth elements against the possibility that their continued supply might be disrupted. The graphs below show the short-term and medium-term criticality of rare earth elements. Dysprosium, terbium, europium, neodymium, and yttrium are used in magnets for wind turbines and electric vehicles or as phosphors in energy-efficient lighting. These elements are at risk of being in short supply to meet the demand between now and 2015 (short term) and are considered "Critical Elements." These elements are expected to remain critical between 2015 and 2025 as well (medium term).



Short Term (Present–2015) Criticality Matrix.



Medium Term (2015–2025) Criticality Matrix

Figures from US Department of Energy Critical Materials Strategy, 2011: http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf (accessed 8/5/14)

The importance of specific rare earth elements and their "critical" status changes with time and market dynamics. For example, lanthanum is used in petroleum refineries and is considered "near critical" in the short term. But the supply of lanthanum is relatively more certain than other REEs, and the refineries can control the amount of lanthanum needed to some extent. Therefore lanthanum is expected to be taken off the "Critical Elements" list during 2015–2025.

More information about REE as critical elements can be found at:

US Department of Energy Critical Materials Strategy:
http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

Fuel cells: Fuel cells generate electricity from the energy released when hydrogen and oxygen are combined to form water. Although some types of fuel cells can use conventional fossil fuels like natural gas or jet fuel as a source of hydrogen, hydrogen gas can also directly be used in fuel cells to combine with oxygen from the air. REEs are used as catalysts and other essential components in some varieties of fuel cells (e.g., solid oxide fuel cells).

More information about fuel cell technology (general information as well as to how REEs are used in fuel cells) can be found at:

“The Use of Rare Earth-Based Materials in Low-Temperature Fuel Cells,” by Antolini and Perez, *International Journal of Hydrogen Energy* 36, no. 24 (December 2011): 15752–65. http://www.sciencedirect.com/science/article/pii/S0360319911020295.

Fuel Cell Basics: http://americanhistory.si.edu/fuelcells/basics.htm.

How Fuel Cells Work: http://www.fueleconomy.gov/feg/fcv_pem.shtml.

“Solid Oxide Fuel Cells and Critical Materials: A Review of Implications,” by J. Thijssen, LLC (May 10, 2011), http://www.netl.doe.gov/File%20Library/research/coal/energy%20systems/fuel%20cells/Rare-Earth-Update-for-RFI-110523final.pdf.

Catalyst: By definition, catalyst is a substance that helps to speed up a chemical reaction without being consumed in the reaction. Catalysts containing cerium and/or lanthanum can store and release oxygen and therefore can efficiently reduce carbon monoxide and nitrogen oxide (NO_x) pollution from cars.

Lanthanum and cerium are also used in petroleum refineries as catalysts for breaking down heavier hydrocarbon molecules in crude petroleum to create lighter gasoline molecules (known as fluid cracking). This process increases gasoline yields and can also reduce sulfur dioxide pollution.

More information about how REEs are used as catalysts can be found at:

“Rare Earth Metals for Automotive Exhaust Catalysts,” by Hirohumi Shinjoh. *Journal of Alloys and Compounds* 408–412 (February 9, 2006): 1061–64, http://www.sciencedirect.com/science/article/pii/S0925838805007127.

“Rare Earth Elements: End Use and Recyclability.” USGS Scientific Investigations Report 2011-5094, (see pages 2–6), http://pubs.usgs.gov/sir/2011/5094/pdf/sir2011-5094.pdf.

U.S. Department of Energy Critical Materials Strategy: http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf.

Magnetic refrigeration: Some rare earth elements, like gadolinium and its alloys, become hot when they are placed in a magnetic field and cold when the magnetic field is removed. The amount of temperature drop depends on the strength of the magnetic field. In magnetic refrigeration, a piece of gadolinium alloy is placed in a strong magnetic field and kept at room temperature by water or other coolants. It is then removed from the magnetic field, at which point the alloy becomes colder than room temperature. This cold alloy is used to cool a second stream of water, which is then used for refrigeration.

Conventional refrigerators use a pump to compress a gas (which used to be chlorofluorocarbons, or CFCs, but is now mostly hydrochlorofluorocarbons, or HCFCs) and then let it become cooler by expanding. Magnetic refrigeration is more environmentally friendly due to the fact that it does not need to use refrigerants like CFCs or HCFCs, which may be harmful to the ozone layer and can also contribute to the greenhouse effect. Also, the magnetic refrigeration process is more energy efficient than conventional refrigeration because the energy needed for magnetic refrigeration is less than that needed to compress a gas.

More information about magnetic refrigeration technology can be found at:

Room-Temperature Magnetic Refrigeration: http://www.ameslab.gov/files/MagFridge_Foundation.pdf.

"The Research of Room Temperature Magnetic Refrigeration Technology," by Zhang Zheng, Guo Hui, Gu Guobiao. *Electrical Machines and Systems, 2005.* ICEMS 2005. Proceedings of the Eighth International Conference on Electrical Machines and Systems. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=1574872.

REE and magnets: What makes a strong magnet? A major use of REE is in creating magnets. Because of the unique electronic configuration of REEs as f-block elements, REE alloys can be made into powerful permanent magnets. The strength of permanent magnets is measured using the following indices (information from http://www.shinetsu-rare-earth-magnet.jp/e/index.html):

Maximum energy product (units of measurements kJ/m^3 or kilojoule per cubic meter, or MGOe or Mega-Gauss-Oersted): This is the maximum amount of magnetic energy that can be stored in a magnet. This index expresses the performance of a permanent magnet. A larger value indicates a stronger magnet.

Residual induction (unit of measurement Gauss, or G): It is the total quantity of magnetic force lines (AKA magnetic flux) per unit area remaining in a saturated magnetic material after the magnetizing field has been removed. This represents the maximum flux output from the given magnet material.

Coercive force (unit of measurement Oersteds, or Oe): This index expresses the difficulty in demagnetizing a permanent magnet by using an external magnetic field. The stronger and more stable a permanent magnet is, the more coercive force is needed to demagnetize it.

The following table compares the values of these indices for some common magnetic materials with the values corresponding to REE magnets shown in bold. The data is from "Standard Specifications for Permanent Magnet Materials," published by Magnetic Materials Producers Association and available at: http://www.smma.org/pdf/permanent-magnet-materials.pdf.

Magnet	Maximum Value Energy Product (MGO)	Residual induction (G)	Coercive Force (Oe)	Density (g/cm^3)
ALNICO (made of	1.4–9	6700–13500	480–2170	6.8–7.3

Al, Ni, Co)				
ceramic (made of Ba, Sr, Fe)	1.05–3.8	2300–4100	1860–3650	4.9
REE (Sm, Pr, Co)	**16–22**	**8300–9500**	**7500–9000**	**8.4**
REE (Sm, transition metal)	**24–30**	**10000–11600**	**6000–10600**	**8.4**
REE (Nd, Pr, Dy, transition metal)	**24–50**	**10000–14100**	**11000–41000**	**7.4**
FeCrCo (isotropic)	1–1.6	8800–10500	200–490	7.7
FeCrCo (anisotropic)	2–5.3	12000–14000	250–641	7.7

From this table it can be seen that permanent magnets containing REEs are much stronger than other types of magnets. Because of their relative strength, magnets containing REEs can be much smaller and more lightweight than other types. Smaller magnets are essential for computers and other electronic devices, various car parts, and a number of other everyday uses.

Smaller, stronger magnets are especially important for reducing the weights of motors in cars and therefore increasing fuel efficiency. Permanent magnets are used in wind turbines for generating electricity. Permanent magnets containing REEs can significantly reduce the size and weight of the generator of larger (>2.5 Mega Watt), more powerful wind turbines. Stronger permanent magnets are also essential in wind turbines with electric generators that run at speeds slower than traditional wind turbines. These turbines can generate electricity at wind speeds lower than traditional high-speed turbines and are therefore more efficient and less prone to mechanical breakdown.

Suggestions for guided discussion for question 6:

It would be helpful for the instructor to guide the student discussion of Question 6 to help students discover how sustainability depends on social, economic, and environmental factors. During this discussion, students can discover how clean energy technologies provide a pathway for reduced dependence on fossil fuels (environmental sustainability) but that those in turn are dependent on economic factors such as supply and demand (economic sustainability), as well as on consumerism and other social forces (social sustainability).

This discussion can be broadened to incorporate the use of REEs in the electronics industry, such as in laptops, cell phone batteries, etc., besides clean energy technologies. REE mining has severe environmental impacts as well, and guided discussion can help students address their personal consumer behavior regarding the impacts of consuming electronics products.

There has been an increased interest in developing new REE mines to break China's hold on the REE market. The location of any new REE mine will depend on the availability of REE reserves, as well as on the environmental impacts of the mining processes (impact of REE extraction processes on soil and water, disposal of thorium-bearing mine tailings, etc.). If time permits, a discussion of the impacts of REE mining (both in terms of the environment and the economy) can be used as a bridge between this unit and the next unit (mining and mining impacts) in this module.

*Environmental impacts of mining REEs***:**

> *"More mining of rare earth metals, however, will mean more environmental degradation and human health hazards. All rare earth metals contain radioactive elements such as uranium and thorium, which can contaminate air, water, soil, and groundwater. Metals such as arsenic, barium, copper, aluminum, lead, and beryllium may be released during mining into the air or water, and can be toxic to human health. Moreover, the refinement process for rare earth metals uses toxic acids and results in polluted wastewater that must be properly disposed of. The Chinese Society of Rare Earths estimated that the refinement of one ton of rare earth metals results in 75 cubic meters of acidic wastewater and one ton of radioactive residue. The 1998 leak of hundreds of thousands of gallons of radioactive wastewater into a nearby lake was a contributing factor to Molycorp's shutdown in 2002. Many new mines, including Molycorp, are now developing more environmentally friendly mining techniques."**

> *"Vast waste ponds scar the landscape on the banks of the Yellow River, 190 kilometers from the city of Baotou in China. Visible from space, the Bayan–Obo iron mine in Inner Mongolia is the world's largest source of rare earths, and the Chinese companies supplying them employ acid to dissolve them out of ore rock that often also contains radioactive elements like thorium, radium, or even uranium. Intensive boiling with strong acids—repeated thousands of times because the elements are so chemically similar—finally separates out the neodymium, dysprosium, or cerium."+*

Other things that can be done:

> *More mining*:
>
> > *"Because of rising prices, there is now renewed interest in seabed mining for rare earth metals. Since the 1960s, scientists have known about the existence of manganese nodules, rocks abundant in water 4,000 to 5,000 meters deep that contain nickel, copper, cobalt, manganese, and rare earth metals, but in the past, mining them never made economic sense. In 2011, a Japanese team found huge deposits of rare earth metals (http://www.reuters.com/article/2011/07/05/us-rareearth-japan-idUSTRE76300320110705) including terbium and dysprosium, in sea*

*mud 3,500 to 6,000 meters deep in the Pacific Ocean. One square kilometer (0.4 square mile) of deposits will be able to provide one-fifth of the current global annual consumption, according to Yasuhiro Kato, an associate professor of earth science at the University of Tokyo."**

Research & Development:

*"Some companies, including GE, Toyota, and Ford, are trying to use less rare earth metals in their products, limit waste, and/or develop substitute metals."**

Recycling:

*"Though recycling e-waste cannot satisfy the rapidly growing demand for rare earth metals, it is one way to help alleviate the shortage. Recycling and reusing materials also saves the energy used in mining and processing, conserves resources, and reduces pollution and greenhouse gas emissions. The U.S. Environmental Protection Agency reports that in 2009, 2.37 million tons of electronics were discarded, but only 25 percent was recycled."**

Mountain Pass Mine

"Molycorp wants to restart operations by 2012 using a new process, which will require Molycorp to essentially rebuild the entire operation at a cost of $500 million. The process employs a strong acid and a base to separate the rare earths—the so-called chlor–alkali solvent extraction method—but it still will not produce pure rare earths; rather it will yield oxides of cerium, lanthanum, praseodymium, and neodymium.

In essence, Mountain Pass will become a chemical plant, sucking up electricity and steam from an on-site natural gas–fired boiler. In addition, the wastewater of the process will be recycled back to produce the strong acid and base necessary to start the process all over again—hydrochloric acid and sodium hydroxide. 'Mining is a very small part of our operation,' Burba says, noting that mining the ore containing the rare earths is only 10 percent of his company's cost. 'The vast majority of what we do is advanced chemistry.'

Of course, there will still be by-products—such as the residual ore, or tailings, from the mining and separation as well as calcium carbonate, magnesium carbonate, and magnesium hydroxide from the chemical process, along with that pesky thorium. But the primary salt from the chlor–alkali process is sodium chloride (otherwise known as table salt), which will be recycled back into the process using some of the steam generated on site and used to make new acid and base using a chlor–alkali unit. 'It's a big saltwater loop,' Burba explains. 'Our water consumption is 10 percent or less of what had been done historically at this site.'"+

There is a fly–over tour at http://www.molycorp.com/resources/photo-tours/mountain-pass-fly-over/ that might be useful for segue into Unit 3. On this site it also says: "*The Mountain Pass deposit is in a 1.4 billion year old Precambrian carbonatite intruded into gneiss, and contains 8% to 12% rare earth oxides, mostly contained in the mineral bastnasite. Gangue minerals include* *calcite, barite, and dolomite. It is a world-class rare-earth mineral deposit.*" This can be mentioned to remind students that *minerals* (from Unit 1) are mined in order to retrieve these elements.

* From "Rare Earth Metals: Will We have Enough?" by Renee Cho, *State of the Planet: Blogs from the Earth Institute,* September 19, 2012. Available online at: http://blogs.ei.columbia.edu/2012/09/19/rare-earth-metals-will-we-have-enough/.

+ From "Rare Earths: Elemental Needs of the Clean-Energy Economy," by David Biello, *Scientific American,* October 13, 2010. Available online at http://www.scientificamerican.com/article.cfm?id=rare-earths-elemental-needs-of-the-clean-energy-economy&page=1.