RFF REPORT

The Supply Chain and Industrial Organization of Rare Earth Materials

Implications for the U.S. Wind Energy Sector

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FEBRUARY 2012

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THE SUPPLY CHAIN AND INDUSTRIAL ORGANIZATION OF RARE EARTH MATERIALS: IMPLICATIONS FOR THE U.S. WIND ENERGY SECTOR

Jhih-Shyang Shih, Joshua Linn, Timothy J. Brennan, Joel Darmstadter, Molly K. Macauley, and Louis Preonas [*]

1. Introduction and Plan of Study

Rare earth (RE) metals play an important role in many new and "green" technologies, such as electric vehicles, energy-efficient lighting, and wind turbines, all of which reduce pollution emissions compared to conventional technologies. Market forces and government policies are likely to cause a large increase in the use of these technologies in the United States and elsewhere over the next several decades. However, China's dominance in producing REs, widespread vertical and horizontal integration by Chinese firms, and China's export quotas have raised concerns about the availability of the metals; in fact, the cost of acquiring these metals from China has increased significantly over the past several years.

This report, prepared at the request of the U.S. Department of Energy, focuses particularly on the use of two rare earth elements (REEs), neodymium (Nd) and dysprosium (Dy), whose magnetic properties make them desirable metals for some types of wind turbines. At first glance, it would not appear that China's market power or export policies would significantly affect the U.S. wind industry or the overall electricity sector because, absent major changes in policy or market conditions, wind generation is not expected to account for much more than 3 percent of U.S. electricity generation, even by 2035 (Energy Information Administration [EIA] 2011a). Also, the use of wind turbines containing permanent magnets (PMs), which are dependent on REs, has not yet proceeded very far in the United States. However, many analysts expect use of the REs to increase over time, conceivably reinforced by policies that directly or indirectly serve to bring about an increase in the construction of new wind turbines in the United States and an associated demand for PMs. Three key dimensions of the issues outlined above make up the bulk of our report: a case study of the physical "supply chain;" an assessment of the implications of China's market power and vertical integration; and the organization of the U.S. wind industry.

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[*] Brennan and Darmstadter are senior fellows, Macauley is vice president for research, Linn and Shih are fellows, and Preonas is a senior research assistant, all at Resources for the Future. We thank Gabriel Sampson and Taylor Martin for their excellent research assistance. We also thank Diana Bauer, Jennifer Li, and their colleagues at the U.S. Department of Energy for their guidance and critique as we completed this study. Many academics and industry representatives also provided insights, and we are especially grateful to Karl A. Gschneider, Jr. (Ames Laboratory, Iowa State University), Ichiro Daigo (University of Tokyo), and Ian M. London (Avalon Rare Metals, Inc.). Discussions with Rod Eggert, of the Colorado School of Mines, provided helpful guidance at the outset of the project. Responsibility for errors and opinions rests with the authors.

The first chapter describes the physical supply chain of the U.S. wind industry, from the mining of REEs to turbine manufacturing. We describe the physical processes that occur at each stage and the uses of the intermediate physical products. We present available data about the quantities of production and vertical and horizontal integration at various stages of the supply chain. The second chapter discusses incentives for vertical integration and the potential harm from market power and vertical integration along the supply chain. The third chapter, largely focused on the United States, describes the organization of the U.S. wind industry in more detail, including substitution possibilities across wind turbine technologies, horizontal integration, and trends in employment and investment in new wind turbines in the United States.

Before presenting our key findings, it is important to note that several topics fall outside the scope of the study. First, although considerable concern has been raised about the environmental consequences of mining REs, gathering and analyzing the necessary data for addressing these concerns is outside the scope of this project. Second, we lack adequate information to discuss national security concerns pertaining to the use of REs in the defense sector. These concerns can be complex, with REs often serving applications in the civil, commercial, and defense sectors of the economy. Third, as will become clear from our exposition, very few data are available for quantitative analysis. In addition to the findings presented below, we conclude that an effort to collect reliable data on RE industries is needed. Fourth, it will be clear as well that the analysis and line of argument pursued in this report is oriented to the long-term prospects for a domestic U.S. wind industry. We rely on studies by EIA and other official estimates for our description of these prospects. And, finally, the global RE and wind turbine market involves a number of important countries which our scope did not allow us to treat in the desired depth.

1.1 Key Findings

1.1.1 The Nd and Dy Physical Supply Chain

- The reserves of REs are large. In the long run, global reserves and undiscovered resources are expected to be sufficient to meet demand. However, there may be short-run supply concerns because new mining projects typically take at least 10 years to begin production.
- Several gaps in the available data prevent a quantitative description of the supply chain for Nd and Dy used in wind turbines. Some of the largest gaps are the lack of (a) consistent RE mining and refining data, (b) international trade data for Nd and Dy, and (c) data describing the amount of Nd and Dy contained in various commodities.
- China's RE export quota decreased 40 percent over the years 2008–2011. China is likely to continue to impose export quotas.
- The Chinese government encourages large companies to consolidate their activities in the RE sector and its supply chain.
- Molycorp and Lynas, two vertically integrated RE production companies (the first, a U.S. company, the second, Australian), are rapidly expanding production capacity. Molycorp's Mountain Pass (California) mine is expected to have a production capacity of 19,050 tonnes/year by 2012 and 40,000 tonnes/year by 2013. Lynas Corporation's Mount Weld (Western Australia) mine is expected to have a production capacity of 22,000 tonnes/year by 2012. Molycorp has a joint venture with Japan's Daido Steel and Mitsubishi Corp. to

manufacture and sell RE magnets. Molycorp has also invested in Boulder Wind Power's turbine technology. Lynas and Siemens have a joint venture to produce magnets for wind turbines.

- Reported RE prices increased by a factor of 8–10 over the years 2008–2011. Although prices have decreased significantly since summer 2011, they are still high compared to three years ago. Future prices are very uncertain.
- Nd-iron-boron (NdFeB) PMs contain Nd and Dy. The magnets have the strongest magnetic energy density and are the most powerful commercial magnets existing today. It may prove difficult to find close substitutes for NdFeB PMs for direct-drive wind turbines in the near future.
- Several other technologies may be used in wind turbines, however, including (a) gearbox technology, (b) lower-grade magnets, and (c) hybrid permanent-magnet generators (PMGs). The substitution of low-grade magnets in direct-drive and hybrid turbines appears to be an ongoing research effort in the industry.
- Wind turbines installed in 2009 in the United States contain approximately 10–48 tonnes of Nd and 1–13 tonnes of Dy. The total RE content for turbines installed in 2010 was significantly lower.

1.1.2 Industrial Organization along the Nd and Dy Supply Chain

- China currently produces upwards of 95 percent of the world's supplies of REs, including Nd and Dy. Whether this implies substantial market power depends on whether the nominally separate major mining companies within China act collectively or independently. However, even if they act as independent competitors, China as a nation may be able to exercise market power through its ability to set the prices and quantities of RE exports.
- The effect on the U.S. economy of market power exercised by a foreign supplier differs from that exercised by a U.S. supplier. The effect on an economy of market power exercised by a U.S. supplier arises primarily because of the reduction in output necessary to bring about profitable increases in price. The profits from that exercise, however, stay within the country. Market power exercised by a non-U.S. supplier entails redistribution of wealth in the form of monopoly profit from the United States to that supplier's country. It also raises the possibility that a foreign country could use control over supplies to injure countries that import the good for reasons unrelated to merely maximizing profits. However, largely because the United States does not rely much on wind power generated by PMs using REs, U.S. consumers do not appear to be vulnerable to the exercise of market power along this supply chain.[1]
- Although vertical integration may reduce transparency, it generally improves operating efficiency and reduces costs, which is why vertical integration—and its close cousins, long term contracts—are so ubiquitous in modern economies. These strategies allow firms to (a) limit the costs of search, quality verification, and monitoring associated with using markets; (b) improve coordination and take advantage of opportunities to spread costs over multiple stages of a supply chain; (c) mitigate the risk of supply and price volatility; and (d) reduce vulnerability to exploitation by others in the supply chain for whom they have made specific

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[1] We did not investigate the potential vulnerability of U.S. buyers (final consumers or firms) to market power along other supply chains.

and irreversible investments. We see examples of many of these benefits in the RE supply chain.

- In special cases, discussed in more detail in chapter 3, vertical integration can increase market power, primarily though evasion of regulation, elimination of a potential entrant along the supply chain, or changing the strategic interaction in the market. None of these factors appears likely to be important in the RE supply chain.
- Our understanding is that two firms control patents for manufacturing PMs using REs, and only one of them controls patents over manufacturing processes that are central to the production of PMs used in wind turbines. If this is the case, then any market power this patent monopoly can exercise leaves less that China could exploit in the wind turbine supply chain through control it could exercise over the dominant share of RE production held by mining companies in China.
- Nevertheless, China's export quotas may have a longer-run effect. Our understanding is that, at present, China does not limit the exports of PMs or wind turbines produced in China. If Chinese producers can obtain REs in China under more favorable prices or with greater assurance of supply than magnet or turbine manufacturers outside of China, then the Chinese producers will then have a competitive advantage over those outside manufacturers. This creates an incentive to relocate those production facilities to China. This could benefit China over the longer term if it is able to combine the experience of these separate producers such that the country has an advantage in coming up with future innovations in manufacturing at these points in the supply chain.
- It is crucial to note that the possibilities that China has market power over REs now and is undertaking a strategy to build up an advantage over innovating in the future both depend on how mining and manufacturing firms are governed within China. If nominal separation implies independent decisionmaking, as one normally expects in the United States (absent illegal collusion), neither possibility is likely. However, corporate governance may not operate in China as in the United States. Further study of the extent to which Chinese firms operate independently or in a coordinated manner, particularly through state controls, would be important for gaining more authoritative knowledge regarding these possibilities.

1.1.3 Effects of the Nd and Dy Supply Chain and Industry Organization on the Wind Sector, Employment, and Welfare

- The relative advantage of direct-drive turbines with RE PMs over conventional geared technologies may be greatest in offshore wind applications. However, the cost of offshore wind, regardless of turbine technology, is significantly higher than the cost of onshore wind.
- During the years 2007–2010, about 5–10 GW of investment per year was made in new wind generator capacity in the United States. The U.S. market for new wind turbines is highly concentrated, with five firms accounting for about 80 percent of new installations (weighted by capacity) during this period, although the concentration has decreased somewhat over the last 10 years.
- About 5 percent of new turbines installed in the United States during the years 2008–2010 use direct-drive turbines that contain RE PMs. The available evidence suggests that other technologies (wind or otherwise) are close substitutes for these turbines.

- Although high-quality employment data are not publicly available, the available evidence suggests that the U.S. wind industry, including manufacturing of components and construction of new wind farms, has grown considerably in the 2000s. Total employment may have been around 25,000–30,000 in 2010.
- EIA's baseline forecast of cumulative new investment (almost entirely onshore) in wind generators is about 17 GW between the years 2010 and 2035. Despite scenarios exploring the potential for a markedly greater volume of new investment (whether dictated by domestic or export demand), the EIA projection implies a significant employment decrease in the U.S. wind industry compared to current levels.
- In the long run, a hypothetical increase in the cost of manufacturing a direct-drive, permanent-magnet turbine would have large negative employment and welfare effects only if aggressive policy or other market forces result in much larger investment in new wind capacity than expected under most forecasts; absent such a cost increase, direct-drive turbines using RE PMs become significantly less costly than alternative generation technologies. In addition to these requirements, two other conditions must hold for employment to be affected: (a) the direct-drive turbines would otherwise be manufactured in the United States and (b) the cost increase would cause manufacturing of other components of wind turbines to move offshore.

2. The Nd and Dy Supply Chain

2.1 Overview

In this chapter, we describe the supply chain of Nd- and Dy-containing PMs used in wind turbines. We provide a comprehensive supply chain framework based on the principles of material flow analysis (MFA), which includes flows and stocks of materials or substances in a well-defined system. We first describe the physical processes involved in producing a wind turbine that contains PMs made with Nd and Dy. Subsequently, we qualitatively describe the flows of materials through the supply chain. We provide information we are able to collect within the limited scope of our project timing and budget. The largest data gaps center on import, export, and stockpiles and an overall problem caused by inconsistent reporting of data definitions and measures across the industry.

The supply chain framework includes seven stages, schematically depicted in Figure 1: (a) mining and producing RE[2] ore, (b) separating and producing Nd and Dy oxides, (c) producing Nd and Dy metals, (d) producing alloys and magnet powders, (e) manufacturing NdFeB PMs that contain Nd and Dy, (f) manufacturing PMGs (i.e., permanent magnet generators), and (g) manufacturing wind turbines, along with numerous other products. For every stage (except RE ore), the framework includes import, export and stockpiling of the RE-containing intermediate products. For every stage, the framework includes the uses for the product other than PMGs, such as hard drives and hybrid vehicle motors, which also use NdFeB magnets. The framework also includes substitution across technologies at the PMG stage and the turbine stage. In particular, the framework includes substitution of NdFeB PMs to lower-grade NdFeB magnets that contain less Dy. At the turbine stage, the framework includes substitution across generator technologies, including conventional gearbox, direct-drive PMGs (PMDDs), and hybrid PMG technologies. Finally, the framework includes end-product recycling and recycling during manufacturing processes. The material flows among countries could be linked through imports and exports of either RE materials or products that contain RE materials.

The rest of this chapter is organized as follows. Section 2.2 presents the basic framework for the supply chain. Section 2.3 briefly describes RE manufacturing processes. Section 2.4 discusses the identification of industrial participants. Section 2.5 discusses the Nd and Dy demand for U.S. wind turbine installations. Section 2.6 briefly discusses recycling issues. Section 2.7 discusses the impacts of Nd and Dy prices on wind turbine capital cost. Section 2.8 briefly discusses the development of the Chinese RE industry. Finally, section 2.9 provides a summary of this chapter's findings.

2.2 The Basic Framework

As noted above, Figure 1 provides the basic framework for describing the Nd and Dy flows through the supply chain for an individual country. But further calibrating the diagram for specific time period(s) requires more data than are presently available in public sources.

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[2] There are 17 REEs, 15 within the chemical group called lanthanides, plus yttrium and scandium. The lanthanides include the following: lanthanum, cerium, praseodymium, Nd, promethium, samarium, europium, gadolinium, terbium, Dy, holmium, erbium, thulium, ytterbium, and lutetium. REs are used in many high-tech applications, ranging from wind turbines and hybrid cars to missile-guidance systems and mobile phones. The lanthnides are often broken into two groups: light rare earth elements (LREEs)—lanthanum through europium (atomic numbers 57–63) and the heavier rare earth elements (HREEs)—gadolinium through lutetium (atomic numbers 64–71). LREE materials have a much larger reserve and are easy to process.

The “RE Ore” box of Figure 1 provides the quantity and composition of RE extraction for the specific year. The next box, “Nd and Dy Oxides,” represents the manufacturing of rare earth oxides (REOs), which are generated from RE ore (left arrow into the box) through a series of beneficiation, chemical cracking, and refinery processes. The arrow pointing away from the box to the right represents the amount used for RE metals. The arrow leading down and to the far right indicates other direct uses and applications.

For each box in the diagram, the triangle on top represents the amount that is stockpiled. The down arrow indicates the amount imported from other countries and the arrow pointing up indicates the amount exported to other countries. The arrow pointing into the box from above indicates recycling.

The next box, “Nd and Dy metals,” represents the generation of RE metals. The RE metals are produced from REOs (from the left arrow) by reduction processes. Imports, exports, recycling, and other uses are defined analogously to the other stages.

The “Alloys and Magnet Powders” box refers to the generation of magnet powders. The magnet powders are produced from mixing metals (from the left arrow). Alloys and powders are used to make NdFeB PMs (right arrow).

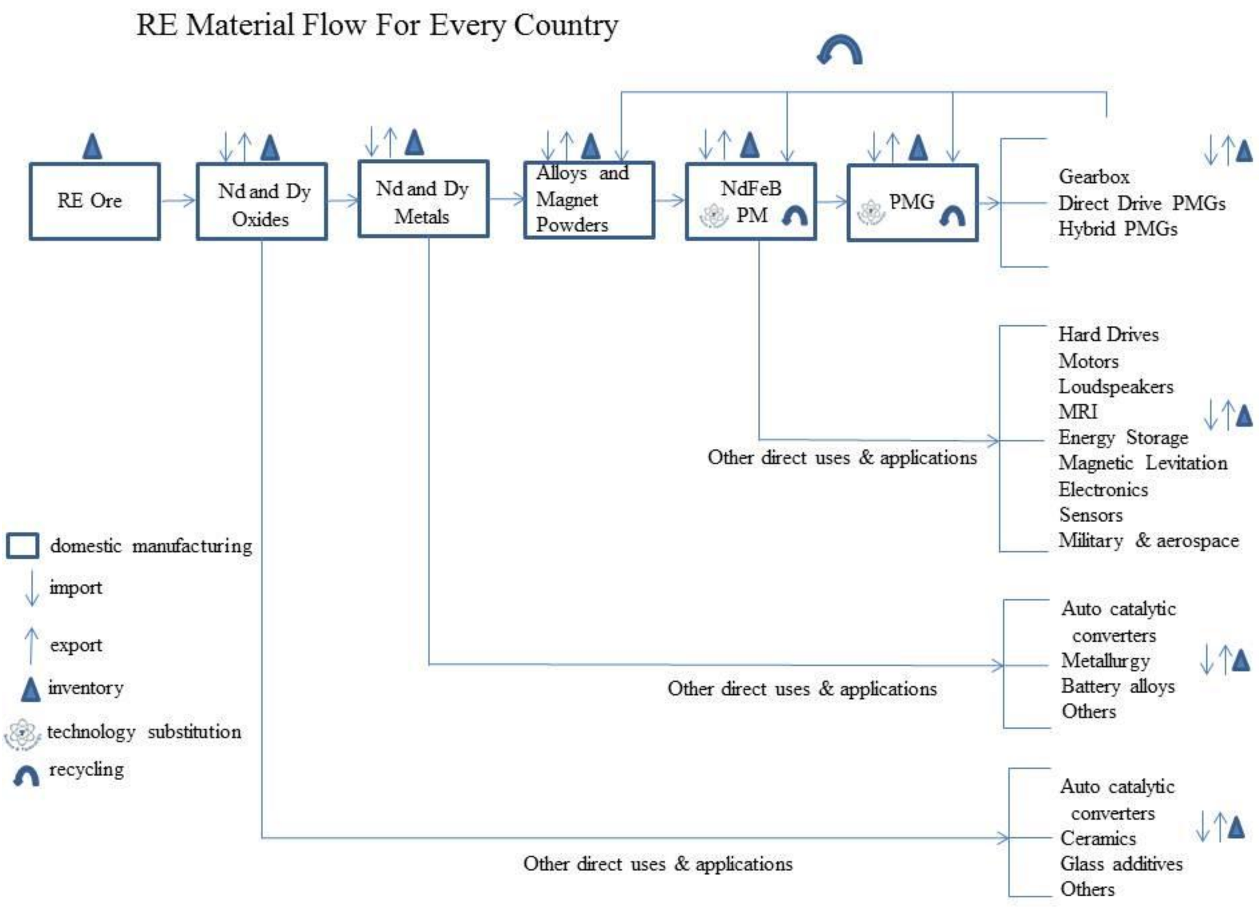
The “NdFeB PM” box refers to manufacturing NdFeB PMs. The PMs are used for PMG manufacturing (right arrow). The discussion below explicitly considers the potential substitutions of other types of magnets for NdFeB PMs. The framework also includes scrap recycling during the magnet manufacturing process.

The box “PMG” represents the manufacturing of the NdFeB PMG. The right arrow shows that the produced PMGs are used for wind turbine manufacturing. We consider different wind turbine technologies that affect Nd and Dy consumption, which is shown on the right side of the diagram. We also consider PMG scrap recycling during the PMG manufacturing process.

The right side of the diagram shows the three industrial groups of Nd and Dy end uses. The first group is wind turbines. The second group includes other uses of NdFeB magnets, such as hard drives. The third group and fourth groups include the end uses of Nd and Dy oxides and metals. For all groups, the supply chain diagram includes domestic uses, inventory, imports, and exports.

Ideally, we would calibrate the comprehensive supply chain model for individual countries, such as China, Japan, and the United States. The individual country supply chain model would be linked through trade data for all the intermediate and end products to give a complete picture of Nd and Dy material flows. However, because of time and data limitations, we provide quantitative estimates when possible and otherwise provide a qualitative description.

Figure 2. Representative Nd and Dy Supply Chain Model



2.3 RE Supply Chain Manufacturing Processes

What follows describes in greater detail the physical processes that occur at each stage. Most of the descriptions in this section are from Kidela Capital Group (2011).

2.3.1 Mining RE Ore and Producing RE Concentrates

The first step of RE production is to mine the ore. Generally, the ores, which contain RE-bearing minerals, such as bastneasite and monazite, contain very low concentrations of the REEs. The next step is to mill the ore, a process referred to as beneficiation or mineral dressing.[3] The equipment, such as crushers and rotating grinding mills, is used to grind the ore to form fine particles less than 1 mm in diameter, or even less than 0.1 mm. The minerals are then concentrated through various separation techniques, such as froth flotation, magnetic separation, and gravity or electrostatic concentration. This process typically recovers 80 percent or more of the RE minerals and raises the concentration ratio by a factor of five or more compared to the original concentration in the ore.

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[3] Because transporting large volumes of RE concentrate is so expensive, the mineral dressing plant is almost always located very close to the mine.

The concentrates go through a series of chemical upgrading processes, collectively referred to as cracking, to further separate and upgrade the REEs. The cracking process includes techniques—such as roasting, salt or caustic fusion, high-temperature sulphation, and acid leaching—that allow the REEs within the concentrates to be dissolved. The leach solutions then can then be processed using selective precipitation, solvent extraction, or ion exchange processes to remove most of the impurities and produce higher-grade intermediate chemical compounds suitable for refining. The products of the chemical upgrading plants are high-grade precipitates, with 50 percent or more REO content, which can be shipped long distances without adding much transportation cost (London 2010).

2.3.2 Producing REOs

The concentrates are refined into high-purity REOs. The typical RE refinery uses ion exchange and/or multistage solvent extraction to separate and purify the REEs. These processes break down the mixed RE compounds by exploiting the small differences among the REEs. To produce 99.9 percent purity (or even higher) REO is not simple. It may take 50 chemical tanks to separate light rare earth elements (LREEs) and up to 1,000 tanks of sequential solvent extraction to properly separate heavy rare earth elements (HREEs).

The refining and mineral dressing (described earlier) can occur at the same plant or separately. Also, the RE refineries are generally sized and configured to suit the unique composition of the feed material. For this reason, a plant designed to purify LREE compounds would normally have difficulty handling an increased proportion of HREEs.

2.3.3 Producing RE Metals

The rapid advance of science and technology has led to some RE applications that require very high purities of individual REEs—as much as 99.999 percent. For these applications, multistage solvent extraction is generally used to refine the REOs.

Two common methods to convert REO to RE metal are calico-thermic reduction and electro-deposition using an electrolytic furnace. Both of these processes are energy intensive, and research is still needed to find other viable alternatives. The process yield for reduction from the REO to the metal is approximately 80 percent, though some more primitive processes yield less than 50 percent. Approximately 14 percent (13 percent) of the Nd (Dy) oxide is oxygen. So theoretically, the maximum yield of Nd (Dy) metal is about 86 percent (87 percent). The production yield could be enhanced by improving the production technology efficiency.

2.3.4 Producing Alloy and Magnet Powders

There are two different types of NdFeB magnets: sintered and bonded. Sintered magnets are heat-treated to produce the higher performance required for electric-drive and larger wind turbine applications (U.S. Department of Energy [DOE] 2010). Bonded NdFeB magnets generally have low magnetic properties from gluing the powder in a mold. Bonded magnets can be used in other applications, such as electronics. In the following discussion, we focus on sintered NdFeB magnets.

The method of making alloy and magnet powder for sintered NdFeB magnets includes the following steps. First, additives including RE metals, iron, boron, cobalt, and others are melted in a vacuum induction furnace to make either the magnet composition or an intermediate composition suitable for later re-melting with additional ingredients to reach the final composition.[4] After completion of various steps in the process, the RE alloys are cooled to form solidified ingots. The ingots are then pulverized into magnet powders with a particle size of 3 microns (equivalent diameter). The crystal structure of RE magnet alloys is such that magnetization can take place along one axis of the crystal. This is called uniaxial crystalline anisotropy. For Nd, 3 microns is about the size at which each particle can be aligned in a single direction. For further details about the preparation of magnet powders, please see NdFeB-Info (2011) and Shin-Etsu Rare Earth Magnets (2011).

2.3.5 Producing PMs

The magnetic powders are placed in a jig and a strong magnetic aligning field is applied. The powder particles are oriented to align the magnetic domains, so the highest possible magnetic field strength is achieved. The magnets are then pressed into shape. Two methods of pressing exist: *perpendicular pressing*, in which magnets are pressed perpendicular to the magnetic field, and *parallel pressing*, in which they are pressed parallel to the field. Given an equal grade of magnet, the perpendicular press method creates a higher-performance magnet. The pressed ingots are heat-treated in a sintering furnace and, finally, are aged in an oven to obtain the desired properties. The PMs are produced in different grades that exhibit a range of properties, such as magnetic strength and heat tolerance.

In terms of the material content of the magnets, it is widely asserted that NdFeB PMs have a chemical formula of $Nd_2Fe_{14}B$. Using this formula, the theoretical Nd percentage by weight in the magnet is 26.7 percent. However, in practice, the NdFeB PM includes other metals; for example, Dy replaces some of the Nd to improve the magnet's performance at high temperature (NdFeB-Info 2011). Because of the other metals, the Nd contents should be less than 26.7 percent by weight. In reality, NdFeB is made of an alloy whose Nd content may be above or below 26.7 percent (NdFeB-Info 2011). That is, the alloy does not follow the theoretical chemical formula, and each manufacturer and product could have a different amount.

The PM could be demagnetized at higher temperatures. To improve the magnet's resistance to demagnetization, Dy is usually added to the NdFeB PM. The downside to adding Dy to a PM is that it actually decreases the magnetic output of the magnet. Thus, there is a trade-off in the use of Dy. The substitutability between Dy and Nd and how substitution affects NdFeB PM properties are not well understood.

2.3.6 Producing PMGs

A PMG is a generator in which the excitation field is provided by a PM instead of a coil. Depending on the design, PMGs can generate either direct current or alternating current. For example, to convert mechanical power from the turbine rotor to electrical power, the armature may rotate through the magnetic field created by PMs that are attached to the stator, thereby generating direct current. PMG design can be very complicated; for a detailed literature review on PMG design and associated dynamic behavior, please see Aleksashkin and Mikkola (2008) and Ross (2011). A persistent magnetic field could impose safety issues during assembly, field service, or repair (U.S. Consumer Product Safety Commission 2011).

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[4] Some of the raw materials can exist in a pre-alloy form. For example, boron can be added as a ferro-boron alloy.

2.3.7 Producing Wind Turbines

As shown in the far right-hand part of Figure 1, wind power generators, in general, fall into three primary types—gearbox, direct drive, and hybrid PMGs.[5] Gearbox generators, sometimes referred to as asynchronous generators, have dominated the market because of their low manufacturing costs and extensive use. However, in recent years, PMDDs using NdFeB PMs have gained some market share. The third category, the hybrid PMG, works with a simpler one- or two-stage gearbox with intermediate output speed and hence a smaller PM. The simpler gearbox enables increased reliability of the whole drive train compared to fully geared generators.

2.4 Identifying Industrial Participants

This section describes the location of production at each stage in the supply chain and flows of materials through the supply chain. When ownership information is available, we describe some patterns of vertical integration and market shares. As described later, in the chapter on market power, caution is required in interpreting these data. In general, countries are not economic competitors with market shares. Virtually 100 percent of the supply of a commodity or service may originate in a single country, but the market will be competitive if that country contains a number of suppliers that act independently. On the other hand, in some countries, firms at various stages in the supply chain may be nominally separate, but because of sector-specific policies and the general rules of corporate operation in those countries, they may not act as autonomous entities; this has implications for their potential to exercise market power over REs as well as strategic implications for China's export quotas. The degree of functional integration, both within markets (horizontal) and across different stages of the supply chain (vertical), in China is difficult for us to ascertain, and remains a topic requiring additional research.

In section 2.4.1, we discuss the world reserves of REs. Section 2.4.2 discusses the world production of REs. Section 2.4.3 discusses the world production of Nd and Dy metals. Section 2.4.4 discusses the production of alloys and PM powder. Section 2.4.5 discusses the production of PMs and U.S. demand. Section 2.4.6 discusses the substitutability of magnets. Section 2.4.7 discusses wind turbine technologies and substitutability.

2.4.1 World Reserves of REs

The world RE reserve was about 114 million tonnes in 2010. China and the United States account for 48.3 and 11.4 percent of world reserve, respectively (Table 1). The quality and quantity of individual mines are different. Table 2 shows some examples of RE mines in the world, including the amount of reserve and the grade in percentage of total rare earth oxides (TREO).

Table 3 shows the Nd oxide (Nd_2O_3) and Dy oxide (Dy_2O_3) contents for several large and potential mines. Dy can be found only in the southeastern part of China. Molycorp is currently exploring U.S. deposits that contain HREE with grades of 4 to 6 percent (Gordon 2011).

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[5] Siemens has announced that they have achieved a fairly significant breakthrough in their high-temperature superconductor (HTS) technology. They will seek to demonstrate that they can use superconducting coils that can improve the efficiency of current power plants over traditional copper coils. The HTS generator is expected to be much smaller, lighter, and more efficient than conventional turbines, but this category is not yet commercialized (Tyler 2009). According to the National Wind Technology Center, it may take as long as 10–15 years for these turbines to be commercially available (Hatch 2009).

Table 1. World RE Reserves

	2009 Reserve		2010 Reserve	
Country	tonnes	%	tonnes	%
China	36,000,000	36.5	55,000,000	48.3
USA	13,000,000	13.2	13,000,000	11.4
Australia	5,400,000	5.5	1,600,000	1.4
CIS	19,000,000	19.3	19,000,000	16.7
India	3,100,000	3.1	3,100,000	2.7
Other	22,078,000	22.4	22,078,000	19.4
Total	98,578,000		113,778,000	

Note: CIS, Commonwealth of Independent States.
Source: U.S. Geological Survey 2010, 2011b.

Table 2. 2010 Examples of TREO Reserves at Individual Potential Mines, Resources

Country	Mine name	Resource (MMT)	Grade (%TREO)	TREO (MMT)
China	Bayan Obo	1,460	3.9	56.9
USA	Mountain Pass	20	9.2	1.8
USA	Bear Lodge	9	4.1	0.4
Greenland	Kvanefjeld	215	1	2.2
Canada	Nechalacho	65	2.1	1.4
Australia	Mount Weld	12	9.7	1.2
Australia	Nolans	30	2.8	0.8
Vietnam	Dong Pao	11	6.9	0.8
Canada	Hoidas Lake	1.5	2.6	0.0

Note: MMT, million metric tons.
Source: Hocquard 2010.

Table 3. Nd Oxide and Dy Oxide Content of Major and Potential Mines (% of TREO)

Mine name	State/province	Country	Nd oxide	Dy oxide
Major				
Bayan Obo	Inner Mongolia	China	18.5	0.1
Potential				
Nangang	Guangdong	China	17.0	0.8
Southeast	Guangdong	China	3.5	9.1
Xunwu	Jiangxi	China	31.7	trace
Longnan	Jiangxi	China	3.0	6.7
Mianning	Sichuan	China	11.1	0.19
Mountain Pass	California	USA	12.0	trace
Green Cove Springs	Florida	USA	17.5	0.9
North Capel	Western Australia	Australia	17.4	0.7
North Stradbroke Island	Queensland	Australia	18.6	0.6
Mount Weld	Western Australia	Australia	15.0	0.2
Eastern Coast		Brazil	18.5	0.4
Lahat, Perak		Malaysia	1.6	8.3

Source: U.S. Geological Survey 2009.

2.4.2 World Production of REs

In 2010, RE ores were primarily mined in China, with smaller amounts mined in India, Brazil, and Malaysia. As Table 4 shows, the amount of world RE production is about 133,600 tonnes. China accounts for 97.3 percent of world production, as of 2010.

China's RE industry is distributed across three large districts—southern, northern, and western (Figure 2). The southern district includes Jiangxi, Guangdong, Fujian, Hunan, and Guangxi; the northern district includes Inner Mongolia and Shandong; and the western district includes Sichuan. Inner Mongolia and Sichuan, and to some extent Shandong, focus on LREEs. Medium and heavy RE mining, including for Dy, occurs in Jiangxi, Guangdong, and Fujian. In 2009, the production quota allocated to Inner Mongolia and Sichuan was about 72,300 tonnes, and the quota allocated to the southern district was about 10,020 tonnes (Hocquard 2010).

Table 4. World RE Production

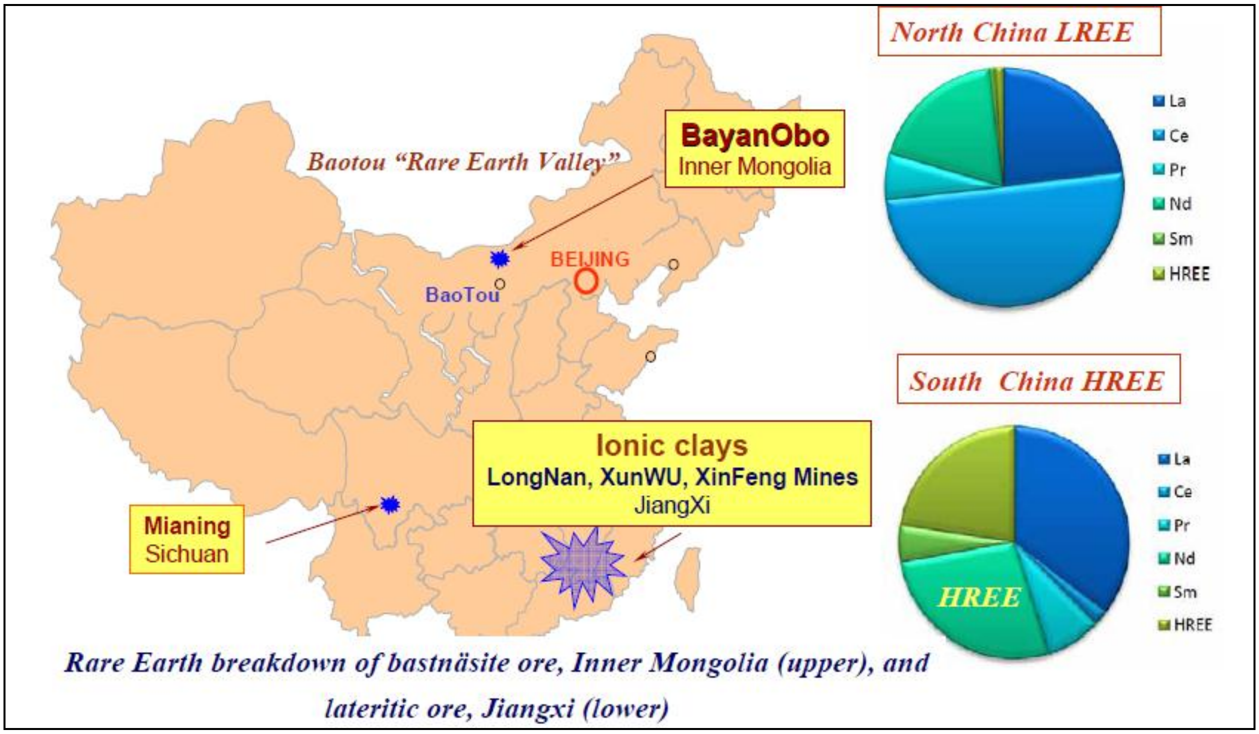
	REO 2009 production		REO 2010 production	
Country	tonnes	%	tonnes	%
China	129,000	97.3	130,000	97.3
Brazil	550	0.4	550	0.4
CIS	NA		NA	
India	2,700	2.0	2,700	2.0
Malaysia	350	0.3	350	0.3
Other[a]	NA		NA	
Total	132,600		133,600	

Note: CIS, Commonwealth of Independent States.

[a] "Other" includes a small amount of REO produced using stockpiled concentrates derived from RE ore that was previously mined at U.S. Mountain Pass.

Source: U.S. Geological Survey 2011b.

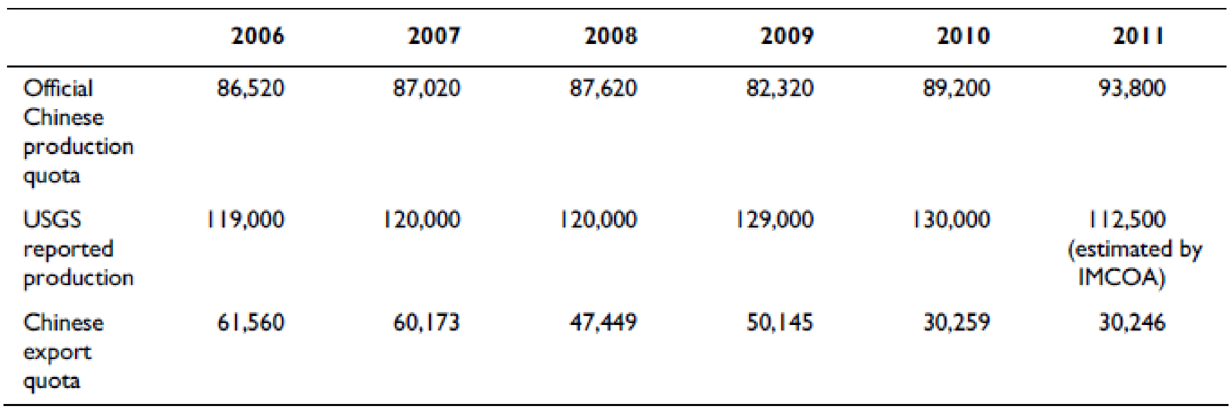
Figure 2. RE Production in China



Source: Hocquard 2010.

Table 5 provides information about China's RE production and export quotas between 2006 and 2011 (Humphries 2011).[6] The U.S. Geological Survey (USGS 2011b) reports that Chinese production exceeded official Chinese production quotas over this time frame. Industry experts suggest that some production occurs outside of government-approved transactions. The experts suggest that this "black market" may lead to great uncertainty in interpreting these data.

Table 5. China's RE Production and Exports, 2006–2011



	2006	2007	2008	2009	2010	2011
Official Chinese production quota	86,520	87,020	87,620	82,320	89,200	93,800
USGS reported production	119,000	120,000	120,000	129,000	130,000	112,500 (estimated by IMCOA)
Chinese export quota	61,560	60,173	47,449	50,145	30,259	30,246

Note: The table was constructed before the recent release of the 2012 export quotas. IMCOA, Industrial Minerals Company of Australia.
Source: Humphries 2011.

Although no RE mining took place in the United States in 2010, U.S.-based Molycorp operates a separation plant at Mountain Pass, California, and sells the RE concentrates and refined products from previously mined above-ground stocks. Nd, praseodymium, and lanthanum oxides are processed, but these materials are not turned into RE metals in the United States. However, Molycorp plans to reopen its RE mining operations. Molycorp's Project Pheonix is currently on time and on budget and is expected to reach a production capacity of 19,050 tonnes/year by the end of 2012 and 40,000 tonnes/year by mid-2013 (Molycorp 2011a).

Lynas Corporation's Mount Weld in Western Australia is another potential RE mine outside China. It was expected to begin production in late 2011, but this has now been postponed to the first quarter of 2012 (Lynas Corporation, Ltd. 2011a). The Great Western Minerals Group (GWMG 2012) also plans to recommission its Steenkampskraal mining operation toward full operations with a production capacity of 5,000 tonnes/year and with a projected launch in the first quarter of 2013. Other advanced exploration projects around the world are ongoing, but they could easily take 10 years to reach production. In the long run, however, USGS expects that global reserves and undiscovered resources are large enough to meet demand (Humphries 2011).

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[6] Since the early 1990s, foreign investors have effectively been prohobited from mining RE and they must form joint ventures with Chinese firms to participate in smelting and separatino. Since the early 1990s, the Ministry of Land and Resource has been responsible for developing overall and province-level production quotas. In 2008, the Ministry of Industry and Information technology began issuing an RE production quota for the country. China also sets export quotas. Currently the Ministry of Commerce is responsible for export licenses. Separate export quotas are set for domestic RE producers and joint-venture RE producers (Tse 2011).

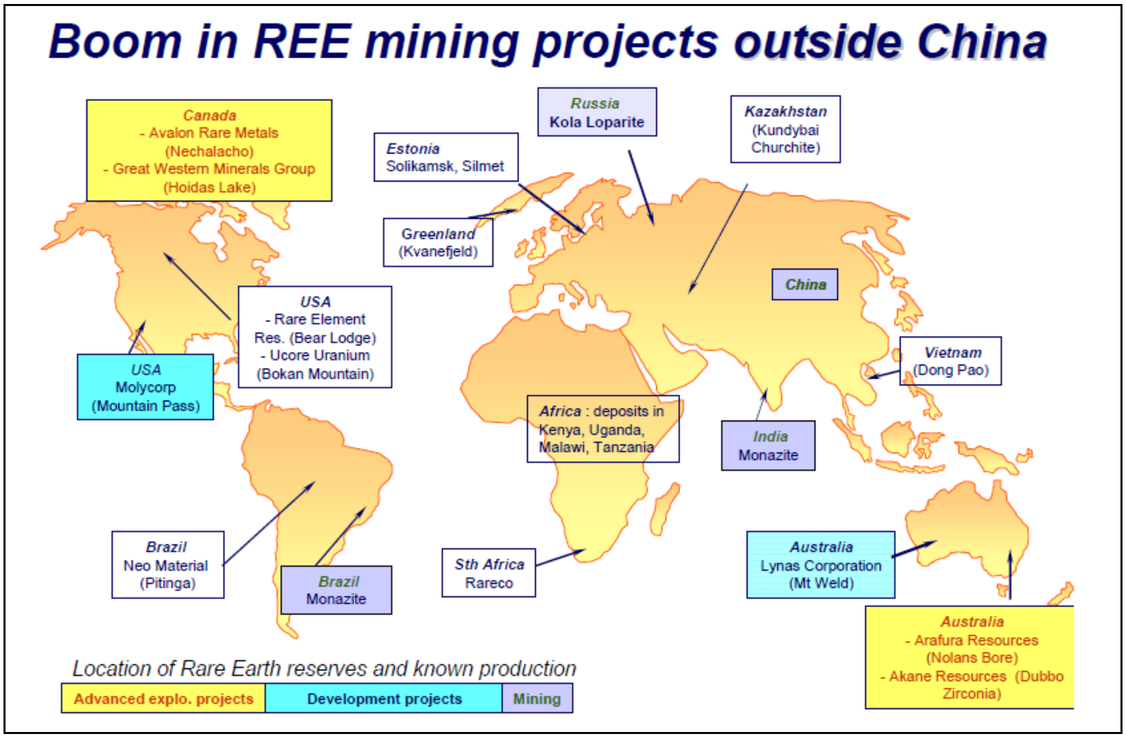
Table 6 provides information about world major and potential RE mineral sources. Figure provides information about the development status of REE mining projects outside of China.

Table 6. World Major and Potential RE Mineral Sources

Company	Mine name	Mine country	Notes
Major			
Sichuan Mianning Mining Co.	Sichuan	China	
Jiangxi Copper	Jiangxi	China	
Baotou Steel Rare Earth	Bayan Obo	China	
Potential			
Molycorp	Mountain Pass	USA (CA)	19,050 tonnes/year, production capacity at Mountain Pass expected by 2012, and 40,000 tonnes/year by mid-2013
U.S. Rare Earths	Diamond Creek	USA (ID)	discovery phase
Rare Element Resources	Bear Lodge	USA (WY)	discovery phase
Ucore Uranium	Bokan Mountain	USA (AK)	Canadian company, discovery phase
Colorado Rare Earths, Inc.		USA (CO)	owns rights to REs in Colorado but no discoveries yet
Lynas	Mount Weld	Australia	22,000 tonnes/year, production capacity at Mount Weld expected in 2012
Alkane Resources	Dubbo Zirconia	Australia	
Arafura Resources	Nolan’s Bore	Australia	
GWMG	Hoidas Lake	Canada	discovery phase
	Steenkampskraal	South Africa	5,000 tonnes/year production capacity in 2013
Avalon Rare Metals Inc.	Nechalacho (Thor Lake)	Canada	producing by 2015
Vietnamese Government/Toyota	Dong Pao	Vietnam	

Sources: Hocquard 2010; Molycorp 2011b; Lynas Corporation, Ltd. 2011a; and GWMG 2012.

Figure 3. RE Mining Projects Outside of China



Source: Hocquard 2010.

According to a recent article in the China Daily, "The central government has indicated that it wants large companies to spearhead the consolidation of the country's rare earths sector to prevent the resource from being undervalued" (Qi 2010). Table 7 provides a list of major Chinese RE enterprises (including mining, smelting and separation, and some end products) that are actively involved in the consolidation.

A list of companies, both Chinese-owned and foreign-owned, receiving REO export quotas in 2011 is provided in Appendix C. Some of these companies belong to part of the large RE enterprises in Table 7. For example, Baotou Huamei Rare Earth Hi-Tech Company, Inner Mongolia Baotou Steel Rare Earth Hi-Tech Company, Inner Mongolia Baogang Hefa Rare Earth Company, and Baotou Tianjiao Seimi Rare Earth Polishing Powder Company are all part of Baoto Steel Rare Earth, which dominates RE production in the northern part of China. Its export quota accounts for about 20 percent of the total export quota for 2011.

China Nonferrous Metal Mining Corp., which owns China Non-ferrous Metal Industry's Foreign Engineering and Construction Co., Ltd., has recently initiated the construction of China Nonferrous Metal South Rare Earths (Xinfeng) Co., Ltd., in Guangdong. It will be the largest plant in China with RE separation capability of 7,000 tonnes/year. The plant will be put into operation in 2013 (China International Investment Promotion Platform 2011).

Table 7. Major Large RE Enterprises in China

Company name		Website
包钢稀土	Baoto Steel Rare Earth	http://www.reht.com/
广晟有色	Guangdong Rising Nonferrous Metals Group Co., Ltd.	http://www.gdnmi.com.cn/profile/index.htm
厦门钨业	Xiamen Tungsten Co., Ltd.	http://www.cxtc.com/listSingleHtml.html?l2menu.uid=5
赣州矿业	Ganzhou Rare Earth Mineral Industry Co., Ltd.	http://www.gz-re.com/
中色建	China Non-ferrous Metal Industry’s Foreign Engineering and Construction Co., Ltd	http://www.nfc.com.cn/
有研稀土	Grirem Advanced Materials Co., Ltd.	http://www.grirem.com/
甘肃稀土	Gansu Rare Earth Group Co., Ltd.	http://www.gsre.com/
中铝公司	Aluminum Corporation of China	http://www.chalco.com.cn/zl/web/chinalco.jsp
五矿集团	China Minmetals Corporation	http://www.minmetals.com.cn/index.jsp

2.4.3 The World Production of Nd and Dy Metals

Partly because of low costs in China, most metal production and melting of metals into alloys occurs in China. Magnet manufacturers within China typically purchase RE metal and melt their own magnet compositions. Some foreign companies purchase RE metal, and others perform their own melting using RE-iron eutectic alloys.

Companies outside of China with the ability to reduce REOs to metal include Santoku (Japan), Molycorp Silmet (plant located in Estonia), and GWMG (Canada). Two more Japanese companies are likely to have this capability soon: Shin-Etsu and Sumitomo Metal-Mining. Alloying capability exists in high volume at GWMG (Canada), and at additional companies in the United States, Japan, and Europe. Table provides an incomplete list of companies that have the capability to reduce RE oxides to metals.

Table 8. Firms Capable of Reducing REOs to Metals

Company	Country	Capacity	Notes
Molycorp Silmet	USA	700 tonnes per year	Molycorp owns 100% of the facility in AS Silmet
Santoku Corporation	Japan		
Shin-Etsu	Japan		likely to start producing
Sumitomo Metal-Mining	Japan		
Less Common Metals	Canada		Subsidiaries of GWMG, Ltd.
Huizhou Hengli Rare-Earth Materials Co.	China		
Ganzhou Goring High Tech Material Co.	China		
Other Chinese firms			

Source: Molycorp 2011c, 2011d; and GWMG 2012.

We next estimate Chinese production of Nd and Dy metals. Nd is typically around 20 percent of the total REEs produced by the Chinese LREE industry. In 2010, the Chinese production of total RE was about 89,000 tonnes, of which 77,000 tonnes (86 percent) were LREEs. This implies that the Chinese production of Nd oxide for 2010 was about 15,000 tonnes. Of the 12,000 tonnes of HREEs produced in China in 2010, 7 percent was reported to be Dy oxide, which implies that 840 tonnes of Dy oxide were produced (Lifton 2011). If we use Chinese RE production data of 130,000 tonnes, reported by USGS (2011b), with 17 percent Nd oxide and 1 percent Dy oxide contents, then our estimates are 22,100 tonnes Nd oxide and 1,300 tonnes Dy oxide (equivalent to 19,006 tonnes of Nd metal and 1,131 tonnes of Dy metal[7]) produced in China in 2010.

Tables 9 and 10 provide incomplete Chinese Nd export data for 2005 and 2010. For 2005, December export data are missing. For 2010, we were able to find data for only three months, from May to July. It is not always possible to determine from the data sources whether the empty cells in the table represent zero exports or missing data It is clear that Japan is the biggest importer of Chinese Nd, followed by Korea, Germany, the United States, and India.

Figure 4 shows the cycle of Japanese Dy metals in 2008. Shi et al. (2010) estimate that Japan imported about 356–399 tonnes of Dy from China, all of which was used to fabricate NdFeB magnets. About 29 percent of Dy in NdFeB magnets was exported back to China, and the rest of it was consumed by various end uses, including, in descending share order, factory automation (29 percent), automobiles (23 percent), voice coil motor for hard disk drives and mobile phone carriers (12 percent), and home electric appliances (7 percent). Shi et al. (2010) also estimate that the Dy stock in use was about 886–1,102 tonnes in 2008.

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[7] We assume that the yields from oxide to metal are 0.86 and 0.87 for Nd and Dy, respectively. We also assume 100 percent production efficiency.

Table 9. 2005 China Nd Metal Exports by Country (kg)

Country month	Japan	Korea	Germany	USA	India	Austria	Canada	Thailand	U.K.	Russia	The Netherlands
December											
November	242,500		10,000						1,000		
October	183,500	5,000	20,000		19,000			9,000			
September	281,000	6,000	20,000								
August	336,913	20,000		18,000							
July		214,370				250	23				
June	244,000		10,000							1,500	
May	190,825	4,000	5,000	18,000		210					
April	237,000		10,000	18,000							
March	269,250		20,000	6,000							
February	275,000	2,000	10,000	200						1,000	3,000
January	88,379										

Source: Ganzhou Rare Earth Mineral Industry Co., Ltd. 2006. We reproduced the table as it appears at this website; a reviewer has pointed out that the entry of 214,370 for Korea may in fact represent a data point for Japan.

Table 10. 2010 China Nd Metal Exports by Country (kg)

Country month	Japan	Korea	Germany	USA	India	Austria	Canada	Thailand	U.K.	Russia	The Netherlands	Ukraine
December												
November												
October												
September												
August												
July	218,469		15,000					500	5,000	1,000		
June	152,385		2,000					10,000				200
May	131,105		20,000					20,200	5,000	1,200		
April												
March												
February												
January												

Source: Global Ferroalloy Net (2010, 2010a and 2010b).

According to estimates by Nakamura (2009), Japan imported 4,800 tonnes of Nd metals in 2006 and 5,400 tonnes in 2008. He also predicted that Japan would import 8,500 tonnes Nd metal**s** in 2011. His estimate that Japan imported 460 tonnes of Dy metals in 2006 and 500 tonnes in 2008 is greater than the estimate reported by Shi et al. (2010). Nakamura (2009) predicted that Japan would import 800 tonnes of Dy metal in 2011. However, given the tsunami-related disruption, the actual amount may have been lower. We have not seen any actual Japanese import demand data after 2008. We have communicated with a researcher in Japan and have suggested that he look into any demand disruption caused by the tsunami disaster in early 2011.

Figure 4. Japanese Dy Cycle

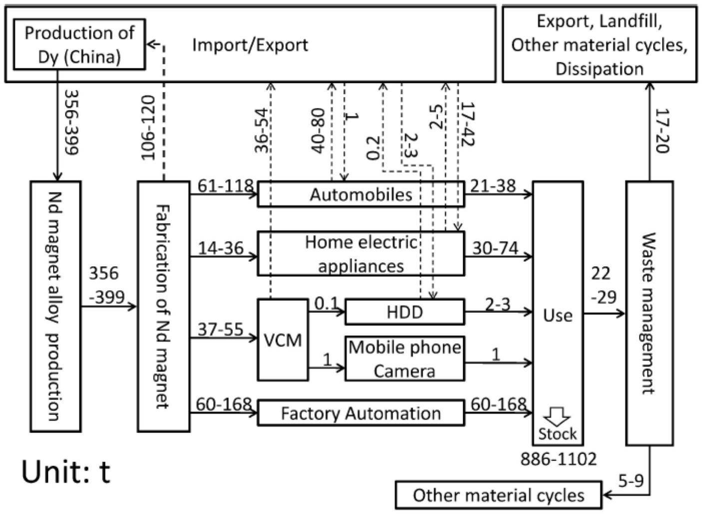


Fig. 4 The cycle of Dy in Japan for 2008.

Source: Shi et al. 2010.

2.4.4 Production of Alloy and PM Powders

Santoku America, Inc., has been one of the world leaders in the production of high-strength magnet alloys, such as NdFeB and SmCo alloys, since the 1980s. Showa Denko has plants in Chichibu, Japan, and two sites in China with a total RE magnetic alloy capacity of 9,000 tonnes/year (Bloomberg 2011). GWMG, which includes two subsidiaries (Less Common Metals in Birkenhead, United Kingdom, and Great Western Technologies in Troy, Michigan), is a major producer of RE alloys and PM powders. Less Common Metals will double its current capacity from approximately 1,100 tonnes/year to more than 2,000 tonnes/year in late 2012 (GWMG 2012). Table 11 provides the available data for an incomplete list of alloy and PM powder producers.

Table 11. Alloys and Magnet Powders

Company/subsidiary name	Country	Capacity as of 2011 (tonnes/year)
Santoku America	USA	
Less Common Metals	Canada	1,100
Great Western Technologies Inc.	Canada	
Ganzhou Goring High Tech Material Co.	China	
Showa Denko K.K. (SDK)	Japan	9,000
Other Chinese firms		

Sources: Bloomberg (2011) and GWMG (2012).

2.4.5 Production of PM and U.S. Demand

Four types of PMs are commercially available: NdFeB, SmCo, AlNiCo, and ferrite (ceramic). In this section, we discuss patents and licensing issues associated with PM production as well as U.S. demand.

2.4.5.1 Patents and Licensing Issues

As described in the 2010 *Critical Materials Strategy* (CMS report; DOE 2010), two firms control master patents on NdFeB magnets: Hitachi Metals (formerly Sumitomo) in Japan and Magnequench, a former U.S. firm that was sold to a China-backed consortium in 1995 (Dent 2009).

As of 2007, Hitachi Metals has entered into sintered NdFeB magnet license agreements with 11 companies in five different countries, including 5 companies in China, 2 in Japan, and 4 in Europe (Hitachi Metals 2007). The list below contains the names of these manufacturers. In addition, six subsidiaries of two Chinese licensees are licensed to manufacture the magnets but are not licensed to sell them. A partial list of PM manufacturers is provided in Appendix D.

- China Licensees
  - Beijing Zhong Ke San Huan High-Tech Co., Ltd.
  - Beijing Jingci Magnetism Technology Co.
  - Advanced Technology & Materials Co.
  - Thinova Co.
  - Ningbo Yunsheng Co.
- Japan Licensees
  - Shin-Etsu
  - TDK
- Europe Licensees
  - Vacuumschmelze GmbH (Germany)

- Magnetfabrik Schramberg GmbH (Germany)
- The Morgan Curcible Company plc (U.K.)
- Neorem Magnets Oy (Finland)

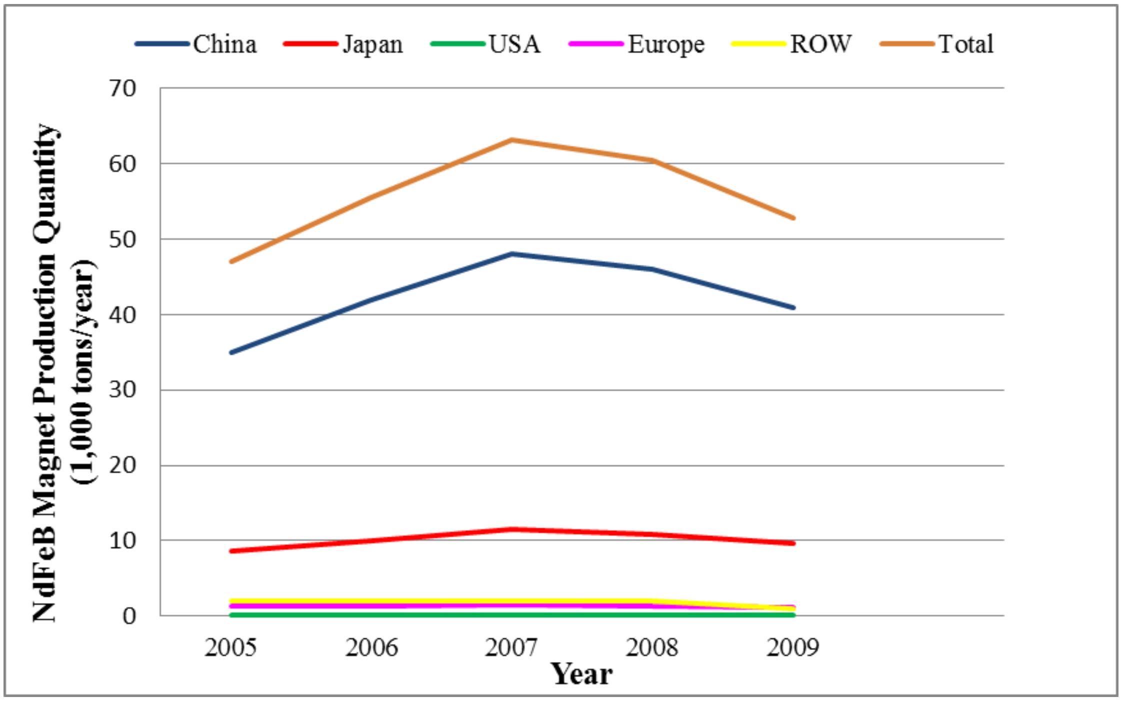
Table 12 shows global PM production by magnet type in 2009 (Benecki et al. 2010). The world suppliers of NdFeB magnets are China, 78 percent; Japan, 18 percent; Europe, 2.3 percent; United States, 0.2 percent; and the rest of the world, 1.9 percent. For comparison, the table shows production by country for other types of magnets. The time trend of NdFeB magnet production between 2005 and 2009 is shown in Figure.

Table 12. 2009 Global PM Production by Type (1,000 tonnes)

	China	USA	Japan	Europe	ROW	Total
NdFeB	41	0.1	9.6	1.2	1	52.9
Ferrite	309	43.7	41.2	49	74	516.9
SmCo	1	0.2	0.2	0.2	0	1.6
AlNiCo	2	0.6	0.6	0.6	1	4.8
Total	353	44.6	51.6	51	76	576.2

Note: ROW, rest of the world.
Source: Benecki et al. (2010).

Figure 5. NdFeB Magnet Production over Time



Note: ROW, rest of the world.

2.4.5.2 U.S. Magnet Demand

Constantinides (2011) estimates that the United States imported approximately 5,330 tonnes of NdFeB magnets in 2010. Karl Gschneidner of DOE's Ames Laboratory provided a similar estimate of 6,000 tonnes (personal communication). By comparison, worldwide production was about 53,000 tonnes in 2009.

2.4.6 Substitutability of Magnets

NdFeB PMs have the strongest magnetic energy density and are the most powerful commercial magnet existing today; therefore, it may prove difficult to find exact substitutes for NdFeB PMs in wind turbines in the near future. Currently, SmCo PMs do not appear to be close substitutes. Compared to NdFeB magnets, SmCo are able to withstand higher temperatures (500°C as opposed to 200°C), but they are considerably more expensive and they are not as strong at moderate temperatures.

Similarly, AlNiCo and ferrite (ceramic) magnets do not appear to be close substitutes for NdFeB magnets in wind turbines. Their maximum energy products (the density of magnetic energy) are much less than those of NdFeB magnets. Also, AlNiCo is hard and brittle; it is prone to chipping and cracking and is very difficult to machine.

In addition to substituting for NdFeB magnets with other types of PMs, another possibility is to consider using a lower-grade NdFeB magnet (Totaro 2011). Conventional PMGs use high-temperature-grade magnets because they have to maintain performance at higher temperatures and maintain a very small air gap to achieve optimal flux and efficiency. Dy is added to improve NdFeB magnet performance at high temperatures. Because Dy is very rare and expensive, the challenge is to find a system design to use lower-temperature-grade magnets with comparable flux capability. More research and development (R&D) is needed in this area.

2.4.7 Substitution across Wind Turbine Technologies

Appendix B provides a list of commercially available wind turbine models, including information on the generator technology.

The next section discusses the wind turbine technologies in more detail, but the main conclusion can be summarized here. The low market share of direct-drive turbines with PMGs in the United States and the available cost estimates suggest that, at present, in terms of costs and performance, conventional geared turbines are close substitutes for direct-drive turbines with PMGs. For turbines that contain PMs, firms could consider other technologies used in wind turbines, including (a) gearbox technology, (b) lower-grade NdFeB magnets, and (c) hybrid PMGs. The substitution of low-grade NdFeB magnets in direct-drive and hybrid turbines appears to be an ongoing research effort in industry (Totaro 2011).[8]

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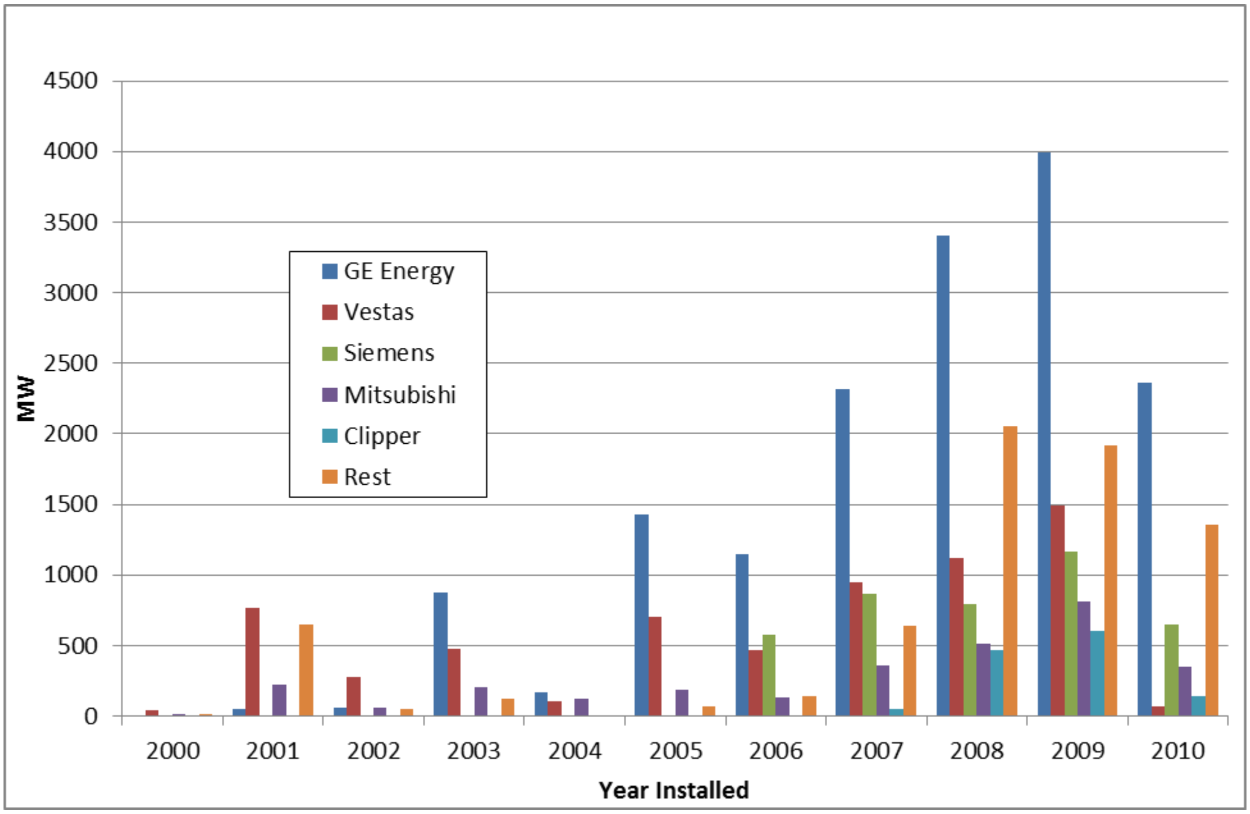
[8] Data are not available to estimate the extent to which firms have done this.

2.5 Nd and Dy Demand for U.S. Wind Turbine Installations

In this section, we focus on Nd and Dy demand for U.S. wind turbine installations only. We were unable to find reliable and detailed information for the market share of global PMG wind turbine installation. In the previous section, we estimated U.S. imports of NdFeB magnets in 2010 to be about 6,000 tonnes. However, no information about the share actually used by the U.S. wind turbine industry is available. We estimate Nd and Dy demand based on wind turbine installation and other information about material contents, including NdFeB PM content in PMGs and Nd and Dy content in NdFeB PMs. Below, we discuss these estimates in detail.

Figure 6 shows U.S. wind installations by manufacturer for the years 2000 to 2010. The incremental capacity peaked in 2009 and then dropped by about 50 percent in 2010. In 2010, the top five wind installations by manufacturers are GE Energy (48 percent), Vestas (13.4 percent), Siemens (13.2 percent), Mitsubishi (7.2 percent), and Clipper (2.8 percent).

Figure 6. U.S. New Wind Installations by Manufacturer



Source: American Wind Energy Association 2011.

Table 13 rovides greater detail for the years 2008 to 2010. In recent years, GE has had the largest market share of turbine installations in the United States (40–47 percent by capacity, 2008–2010). Vestas, Siemens, Mitsubishi, and Clipper, combined, account for an additional 25–40 percent of the market.

Table 13. U.S. Wind Installations by Manufacturer, 2008–2010

Manufacturer	2008	2009	2010
GE Energy	3403.5	3994.5	2362.6
Vestas	1120.64	1488.71	66
Siemens	791.2	1161.5	648.6
Mitsubishi	516.4	814.4	352.8
Clipper	470	605	140
Rest	2052	1914	1353

Source: American Wind Energy Association 2011.

To infer which installations include REs, we use data on the turbine manufacturer and turbine size for all wind projects in the United States from 2008 to 2010 (American Wind Energy Association [AWEA] 2011 and EIA 2010). We find that Clipper was the only manufacturer to install large turbines with REs during this period in the United States.

Using U.S. wind installation data as well as information provided by DOE on the Nd and Dy contents of NdFeB PMs, we estimate the NdFeB PM, Nd, and Dy demand for wind turbine installations between 2008 and 2010. As shown in Table 14, we estimate that the turbines installed in 2009 contain 10–48 tonnes of Nd and 1–13 tonnes of Dy. The total RE content for turbines installed in 2010 was significantly lower because Clipper installed fewer turbines. (Total wind turbine investment was also much lower in 2010 compared to 2009, and the Chinese export restrictions probably are not the driver behind the decrease in Clipper's activity.)

NdFeB PM demand for wind turbine installations in 2010 was between 14 and 35 tonnes. Compared to NdFeB PM imports for 2010, which was about 6,000 tonnes, the PM demand for wind turbines was very small. Our high estimates for Nd and Dy demands are 11 and 3 tonnes, respectively. Compared to estimates of Chinese Nd and Dy production (15,000 tonnes and 840 tonnes, respectively), their estimated use in U.S. wind turbines is very small.

Table 14. Estimated U.S. Wind Demand for NdFeB PMs, Nd, and Dy (2008–2010)

Year	U.S. wind installed (MW)	% with magnets	Range of PM (tonnes)	Range of Nd (tonnes)	Range of Dy (tonnes)
2008	8,353	5.6	48–120	7–36	1–10
2009	9,978	6.1	64–159	10–48	1–13
2010	4,923	2.8	14–35	2–11	0–3
Total	23,254	5.3	126–313	19–94	3–25

Notes and Sources: Unpublished calculations by Resources for the Future using AWEA wind installation data, information compiled on specific turbine models (in Appendix B), a range of estimates of the amount (in kilograms) of PMs per megawatt in direct-drive and hybrid models, and a range of estimates of the percentage (by weight) of Nd and Dy in PMs.

2.6 Recycling

For both technological and economic reasons, very little recycling of REOs currently takes place, even though the prices of Nd and Dy have increased nearly 8 and 10 times, respectively, over the last three years (Lynas Corporation, Ltd. 2011b).[9] Such very high prices of REEs could make recycling attractive. Future shortages could cause sustained higher costs for these materials, providing a greater incentive for recycling. A 2011 USGS report estimated that, in 2008, 76 percent of Nd oxide and 100 percent of Dy oxide was consumed by NdFeB PMs. No estimates for manufacturer-generated scarp are available. NdFeB magnets have the potential to be recycled, remanufactured, and reused because the magnets can be removed from the assemblies in which they are used (USGS 2011a).

Until recently, however, there has been no evidence of ongoing recovery and recycling. There are some barriers for NdFeB recycling. First, most NdFeB magnets are nickel-plated, which complicates recycling. Second, NdFeB magnets often corrode with use, which increases the cost to recover useful elements (USGS 2011a). Re-melting contaminated NdFeB magnets results in low yields and often is not economical. When the NdFeB magnet has degraded or shows signs of corrosion, it is likely that the material will not reprocess satisfactorily and will require refining to remove oxides and hydroxides. Third, recycling poses challenges related to intellectual property rights. Japanese patents exist for the processes involved in recycling magnets, including the recovery of scraps of RE magnets (e.g., JP58136728, JP2002348632); the separation and recovery of RE metals (JP62187112, JP58193331); and the recovery of magnetic powder from bonded magnet materials (e.g., JP2001143916, JP2001110615; Goodier 2005).

Japan is the world’s largest importer of REs. Many Japanese companies and the government have invested R&D on RE recycling efforts as China has reduced its exports. Hitachi has developed technology to recover RE magnets from compressors and hard disk drives, and has successfully extracted REs from NdFeB magnets (Hitachi, Ltd. 2010). Copper processor Mitsubishi Materials Corp. has started recycling ventures with Panasonic Corp. and Sharp Corp. to research the extraction of Nd and Dy from washing machines and air conditioners (Clenfield et al. 2010). Showa Denko has established an RE metal recycling plant in Vietnam (Bloomberg 2011).

2.7 Prices

In this section, we conduct a simple calculation to approximate roughly the impact of Nd and Dy material costs on the capital cost of wind turbines. We provide a very crude estimate of the cost share of Nd and Dy materials in wind turbine manufacturing, and we investigate the implications for the wind turbine industry of recent increases in RE material prices.

The four charts in Figure 7 show the Nd (top) and Dy (bottom) prices both in China (left) and free on board (FOB, right) between March and September 2011. Using these data as inputs, along with Nd, Dy, and PM content information, we estimate RE costs per megawatt and the ratios of RE costs in total

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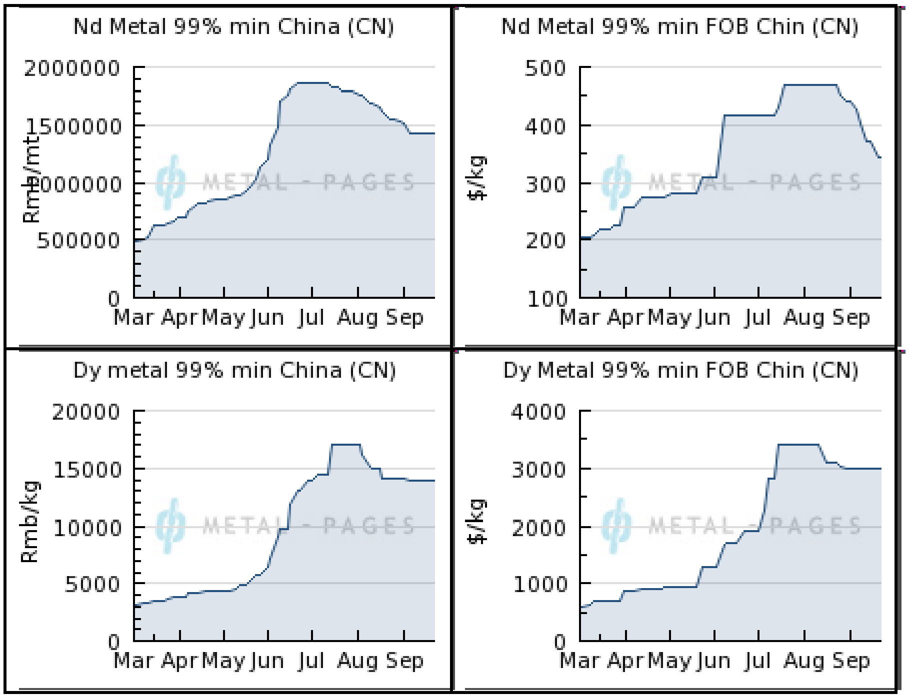
[9] The prices of REOs reached a record high in summer 2011 and then declined about 50 percent by the end of 2011. Even though the prices have decreased a bit, they are still high compared to three years ago. The Nd price reached a record high in mid-July, 2011, and then dropped about 30 percent by late September. The Dy price reached a record high at about the same time, after which the price decreased and stabilized. Prices are expected to remain relatively constant. The prices of REs have fallen for several reasons, including selling by speculators, Tsunami- related disruptions in Japan, and industrial recycling and substitution (Bloomberg 2011).

overnight capital costs (OCC)[10] for different PMG technologies and for the March and July 2011 periods. We assume that wind turbine OCC is $2 million/MW. We assume that every PMG technology has a PM content in kilograms per megawatt, and that all PMs have fixed Nd and Dy weight percentages. We assume 28 percent and 6 percent for Nd and Dy, respectively.

The results show that the share of Nd and Dy materials costs in total wind turbine capital costs are between 0.7 percent and 4.6 percent using March 2011 Nd and Dy material prices. The variation is from the wind turbine technology and the range of magnet content considered. The Nd and Dy material cost share could go as high as 17 percent using July material prices.

Figure 7. Nd (Top) and Dy (Bottom) Metal Prices in China (left) and FOB (right) in 2011



Notes: CN, China; FOB, free on board; Rmb, renminbi.
Source: Metal-Pages 2011.

2.8 Industry in China

Currently there are more than 100 RE smelting and separation plants in China.[11] The government plans to reduce the number of mines from more than 100 to fewer than 10, consolidate separation plants, and cut the number of separation plants from more than 100 currently to about 20 in the future (*China Securities Journal* 2010; Qi 2010).

The Chinese government has indicated that it wants large companies to lead the consolidation of the RE sector (Qi 2011). Currently, seven large companies dominate the Chinese RE sector. They include Baoto Steel Rare Earth; Guangdong Rising Nonferrous Metals Group Co., Ltd.; Xiamen Tungsten Co., Ltd.; Ganzhou Rare Earth Mineral Industry Co., Ltd.; China Non-ferrous Metal Industry's Foreign

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[10] Overnight capital cost is the capital cost of a project if it could be constructed overnight. This cost does not include the interest cost of funds used during construction.

[11] An example list can be found at Goodlawyer.cn (2011).

Engineering and Construction Co., Ltd.; Aluminum Corporation of China; and China Minmetals Corporation (Baidu 2010).

Because of the consolidation and limited quota allocations, many separation plants are running out of their supply of RE raw materials. These separation plants have considered options, such as recycling the residuals from previous operations, and shutting down operations (Sina.com.cn 2011).

2.9 Summary of Supply Chain Findings

We have developed a comprehensive framework based on the principles of MFA to identify the supply chain of Ny- and Dy-containing PMs used in wind turbines. We find that the RE reserve is large and that, in the long run, global reserves and undiscovered resources are expected to be sufficient to meet demand. However, concerns about short-term supply arise because new mining projects may take 10 years or longer to reach production (Humphries 2011). Our discussion is severely limited by data gaps, including inconsistency in the data about RE supply and a lack of international trade data for Nd and Dy as well as for Nd- and Dy-containing commodities.

China's RE export quota decreased 40 percent over the last three years. China is likely to continue to exercise export quota limitations. The Chinese government has a plan to consolidate the country's RE sector and to better control such resources. The Chinese government is also encouraging large companies to spearhead the consolidation of the country's RE sector. Other companies are consolidating as well. These changes occur frequently, and it is difficult to capture them here. For example, both Molycorp and Lynas are actively seeking vertical integration. Molycorp is expected to reach a production capacity of 19,050 tonnes/year by 2012 and 40,000 tonnes/year by 2013. Mount Weld of Lynas is expected to have a production capacity of 22,000 tonnes/year by 2012. Molycorp has formed a joint venture with Japan's Daido Steel and Mitsubishi Corp. to manufacture and sell high-powered RE magnets, and Molycorp also invests in Boulder Wind Power's Dy-free PM wind turbine technology. Lynas and Siemens have established a joint venture for magnet production for wind turbine generators.

Substitution and recycling could be good options for addressing Nd and Dy supply issues. NdFeB PMs have the strongest magnetic energy density and are the most powerful commercial magnet existing today; it may prove difficult to find exact substitutes for NdFeB PMs in wind turbines in the near future. Companies may choose to reduce PM demand through technology innovation and better wind turbine system design by actions such as (a) substituting away from PMs in favor of gearbox technology; (b) using a more efficient or economic system design, such as hybrid PMGs; or (c) using lower-grade magnets in both direct-drive and hybrid PMGs (Totaro 2011).

3. Industrial Organization along the Nd and Dy Supply Chains

3.1 Overview

In at least three ways, the industrial structure of the RE supply chain,[12] from initial mining to the installation of wind turbines using RE alloy magnets, may raise some concerns regarding competition (which we distinguish from "competitiveness"). In all cases, the validity of the concerns with regard to the exercise of market power should be qualified.

Single country as primary supplier. First, in the case of Nd and Dy, the global supply at present (e.g., as much as an estimated 97 percent of the world supply of Nd) comes almost entirely from one country, China.[13] Supplies coming from a single country are not problematic if separate suppliers in that country act competitively, but whether this is true in this instance requires examination.

Vertical integration. The second factor that may raise market power concerns is the widespread presence of vertical integration—or its close cousin, long-term contracts—in the supply chain. For example, as the CMS report (DOE 2010) and our subsequent research indicate, Nd and its refinements into oxides and alloys are not widely traded on open exchanges. Rather, they generally appear to be provided under long-term contracts to particular manufacturers. In addition, the CMS report observes that this reduces "transparency" in the market (DOE 2010, 93–94).[14] Because vertical integration internalizes transactions and reduces the ability of firms to participate in only single stages of production, it may make markets look less transparent.

Export quotas and limitations. A third factor involves a country's limitations on the exports of RE ore and oxides.

We examine these issues in turn. First we look at issues relating to market power: why market power is difficult to measure, particularly in the Chinese institutional context; the potential harms resulting from market power, both from a profit-maximizing and a geopolitical perspective; and our present sense of the likelihood of those harms. Market power need not be a concern if that 97 percent were supplied competitively, but to the extent that China can and does control the output of its suppliers through export fees or quotas, that 97 percent could be regarded, from the perspective of the rest of the world, as the output of a single supplier. Even with that, a large market share need not imply power over price, and we discuss below some of the relevant factors that affect the vulnerability of the United States and other buyers along a RE supply chain.

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[12] The issues for Dy appear somewhat similar, but Nd appears to be a more significant RE in supply chains, including U.S. and international wind energy markets.

[13] An issue relevant to the market power discussion is that, with respect to Nd, our understanding from the 2010 CMS report is that two firms hold "master patents" on Nd alloy magnets, and only one of those appears to affect PMs for wind turbines (DOE 2010, 17; the discussion on p. 16 highlights that two firms hold patents over the manufacture of PMs, but Figure 2.2 on p. 17 indicates that only a firm in Japan holds patents relevant for manufacturing magnets in the wind turbine supply chain). This raises concerns that the holder of the patent relevant to wind turbines would extract market power, limiting that which China could obtain through unified control of its domestic mining and refining companies. We discuss the role of patents below in sections on market power and vertical integration.

[14] Our research revealed a further complication in getting reliable information: claims that a substantial portion of Nd sales from China take place "off the books." It is almost by definition difficult to know how such sales affect the supply chain. Because our concern is how Nd supplies ultimately affect the wind turbine sector, our surmise is that consumers of PMs for wind turbines require reliable and predictable sources, which is inconsistent with a significant reliance on a black market–like part of the supply chain.

We then turn to vertical integration. Although that integration reduces transparency, it is important to recognize that, in general, vertical integration is desirable and does not enhance market power beyond the ways in which more efficient organization can make a firm a more formidable competitor. In some cases, vertical integration could enhance market power, but one has to be careful not to exaggerate those possibilities.

However, certain aspects of China's practices in the RE supply chain suggest a possible strategic effort to enhance market power over the supply chain in the future; section 3.3 sets out what this effort might entail. Although the focus is on the potential harms of this effort, it may be important that, at least at present, China imposes no restrictions on the export of magnets and other products further down the supply chain. This suggests the possibility that the objective of China's RE policies is not the exercise of monopoly power that arises from its resource endowments. Rather, the objective may be to support innovation further down the RE supply chain. We conclude with suggestions for future information gathering that might improve understanding of all of these points.

3.2 Market Power

3.2.1 Background

A firm has market power to the extent that it finds it profitable to withhold output and raise the price. It may be helpful to distinguish a firm with market power from a firm that lacks market power. A firm lacking market power acts as if its output decisions have little effect on the market price and chooses to supply its output up to the point where its cost just equals the market price. By comparison, a firm with market power holds output below that point because doing so allows it to increase profits by raising the price.

Market power matters because the ability to profit by withholding output leads to the reduction of output below efficient levels. This typically leads to prices above the marginal cost, discouraging uses that produce overall net economic benefits—that is, where the benefit to a buyer (reflected in their willingness to pay the price) exceeds the marginal cost. To economists, although perhaps not the public, the profits resulting from the exercise of market power above competitive levels are, in economic parlance, "just a transfer" between the buyers and the monopolist.

If U.S. consumers or firms are subject to market power from a foreign supplier, this conventional story changes in two respects. First, the profits gained from the exercise of market power are no longer "just a transfer" from the U.S. perspective, but a flow of wealth out of the United States to the country of the foreign supplier. Second, dependence on a single country for supplies raises the possibility that the country might threaten to raise the price above the profit-maximizing level—or maybe to withhold supply altogether—to achieve some geopolitical objective. The potential harm to the United States, should that threat be carried out, could be many multiples of the losses due solely to the wealth transfer that arises with a profit-maximizing monopolist. Such a threat would be implausible for a profit-maximizing enterprise, but perhaps not for a country with different goals.

In considering the latter possibilities, it is crucial to keep in mind that international trade is, in general, beneficial. At its heart, international trade is no different from any other trade—it takes place only when the benefits to the buyer exceed the costs to the seller. The only difference is that the buyers and sellers may be in different countries. Choices to import most or all of a particular product are no exception to this principle; in fact, they exemplify it—the benefit to importers exceeds the price they pay, and exporters get revenues exceeding their production cost. The market power concerns arise, not out of any generic concern regarding international trade, but from the effects when exporters and importers do not act competitively.

Market power is relatively simple to describe in theory, but can be difficult to ascertain in practice. Almost every supplier of a product is at least minimally differentiated from its competitors, so setting a price above its marginal cost need not drive away all of its customers. The question is the point at which an individual firm has market power.[15] Profits are not a measure, as a firm can make a lot of money because it has a cost advantage over its rivals, but still have no ability to raise the price by reducing supply. In the other direction, the presence of active competitors can be consistent with market power because a firm will typically raise the price until consumers are willing to turn to alternatives that would not be of interest at a competitive price.[16]

For these reasons, analysts typically look for a combination of indicators to determine whether a seller has market power.[17] These indicators include market share, profits, ability and willingness of buyers to turn to substitutes, quality and other characteristics of substitutes, differences between price and marginal cost, capacity limits of existing competitors, and barriers to the entry of new rivals who might otherwise limit the ability of the firm in question to raise the price.

The role of China's government complicates the measurement of market power. Although our analysis of the RE supply chain confirms the view that 95 percent or more of REs come from China, that analysis also identifies three different suppliers of those REs within China. Normally, one would not infer from this that the market has been monopolized; there are at least three significant competitors. Firms are generally the relevant competitors in a market; countries are not. By analogy, one could just as easily observe that virtually all smart phones run on operating systems from Apple, Google, and Microsoft, but it would be incorrect to infer a monopoly because, other than Blackberry, "the United States dominates that market."

Certainly, the Chinese government can act as a monopoly in setting quotas or export tariffs that help firms exercise market power over REs. This, however, leaves open the question of how prices are set within China—an important issue because, as we discuss below, the effect of China's quotas may be to encourage firms down the supply chain to transfer operations to China. We acknowledge that it may not be appropriate to draw conclusions on how Chinese firms behave based on how U.S. firms behave. Chinese firms in general, and these RE mining companies in particular, may not act as independent competitors. Rather, they may coordinate their actions under the explicit control or implicit guidance of the central government. Such controls may be part of the business culture, where a firm restrains its sales to protect its fellow competitors. That there is reportedly a significant black market in REs indicates the presence of some competition, but the reported efforts of the government to consolidate

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[15] Market power is also a factor in merger assessments, but there the question is not whether an individual firm has market power, but whether the combination of two firms will make it more profitable for them to raise the price or facilitate collusion with competitors in a relevant market (U.S. Department of Justice and Federal Trade Commission 2010). For that reason, merger guideline tests do not pertain to the question of when an individual firm has market power.

[16] The incorrect inference that the presence of competitors indicates a lack of market power is known in antitrust circles as the "Cellophane fallacy," after a 1956 Supreme Court case (U.S. v. du Pont, 351 U.S. 377 (1956)) where it incorrectly concluded that Du Pont lacked market power in Cellophane just because buyers began to use other types of wrapping materials.

[17] A theoretically sound way to ascertain whether a firm has market power would be to see what would happen if outside forces brought about a small but significant reduction in price (Brennan 2008a, 144–45). A firm with market power would no longer find it profitable to withhold output, and thus would increase sales. A firm acting like a competitive price taker would find marginal sales unprofitable at the lower price, and thus reduce output. Although this "raise or lower output in response to a price cut" test is theoretically sound, it is almost completely impractical.

supplies of REs indicates that independence may be more nominal than real when assessed across the entire market.[18]

3.2.2 China's Potential Market Power in the RE–Wind Turbine Supply Chain

Our assessment at this time, based on our above analysis of the RE supply chain, is that despite having control over the RE market, the Chinese suppliers, even if treated as a single enterprise, do not possess substantial market power, at least relative to U.S. buyers and users of wind energy. To see this, we look at some of the factors described above, focusing primarily on Nd.

Certainly, China's 95 percent-plus market share in mining and the difficulty of entering the production of REs suggests that it likely has market power at the early stages of the supply chain. In particular, China's government can use export quotas to manage foreign sales even if the mining companies otherwise act independently. Because of vertical integration, as we discuss below, market power at that stage may not show up until the production of REOs, and perhaps the magnetic alloys themselves. Down the chain, there may be some opportunities to use different concentrations of Nd alloys in magnet construction, creating some resistance to price increases.

The most important factor affecting market power is that the vulnerability of the United States to high RE prices in the near term depends on the willingness of U.S. electricity purchasers to switch to energy from generation technologies that do not rely on REs. In the near term, wind production in the United States will be primarily onshore, and for onshore production, alternative technologies for wind turbines are good substitutes for those using PMs. Moreover, for meeting renewable or clean energy targets in the United States, wind power has substitutes from other forms of electricity generation. Therefore, neither U.S. wind sectors, nor the renewable and clean electricity sectors more generally, are particularly vulnerable to the exercise of market power over Nd or other REs. If the relevant nexus of competition includes all electricity providers, the ability to impose harms on consumers through high RE prices is even smaller.

However, other sectors of the U.S. economy using REs, and the world wind turbine market, which U.S. producers may sell into, may be vulnerable to China's market power. Offshore wind, which relies on PMs, appears to be a more important part of the foreign electricity sector. Depending on economic and policy developments affecting the cost of fossil fuels and the demand for renewable energy sources, offshore wind may become a more important part of the U.S. energy landscape. Perhaps most important is that China's practices in the RE market may be setting the stage for China to dominate the ability to innovate in the RE-to-wind power supply chain in the future. Before we get to that, we should look at the role of vertical integration in the supply chain.

3.3 Vertical Integration

It is important to begin with the observation that vertical integration is not a binary "yes or no" aspect of the organization of an industrial supply chain. It represents one end of a continuum of ways to coordinate the supply chain. At the other end are transactions in spot markets between unrelated buyers and sellers. Between the two endpoints, one observes contracts that involve varying lengths of time, quantities of goods bought and sold, transaction prices, performance incentives, and terms and conditions regarding product quality, delivery, and the like. As the contracts expand over longer terms

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[18] The relevance to the RE supply chain of those "spot" sales is at least an open question. As we discuss below, a business depending on steady supplies of REs at known purities is unlikely to find a black market an adequate source of supply.

and cover the quantities and conditions of sale with greater specificity, they begin to look more and more like explicitly joint ownership and coordinated control of buyer and seller activities—that is, vertical integration. And even within vertical integration, the management of the entity can impose varying degrees of control and reward systems as well.

In these various guises, vertical integration and long-term contracts are organizational strategies designed to improve operations and reduce costs along the supply chain by (a) avoiding the costs of using markets, (b) sharing costs, (c) improving coordination, (d) encouraging complementary investments, (e) insuring against supply volatility, and (f) mitigating market power harms. This breadth of possibilities reflects a second important aspect of vertical integration—its ubiquity. Vertical integration is a routine aspect of almost every economic organization in a minimally advanced economy. It would be difficult to find a supply chain without some vertical integration or long-term contracting within it at some juncture. The RE supply chain is no different.

We elaborate on the rationales for vertical integration, point out where they probably apply in the RE supply chain, and help explain the reportedly large extent of vertical integration in this supply chain, particularly in its upstream stages.

Avoiding costs of using markets. Buying or selling in markets is not without costs. For example, spot markets can offer lower prices, but buyers must search for suppliers, verify that they have the products to meet their needs, and monitor the quality and performance of the products. Vertical integration and its close cousin, the long-term contract, are best regarded as benign methods for reducing those costs associated with search, verification, and monitoring of quality and performance (Coase 1937).

With regard to REs, it is worth noting that when vertical integration or long-term contracting is the dominant form of organization in a supply chain, one will not observe transactions between nonintegrated buyers and sellers. This suggests a paradox between the reported extensive use of vertical integration at the early stages of the supply chain and the existence of historical RE price data (e.g., DOE 2010, 46, Figure 3.4), which normally imply spot transactions at which prices can be measured. Ian London of Avalon Rare Metals in Toronto has told us that these “prices” are not actual transaction prices, but based on estimates from buyers who procure REs under long-term contracts. Another expert, Prof. Karl Gschneidner in the Materials Science and Engineering Department at Iowa State University, has told us that these reported commodity prices come from transactions outside of standard Chinese supply channels that, for reasons suggested below, may be of limited relevance to the cost of Nd that eventually makes it into wind turbines.

Shared costs. Different stages in the supply chain may be combined within a single enterprise simply because producing at one stage may reduce the costs of producing at other stages. The general term for this is *economies of scope*—the idea that it is cheaper to do two things together rather than separately.

Internalizing externalities. A closely related idea begins with the observation that, in all but the simplest supply chains, there will be instances where decisions at one stage of the supply chain affect costs or demand at other stages. The design of a product made at one stage often depends on the nature of the inputs that go into making that product or aspects of production, distribution, or marketing at other stages of the supply chain. This creates a need to coordinate actions across two or more of these stages. Centralizing control across stages—within a firm—is the most direct means to achieve that coordination. A possible example in REs would be coordinating the design of mineral-refining facilities with the scheduling and availability of materials from a particular mine.

Encouraging investments in specific buyer–seller relationships. The need to coordinate across stages in the supply chain usually entails investments at those stages specific to a particular supplier. This sets up the possibility that, after one side initially sinks significant costs to work with a specific supplier or buyer, the other side could threaten not to cover the sunk costs. The initial investor, foreseeing this eventuality, will be reluctant to make these client-specific investments, to the detriment of both parties and to the economy as a whole. Recovery of the costs of those investments often cannot be guaranteed without a long-term contractual commitment or vertical integration (Klein et al. 1978).

Our research indicates that this "asset specificity" rationale applies particularly to Nd, and particularly at the early stages of the supply chain. Plants that refine the ores are located near the mine to minimize transportation costs and, we understand, are designed to process the type of ore that comes out of the mine.[19] In addition, PM manufacturers design their processes to work with ores or alloys with the purity produced by a particular supplier, and thus will have long-term relationships, if not outright integration, with those suppliers. Finally, turbines need to be designed around the magnets that will fit into them and vice versa, suggesting that long-term contracts between magnet producers and wind turbine manufacturers are likely.

Insuring against volatile supply or demand. In some markets—and RE markets appear to be among them—prices or, equivalently, availability of supplies can be highly volatile. This presents a risk that buyers and sellers might like to avoid. An important economic function of long-term contracts or vertical integration is that it provides insurance against price volatility. The contracts can include all manner of terms to manage the price risk.

Preventing "double marginalization." In some cases, firms with substantial market power may dominate different stages in a supply chain. If these firms set prices independently to maximize their profits, each firm will not take into account that the higher the price at one stage, the lower will be demand and profits at the other stage. If these firms merge, they will recognize these profit effects when setting prices, resulting in lower prices at each stage and overall, and benefiting not just themselves but also the consumers at the end of the supply chain.

That said, ascertaining the actual degree of vertical integration in the supply chain, especially the Chinese component, is difficult. The reasons are the same aforementioned reasons for the difficulty of determining whether nominally separate companies within a stage of the supply chain act competitively or collectively. Whereas in the United States, the strength of the ties between firms at different stages of the supply chain can be determined by looking at records of ownership or contracts, in China, firms may appear independent but act by taking each other's interests into account because of implicit ties or explicit central control.

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[19] Lynas, an RE mining company in Australia, is planning to transport its REs to a plant in Malaysia, "due to the readily available industrial infrastructure, including industrial land, sources of gas, water and electricity, re-agents from local suppliers and a port that can manage container, chemical and bulk shipments. The area where the plant is being built also offers much knowledge infrastructure, such as technical and trade skills and chemical industry experience. The government infrastructure is in place and provides accountable regulators, clear legal frameworks and FDI incentives" (Lynas Corporation, Ltd. 2012). Refining and mining are vertically integrated, with the Malaysia refinery designed to process ore from the Mount Weld mine in Australia. Apparently the advantages listed by Lynas in refining REs in Malaysia rather than Australia justify the cost of ocean transport of the ore to Malaysia.

One also needs to know just what it is that nominal entities within the supply chain in China do. To take an example, our investigation revealed that dozens of entities in China hold rights to export specific amounts of Nd under the quota. At first glance, this indicates a lack of vertical integration somewhere between the mining of ore containing Nd and the ability to supply refined Nd metal. However, the dozens of export rights holders on this list need not be actual producers; they may be nothing more than sales agents for the actual producers of ore, or intermediaries who can buy that ore from those who produce it and profit from the license to export.

This favorable picture of vertical integration is not without its criticisms or exceptions. A longstanding concern is that a monopolist uses its vertical integration to expand its profits and to make it harder for other firms to enter markets because entry at multiple stages is required. A concern in this context would be China expanding from a monopoly in RE mining and refining to further production stages in the supply chain. This concern, though, fails to recognize that a monopolist in one stage of a supply chain generally should benefit from enhanced competition at other stages, whether that monopolist is a single firm unto itself or whether China exercises control so that its nominally separate domestic producers act as a single supplier. That competition raises demand for the monopolist's products and therefore its profits. Were there a firm with market power at another stage, profits would fall because of the "double marginalization" phenomenon described above.

The extreme version of this argument, the "single monopoly profit" argument, says that vertical integration can never be harmful because a monopoly at any stage of the supply chain can extract all of the profits obtainable throughout the supply chain, making vertical integration inconsequential (Bork 1978, 228–31). This theory generally requires that the monopolist's product is used in a fixed ratio to final output in the supply chain; otherwise, attempts to raise its price will induce substitution with other inputs coming from other branches of the supply chain. Although this substitution may mitigate the ability of an input monopolist to raise prices, it unfortunately leads firms to choose their inputs in ways that do not minimize the underlying cost of production. For example, in principle, higher magnet prices could cause a wind generator or turbine designer to use different tower heights or turbine sizes.

In addition, the "single monopoly profit" principle will not hold if regulation limits the ability of the monopolist to raise price directly, in which case vertical integration can enable a firm to exercise market power in ways that the regulation was designed to mitigate.[20] Vertical integration can also facilitate charging different prices to different buyers, which could be beneficial when doing so allows those with lower willingness to pay to purchase the product at a lower price. In addition, vertical integration can raise market power concerns if vertical partners would have otherwise competed in each other's markets.[21] For example, vertical integration between an automobile monopoly and a steel monopoly could have anticompetitive consequences were there reason to believe that the steel monopoly was the most likely potential entrant into automobile manufacturing or that the automobile

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[20] The leading example would be for a price-regulated firm to enter an unregulated market for a good or service that depends on the quality of access to the regulated product, as well as its price. That vertically integrated firm would then have an incentive to discriminate against its competitors in the unregulated market, creating an artificial competitive advantage that allows it to raise the price in that market. In effect, it indirectly exercises its market power over the regulated product, despite the regulation that limits its ability to do so directly by charging the monopoly price for its unregulated product. This concern has been a leading reason why the Federal Energy Regulatory Commission has required regulated transmission companies to be operated through entities independent of generation companies that might use control over access to impede competition in wholesale power markets (Brennan et al. 2002, ch. 7).

[21] The possibilities in this paragraph are discussed at length in Farrell and Weiser (2003, 105–19).

company was likely to go into the steel business.[22] In highly specialized settings, vertical relationships could have strategic consequences that could deter entry and create market power (Tirole 1989; Carlton and Waldman 2002).

Recognizing the considerations that limit the applicability of the "single monopoly profit" theory, it remains the case that the more profit a monopolist at one stage of the supply chain extracts, the less remains to be extracted by the creation of monopoly at other stages. This last consideration is particularly relevant to the RE supply chain. The CMS report (DOE 2010) notes that two firms, one Japanese and one Chinese, control patents on the manufacture of Nd-based PMs used in wind turbines, but only one, Hitachi in Japan, holds a patent relevant to the process used to produce magnets used in wind turbines (DOE 2010, 16–17). To the extent that this duopoly leads to the exercise of market power at this stage of the supply chain—and as noted above, it need not—the market power that China could extract through its control over the supply of REs is further limited.

3.4 Export Quotas

So far, it appears that, although China may have market power over REs, it has a limited ability to affect the supply chain. Moreover, concerns that the industry is characterized by widespread vertical integration are not well founded. Such integration appears more likely to be motivated by a host of actions to promote efficient production and reduce costs and prices than the reverse.

Nevertheless, China has continued to set quotas on RE exports. To the extent that a country has market power, its quotas and tariffs could be viewed as a way to raise prices and national income by restricting output. Were profit maximization the goal, however, the country would charge its own domestic RE users the same high price foreign users have to pay as a result of the export quotas. Using REs as an example, if a foreign buyer could turn REs into alloys, magnets, or wind turbines at lower cost than competitors within China, it would be willing to pay more for the REs; China would lose money by favoring domestic suppliers.

This story is predicated on market power, and our analysis so far indicates that conditions in the wind generation sector, particularly in the United States, mitigate any adverse domestic effects of market power. Quotas, however, could have a strategic effect in this context worth future investigation and analysis. Some press reports suggest that companies farther along the supply chain that relocate to China can obtain REs on more favorable terms than foreign suppliers (Bradsher 2011). These advantages could take the form of lower prices or the ability to obtain explicit or implicit long-term supply guarantees without being exposed to high price volatility. If—and this may change—China does not impose quotas or tariffs on products that include REs, producers who relocate to China obtain a competitive cost advantage over those who do not. This creates an additional incentive to relocate operations to China, over and above other advantages of producing in China, such as lower labor costs (Lifton 2009). Moreover, if these downstream products are available at competitive prices because REs are available in China as a result of competition among the three leading suppliers, then the RE quota is of even less consequence to buyers along the supply chain.

The combination of lower costs and better access to REs in China, along with an absence of similar quotas and export controls on magnets or turbines produced in China, indicate that the purpose of the

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[22] The possibility that, in effect, vertical integration between browsers and computer operating systems could preempt the evolution of competition between them as browsers become application platforms was at the heart of the U.S. Department of Justice's antitrust case against Microsoft (Brennan 2001).

RE quotas is not so much to exploit market power over REs but to encourage domestic production in China. The question is why. For answers, we can only speculate because of the uncertainties regarding the operation of firms in China that we discussed in relation to market power and vertical integration. In principle, multiple firms moving to China would still be independent actors, with no anticompetitive consequences—even if the lion's share of downstream manufacturing relocated to China.[23]

The story changes, however, if these firms are not independently competing profit maximizers, but are instead managed collectively by the Chinese government. Relocation of a dominant share of manufacturing to China may have an effect if those firms were managed or owned collectively. One possibility is that operating in China would give the Chinese access to knowledge of production processes and potential routes to innovation. If all those firms operate in China, and if the knowledge from each were to be exploited through a single entity within China, this knowledge could then perhaps be combined to give that entity an advantage in innovating and result in the future monopolization of PMs, wind turbines, or other products.[24]

In short, China could use its monopoly over REs to induce downstream firms to relocate to China. China could then obtain access to manufacturing knowledge from firms that relocate to China.

3.5 Future Research and Data Needs

It is crucial to say that much of this discussion is speculative, given severe data limitations and the short recent time span of these current events. That said, our discussion suggests important avenues for future investigation. With no quotas or tariffs farther along the supply chain, the economic effects and justifications of quotas or tariffs at one stage are relatively subtle. Understanding them may require intimate knowledge of how firms operate within the countries that act as sole providers—in our case, the pathways by which Chinese suppliers might obtain knowledge that would otherwise be proprietary.

This concern also requires verification of the size of the incentive to relocate. If REs are available within a country only at the same monopoly prices paid by producers outside the country, the quotas provide no price differential and no incentive to innovate. Judging the size of this differential would be usefully informed by knowledge of the extent to which the three nominally separate RE mining companies in fact operate collectively through either implicit norms or explicit public control. In this context, information from firms that have relocated to China can help us understand the advantages, if any, of preferential access to REs in China created by the export quota system. These firms can also tell us the extent to which they are able to maintain proprietary control over production process information.

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[23] Relocation may have dislocation effects; other sections of this report describe the potential effects of relocation and high RE prices on U.S. labor markets.

[24] The theory of how a firm could exclude rivals from a market by monopolizing markets in complementary goods, such as inputs, is set out in Brennan (2007, 2008b, 2011).

4. Effects of the Nd and Dy Supply Chain and Industry Organization on the Wind Sector, Employment, and Welfare

4.1 Overview

This chapter complements our discussion of the supply chain and industry organization by focusing on developments that could adversely affect U.S. labor markets and electricity markets. Employment in manufacturing products used in wind turbines has increased steadily in the past several years, but vertical integration in the production of RE PMGs and the relocation of manufacturing to China and other countries could significantly reduce U.S. employment. There are also concerns that concentrating the production of RE PMGs among a few foreign producers could increase the cost of policies that promote cleaner electricity generation, such as renewable portfolio standards.

We discuss the available evidence related to the effects of vertical integration and the location of manufacturing outside of the United States. These effects depend on the substitutability and horizontal structure of the wind turbine industry, as well as likely future employment levels. Consequently, the first two parts of this section discuss available data on substitution across wind technologies, horizontal integration, and employment.

The final part of this section discusses the long-run implications of vertical integration and of locating manufacturing outside of the United States. We discuss qualitatively the conditions under which these developments would have large adverse effects on the U.S. wind industry and on U.S. electricity consumers.

4.2 Wind Turbine Technologies

The analysis includes the geared turbines, PMDDs, and hybrid PMGs—that is, the first- and second-generation technologies. Throughout, we use PMGs to refer to direct-drive and hybrid technologies. Consistent with the supply chain analysis, we do not include superconducting technologies, which are not yet commercialized and for which much less information about cost and performance is available.

We discuss technologies separately by application—that is, offshore vs. onshore. We first discuss differences in performance and operation across technologies and applications, and then discuss costs.

4.2.1 Performance and Operation

As of 2010, geared turbines account for nearly the entire U.S. market for new wind turbines—perhaps 95 percent as estimated in section 2.5. For large turbines, the blades rotate at a lower speed than necessary to generate electricity to be supplied to the grid. The gearbox increases the rotational speed from roughly 10–20 rotations per minute (rpm; i.e., the speed of the wind blades) to over 1,000 rpm in the turbine itself. Although wind turbines are designed to last at least 20 years, the gearbox often fails within 5 years and needs to be repaired or replaced. The gearbox thus accounts for a significant share of maintenance costs.

The geared technology evolved in the late 1990s from multiple-stage gearboxes to variable-speed gearboxes; this has improved performance and reduced noise from the blades. Previously in the United States, most turbines had a capacity below 1.5 MW, but recently turbines with a capacity of 1.5

MW or greater have become more common; average turbine size doubled between the years 2000 and 2009, from 0.88 MW to 1.74 MW (Wiser and Bolinger 2010).

For several reasons, PMDD turbines are gaining increasing importance in the U.S. and world energy sectors.[25] PMDDs have a few advantages over direct-drive generators that use other types of magnets: (a) PMDDs weigh less (although they weigh more than a conventional geared system because the lower rotational speed necessitates a larger-diameter magnet), which reduces the costs of the tower and other components, and (b) they are more efficient. On the other hand, design and operational challenges arise because of the need to employ advanced electronics and to maintain very small gaps between rotors and stators.

Compared to a geared system, the main advantages of a PMDD are the simpler design and the reduced maintenance costs. However, a large amount of Nd and Dy is needed in a PMDD; this increases the sensitivity of turbine costs to the costs of Nd and Dy.

Hybrid generators incorporate PMs in geared turbines, and are becoming more common in the U.S. and world markets. Hybrid generators typically have a smaller and simpler gearbox than a conventional geared system, with the goal of improving the reliability of the gearbox. Because the gearbox increases rotational speed, a smaller magnet is needed than on a PMDD; this reduces the cost of the magnet and the sensitivity of the turbine costs to the costs of Nd and Dy. In other words, the hybrid technology attempts to combine the advantages of the geared and PMDD technologies while reducing their downsides.

It is important to distinguish between onshore and offshore applications. From a technological standpoint, the main benefits of offshore wind are that (on average) the wind resource is greater than even the best onshore locations (Musial and Ram 2010), and the temporal correlation between generation and electricity prices is greater than for many onshore locations. Capital and operating costs, however, tend to be much higher for offshore compared to onshore wind. The greater costs arise partly from the larger systems and also because the best locations are often far from shore, which creates significant engineering and construction challenges. Installing turbines offshore is much more complicated than onshore, even in shallow water. Maintenance costs are also much higher because of the difficulty of accessing and repairing offshore turbines.

For offshore applications, PMDDs enjoy the same two advantages over geared turbines as for onshore applications. The difference between offshore and onshore is that the advantages of PMDDs may be greater for offshore than for onshore. The high-quality offshore wind resource increases the benefit of using very large turbines. Onshore, turbine size is limited by trucking constraints that are less important for offshore installations. The simpler design of a PMDD compared to a geared turbine may make it easier to scale up the turbine to larger sizes. Furthermore, by eliminating the more troublesome gearbox, the PMDD would have significantly lower maintenance costs than geared turbines.

4.2.2 Costs

We have reviewed the literature and computational models (e.g., EIA's National Energy Modeling System [NEMS]) and have compiled estimates of the cost of generating electricity from wind turbines.

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[25] Enercon produces direct-drive turbines that do not contain PMs. However, in the current U.S. market, direct-drive corresponds to PMGs.

Although some important data are missing, we do not find strong evidence that PMGs enjoy a significant cost advantage over geared turbines.

Tables 15 and 16 show several estimates of the levelized cost of energy (LCOE) for onshore and offshore wind turbines. LCOE is defined as the discounted costs over the life of the wind turbine divided by the discounted energy production. Costs include the cost of constructing, operating, and maintaining the turbine, as well as financing costs, taxes, and decommissioning costs. Energy production depends on the size of the turbine and the capacity factor, which measures the fraction of theoretical capacity actually used at the site. For example, the National Renewable Energy Laboratory's (NREL) Strategic Energy Analysis Center model assumes an average capital cost (i.e., overnight cost) equal to $1,820/kW for a 100-MW onshore wind farm; this implies a total construction cost of $182 million. The model assumes a 43 percent capacity factor so that the 100-MW farm produces 376,680 MWh/year (100 MW × 43 percent × 8,760 hours/year; see table notes for further details on the assumptions).

Because of our interest in comparing technologies, we wish to focus on the costs of constructing, operating, and maintaining wind generators. However, LCOE depends on many factors, making it difficult to compare the estimates from the different studies. Differences could arise because of different assumptions about the technology costs (capital costs, operating costs, and maintenance costs), because of different financial assumptions (financing structure and taxes), or because of different capacity factors. Simply comparing LCOE across studies could yield misleading conclusions about the extent to which they agree about the technology costs. Therefore, in addition to reporting the LCOE estimates from each study, we estimate LCOE using the technology costs from each study and a consistent set of financial and capacity factor assumptions.

Table 15. LCOE Estimates for Onshore Wind

Source	Year of estimate	Size (MW)	OCC ($/kW)	Variable O&M cost ($/MWh)	Fixed O&M cost ($/kW-year)	Capacity factors (%)	Plant lifetime (years)	LCOE ($/MWh)	Simple LCOE calculation ($/MWh)
EIA NEMS	2011	100	2,409	0	27.73	40–46	not fixed	—	$76.66
EIA NEMS	2009	50	1,872	0	31.51	44	not fixed	$68.87	$62.42
DOE GPRA	2009	50	1,508	0	25.72	43	20	$39.21	$50.38
NREL-SEAC	2008	100	1,820	5.42	12.46	43	20	$53.12	$60.91
PNNL MiniCAM	2008	50	1,300	6.15	13.09	42	30	$42.30	$46.98
EPA IPM	2009	50	—	0	31.5	39	not fixed	$66.47	—
EPRI MERGE	2009	100	—	—	—	35	30	$122.93	—
IEA	2010	150	2,109	8.79	0	41	not fixed	$70.47	$68.98

Table 16. LCOE Estimates for Offshore Wind

Source	Year of estimate	Size (MW)	OCC ($/kW)	Variable O&M cost ($/MWh)	Fixed O&M cost ($/kW-year)	Capacity factors (%)	Plant lifetime (years)	LCOE ($/MWh)	Simple LCOE calculation ($/MWh)
EIA NEMS	2011	400	6056	0	86.98	43–45	not fixed	—	$197.65
EIA NEMS	2009	100	3796	0	93.06	40	not fixed	$141.76	$134.89
DOE GPRA	2009	100	3016	0	135.64	36	20	$93.79	$124.78
NREL-SEAC	2008	100	2548	17.34	16.26	45	20	$80.03	$94.69
IEA	2010	300	4394	23.92	0	43	not fixed	$141.76	$149.32

Notes and Sources (for Tables 15 and 16): EIA (2011b, 97); Tidball et al. (2010); International Energy Agency (IEA 2010, 62). Tidball et al. is an NREL report that cites six different LCOE estimates: EIA's Annual Energy Outlook using the National Energy Modeling System model (EIA NEMS); DOE's Government Performance and Results Act using the MARKAL model (DOE GPRA); NREL-Strategic Energy Analysis Center using the Regional Energy Deployment System model (NREL-SEAC); the Pacific Northwest National Laboratory's Mini Climate Assessment Model (PNNL MiniCAM); the U.S. Environmental Protection Agency using the Integrated Planning Model (EPA IPM); and the Electric Power Research Institute's Model for Estimating the Regional and Global Effects of Greenhouse Gas Reductions (EPRI MERGE). EIA cost estimates incorporate lead times of three years for onshore wind and four years for offshore wind. All estimates assume 7 percent discount rates except IEA, where the discount rate shown is 10 percent.

The two rightmost columns of Tables 15 and 16 show the main results: the estimated LCOE from each study or model and the LCOE we estimate using a consistent set of assumptions. Both sets of estimates underline the considerable heterogeneity in current wind technology cost estimates. The contemporaneous Government Performance and Results Act MARKAL model and the Model for Estimating the Regional and Global Effects of Greenhouse Gas Reductions estimate a three-fold difference in onshore wind LCOEs. The final column shows that these differences arise from the cost assumptions rather than the assumptions about discount rates, financing, and capacity factor—and thus represent significant uncertainty about the cost of constructing, operating, and maintaining wind generators.

The cost estimates in Tables 15 and 16 all correspond to the geared technology. We have been unable to find comparable recent estimates for the hybrid or PMDD technologies. The available evidence supports two conclusions related to the relative costs of geared turbines, PMDDs, and hybrid generators. First, the cost advantage of RE PMGs for onshore locations was not large in studies conducted in the early and mid-2000s. Second, even accounting for the advantages of RE PMGs over geared turbines in offshore applications, significant barriers remain to widespread investment in offshore turbines, particularly in the United States. This implies that even if RE PMGs are less costly than geared turbines in offshore applications, they are unlikely to account for a significant share of total U.S. wind investment.[26]

More specifically, several NREL studies from the early 2000s compare the costs of the different technologies across a range of turbine sizes. The analysis is based on a scaling model that estimates capital and maintenance costs as a function of turbine size and technology. The model accounts for changes in weight and design that must occur as turbine size changes. The general conclusion from these studies is that, for some configurations, the PMDD technology or the hybrid technology has a

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[26] That is, we assume the absence of policies that specifically promote offshore wind.

lower cost than the geared technology. However, the cost advantage tends to be very small, on the order of 5–10 percent (Bywaters et al. 2007; Maples et al. 2010).

How the estimated cost advantage in the scaling model translates to the total cost of future systems is unclear. At present, because firms have less experience with the direct-drive and hybrid technologies, the actual costs may be higher than the modeled cost, whereas the actual cost of a geared turbine may be closer to the actual cost.[27] Over time, as manufacturers and users acquire more experience, the relative costs of the PMDD and hybrid technologies are likely to decrease. Many firms are introducing wind turbines that use direct-drive or hybrid technology, but we have not found expert analysts who predict quantitatively how much the cost of these technologies may decline in the next several years.

Although the onshore and offshore LCOE estimates in Tables 15 and 16 are based on the geared technology, they suggest a significant challenge for offshore RE PMGs. Comparing the two tables, each study that looks at LCOEs for both onshore and offshore wind predicts offshore wind to be 1.5 to 3 times more expensive per megawatt-hour. Note that the estimates are based on similar capacity factors for onshore and offshore wind, but even allowing for a significantly higher capacity factor would yield the same conclusion that current LCOE estimates for offshore wind are significantly higher than estimates for onshore wind.

The tables show that the main reason why the LCOE for offshore wind is so much higher than that for onshore wind is that the capital costs are higher. Even if RE PMGs reduce maintenance costs to zero, the capacity factor for offshore wind would have to be much higher than for onshore, or capital costs per kilowatt-hour would have to decline significantly for the larger offshore turbines, for offshore RE PMGs to be cost-competitive with onshore. This suggests that the market for RE PMGs is likely to be small in the United States (absent major policy changes as discussed below).

4.3 Organization of the U.S. Wind Industry

To complete the picture of the supply chain, this section provides some background on the organization of the U.S. wind industry, focusing on the magnitudes and recent trends in wind turbine installations, the use of PMGs, and employment in the wind industry.

4.3.1 Market Shares for Wind Turbine Installations

In the late 2000s, GE had the highest market share of new wind installations by installed capacity, followed by Vestas. The overall market concentration has been rather high in the past 10 years, although it has decreased slightly in recent years. Over the years 2003–2005, the top five firms accounted for 99 percent of the market (by installed capacity). Over the years 2008–2010, the top five firms accounted for 80 percent, which is somewhat lower than in previous years although still rather high (AWEA 2010).

To provide some context for the U.S. market, Figure 8 shows wind investment (capacity additions, in megawatts) by year for the United States, the European Union, and China. Investment in the early 2000s in the United States was rather uneven; this is most likely attributable to uncertainty regarding the federal production tax credit, which expired in 2000, 2002, and 2004, only to be subsequently renewed. After 2004, investment in the United States increased steadily and peaked in 2009, before

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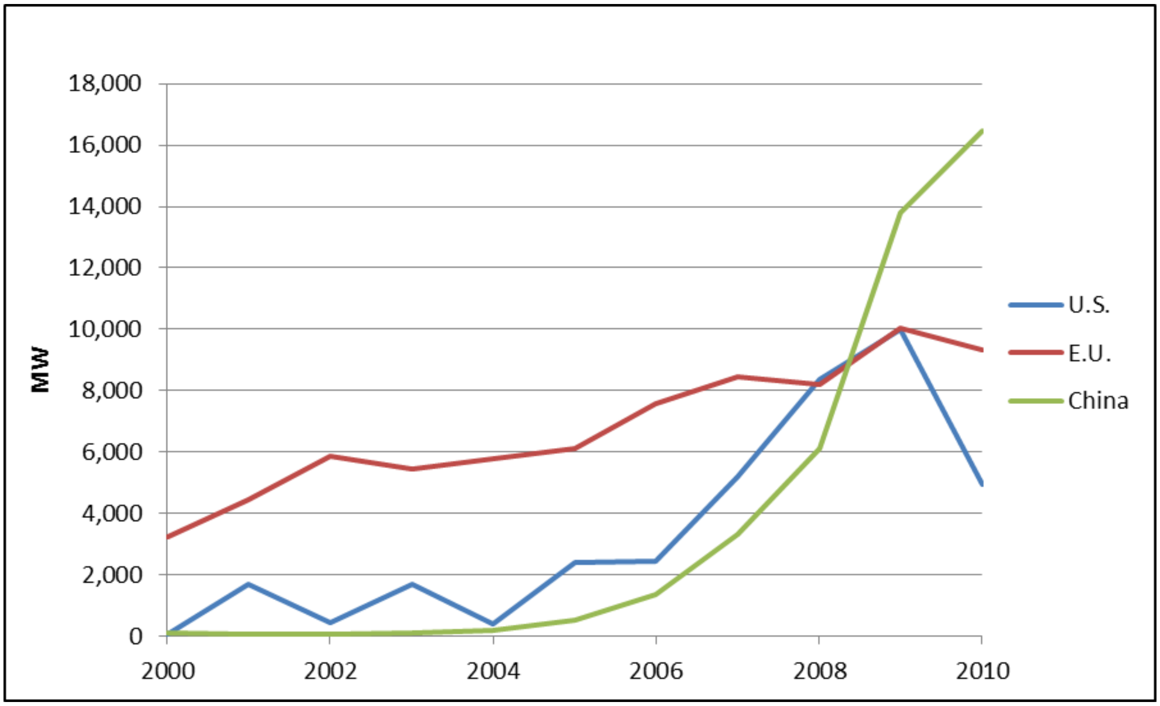
[27] Future costs of PMG and hybrid technologies would be higher than modeled costs to the extent that the models do not account for the design, construction, and operation challenges of the newer technologies.

decreasing by about half in 2010. Overall, during the second half of the decade, wind investment represented close to 40 percent of total investment in new electricity generation capacity in the U.S. electricity sector. On the other hand, wind generation accounts for just 2 percent of total generation in the United States (EIA 2010).

By comparison, wind investment in the European Union has increased more steadily. Investment in China was low at the beginning of the decade but has accelerated toward the end. It is beyond the scope of this report to assess the underlying causes for these patterns, but we observe that the annual capacity additions in the United States are comparable to investment in other regions of the world.

Figure 8. Annual Wind Turbine Investment for the United States, European Union, and China, 2000–2010



Sources: EIA 2010, AWEA 2011 (for U.S. data); European Commission 2011, European Wind Energy Association 2011 (for E.U. data); Global Wind Energy Council 2011, Li et al. 2010 (for China data).

4.3.2 Use of PMs in Wind Turbines

The supply chain analysis estimated the use of RE PMGs in U.S.-produced wind turbines. We concluded that only Clipper sells models that contain PMs, and that these turbines use the hybrid technology. Over the years 2008–2010, about 5 percent of wind turbines installed in the United States contained PMDDs or hybrid turbines (weighted by capacity); this estimate corresponds to Clipper's share of U.S. sales over the same years.

Many firms in the United States and other regions are introducing wind turbines that contain PMs, either the hybrid or direct-drive technology. There is currently a lot of uncertainty over the future market shares of these products, although the market shares are generally expected to increase. We have not been able to locate in the public domain any forecasts of future use of PMGs in the U.S. industry. The share of wind turbines with PMGs could increase or decrease over time, depending on the evolution of the technologies and the demand and supply conditions in other regions of the world. Those are the issues we analyze below.

4.3.3 U.S. Manufacturing of Wind Components and Employment

As we discuss above, we consider the employment effects of vertical integration and RE PMG manufacturing abroad. To provide a baseline against which to compare, we characterize current employment in the wind industry. Following several recent studies (e.g., Munro et al. 2011), we define the wind industry broadly to include firms that manufacture parts used in wind turbines as well as firms involved in the installation and operation of wind turbines. Note that this definition does not include employment in supporting service industries, such as bankers and contractors, which is sometimes referred to as *indirect employment* (e.g., DOE 2008).

We offer two caveats in relation to this definition. The first is that wind industry employment does not reflect the number of jobs as compared to a well-defined counterfactual scenario. For example, one alternative definition could be the jobs that would not exist if U.S. wind investment and wind exports equaled zero.[28] Such a definition would include indirect effects, for example, accounting for the fact that employees at turbine manufacturing plants would spend their income and cause job creation in other industries. However, estimating the size of the wind industry would require estimating a counterfactual scenario, such as a scenario with no wind investment or exports. That would be much more difficult than the definition that we use, which simply requires counting employment in specific industries.

That said, a second caveat concerns intermediate inputs. For example, employment at wind turbine manufacturing plants should clearly be included. But data are not available to determine the share of employment in many industries that produce products used in or used to make wind turbines, primarily because the categories include many products that are not specific to wind turbines. For example, total employment in tools industries should not be counted because some of the tools are used to construct wind turbines and some tools are used for purposes outside of the wind industry. Similarly, in publicly available data sets, blades are classified in the same industry as many other products.

Because of these limitations, we offer two estimates of wind industry employment and employment growth. The first is obtained by counting employees, and the second is obtained by analyzing wind investments and imports of wind components.

AWEA (2010) and Munro et al. (2011) provide independent estimates of wind industry employment. Both use information supplied to AWEA from member organizations. Munro et al. include establishments that produce products that are used only in turbines (e.g., blades), as well as establishments that provide services or products that are unique to the wind industry. AWEA does not provide additional documentation so it is difficult to compare methodologies. Nevertheless, the estimates from the two studies are similar: Munro et al. estimate about 25,000 wind industry employees, and AWEA estimates about 30,000 employees in 2010. By comparison, the Pew Charitable Trusts (2009) estimate about 5,000 employees in 2007. The discrepancy may be due to the latter study's reliance on Census industry codes, whereas Munro et al. and AWEA also included firms that

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[28] Note the distinction between *jobs* and *employment*. Employment refers to the total number of jobs, whereas the term job refers to specific jobs at specific firms; we focus on employment rather than jobs.

are members of AWEA but do not belong to industries whose names indicate a close connection to the wind industry.

An alternative approach to estimating employment growth, if not employment levels, is to examine trade data. We interpret the value of annual U.S. wind turbine investment, minus imports, plus exports, as the value of domestic manufacturing of wind components. The value of wind investment is obtained by multiplying the capacity installed in each year by the estimated average capital cost per unit of capacity (from AWEA 2011 and Wiser and Bollinger 2010).

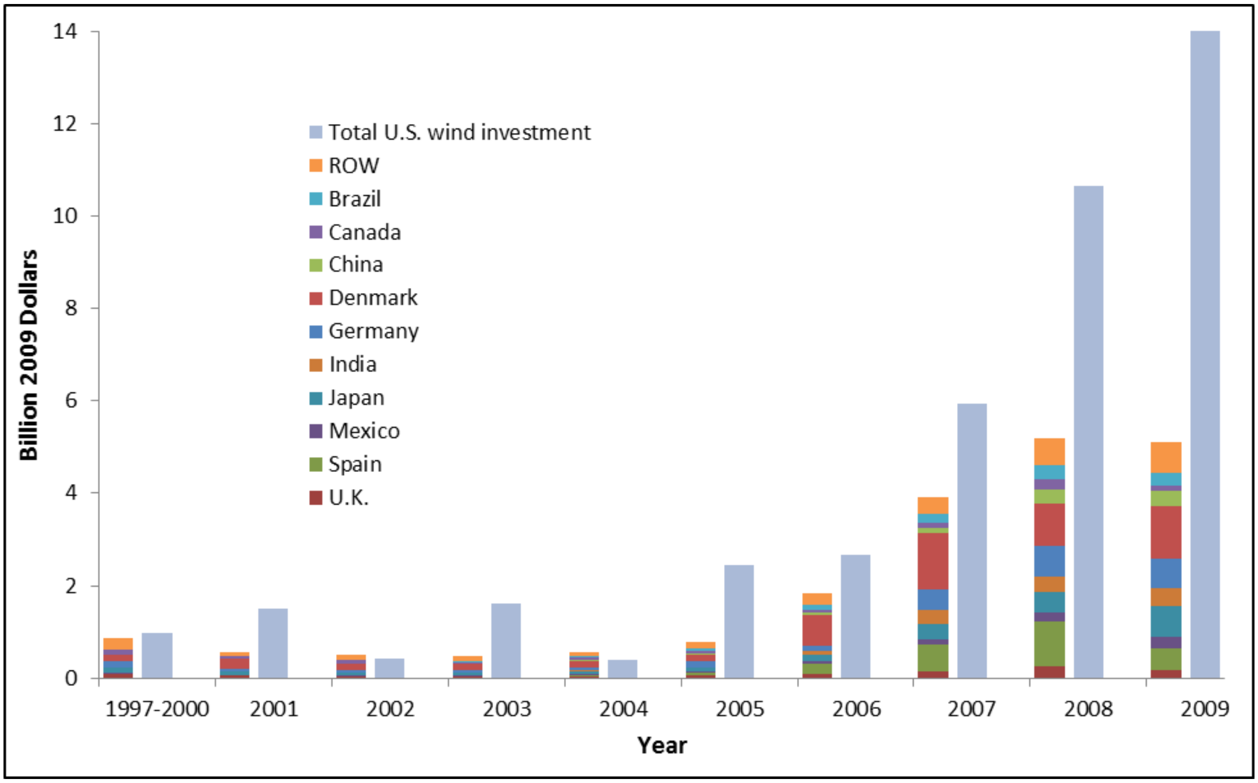
To estimate imports, we follow the methodology in Wiser and Bollinger (2010), updating the data to 2010. The U.S. International Trade Commission (ITC; 2011) provides data on its website on the annual dollar value of imports from each country of certain wind components: hubs, wind generating sets, generators, multiple-/variable-/fixed-ratio speed changers, blades, and towers. (The RE PMGs are potentially included in the generating sets or generators.) We consider the same Harmonized Tariff Schedule (HTS) codes as in Wiser and Bolinger (2010). We use the assumptions in that report to account for the fact that some of the imports that have HTS codes are used in other products besides wind turbines. For each HTS code, we multiply the measured dollar value of imports by the estimated fraction of goods used in wind turbines (the fraction varies by code). A source of measurement error is the fact that many components used in wind turbines are not reported at a sufficient level of disaggregation to identify imports of components used in wind turbines. For example, GE may import many parts used to manufacture its turbines, but these parts may not be included in the above categories. Because we focus on growth rates of investment and imports, this measurement error affects the results to the extent that the ratio of such imports to total investment has changed over time.

Following Wiser and Bolinger (2010), we lag imports by four months relative to the wind investment to approximate the delay between the time of import and the time at which the products are installed at the wind farm. We deflate import and investment values by the producer price index from the U.S. Bureau of Economic Analysis.

Finally, we use ITC data to estimate the value of exports for a similar set of product codes. We are not able to account for products used for purposes outside of the wind industry. This limitation does not affect the main conclusions because, in practice, the value of exports is much smaller than that of imports or investment.

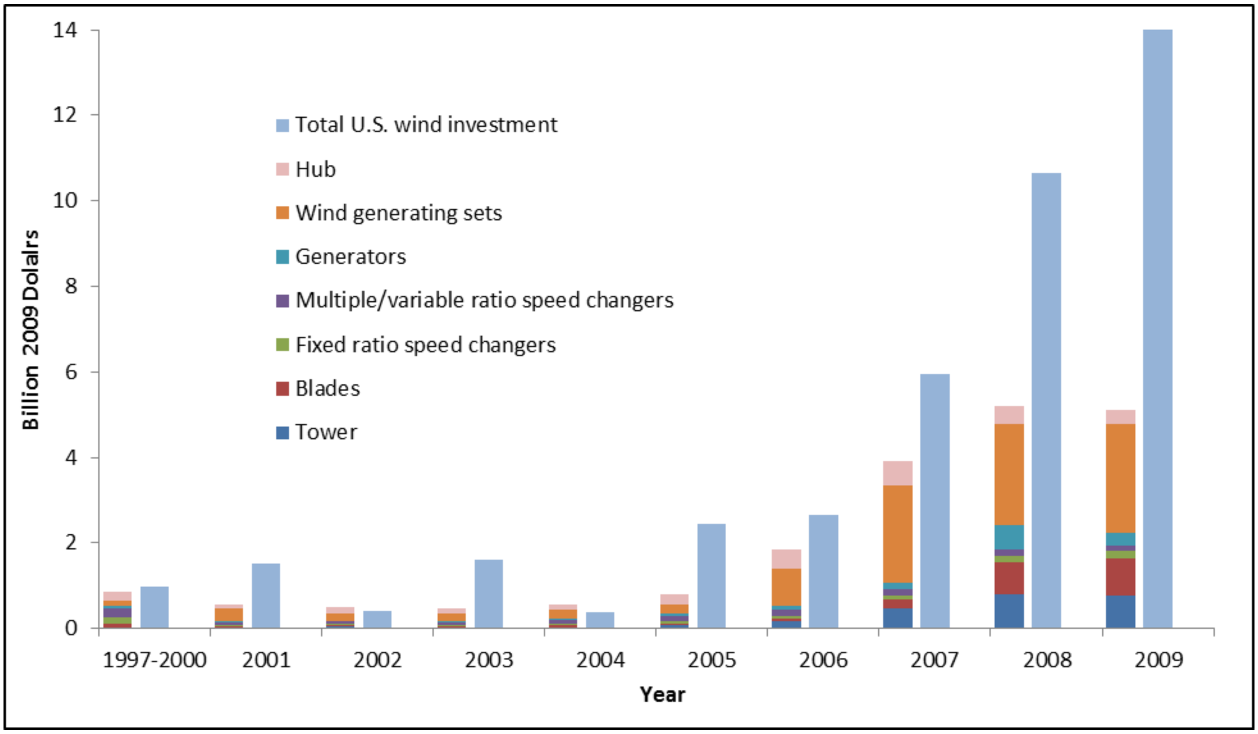
In Figure 9 and Figure 10, we observe that imports track wind investments fairly closely until about 2007; from 2000 to 2006, investment changes are positively associated with import changes, and the difference between investment and imports is typically small. In 2008 and 2009, however, investments increase dramatically, whereas imports do not increase by much. Over the same time period, exports remained quite small in magnitude relative to imports and investment (see Figure 11 and Figure 12). This pattern suggests that the U.S. wind manufacturing industry increased dramatically during these years, which is broadly consistent with Munro et al. 2011 and the NREL Wind Technologies Market Reports (Wiser and Bolinger 2010, 2011), which estimate that about 5,000–7,000 new wind manufacturing jobs were created from 2007 to 2010. We treat the conclusions from the trade data cautiously, however, for the reasons given above.

Figure 9. Value of U.S. Wind Investment and Imports, by Country



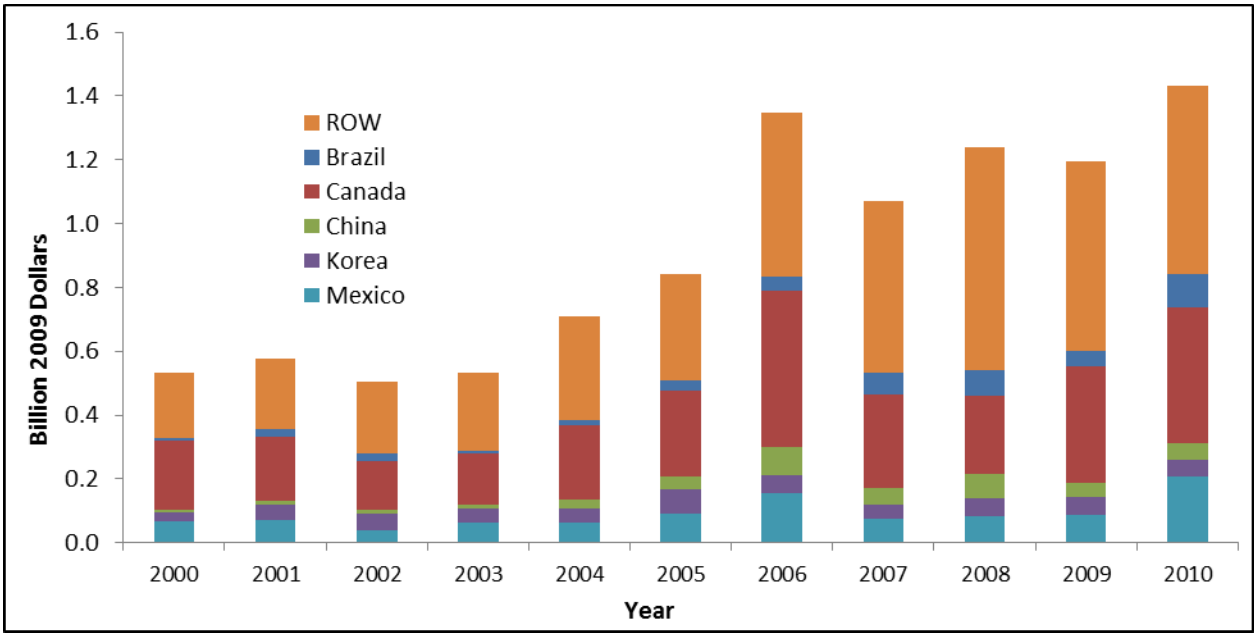
Notes and Sources: Solid blue bars plot the value of wind investment capital costs by multiplying the capacity of new investment (AWEA 2011) by the estimated capital cost per unit of investment (Wiser and Bolinger 2010). The stacked bars plot the value of total imports of wind components from each country (ITC). Wiser and Bollinger (2010) provide a list of HTS codes that contain the products used in wind turbines and in other goods. The report also contains assumptions on the fraction of imports of those products that are used in wind turbines. This information is used to calculate the dollar value of imports by month and country for all products used in wind turbines. Imports are lagged four months, so that imports for a particular year correspond to actual imports between August of the previous year and August of the current year. All values are converted to 2009 dollars using the producer price index (U.S. Bureau of Economic Analysis 2011). ROW, rest of the world.

Figure 10. Value of U.S. Wind Investment and Imports, by Component



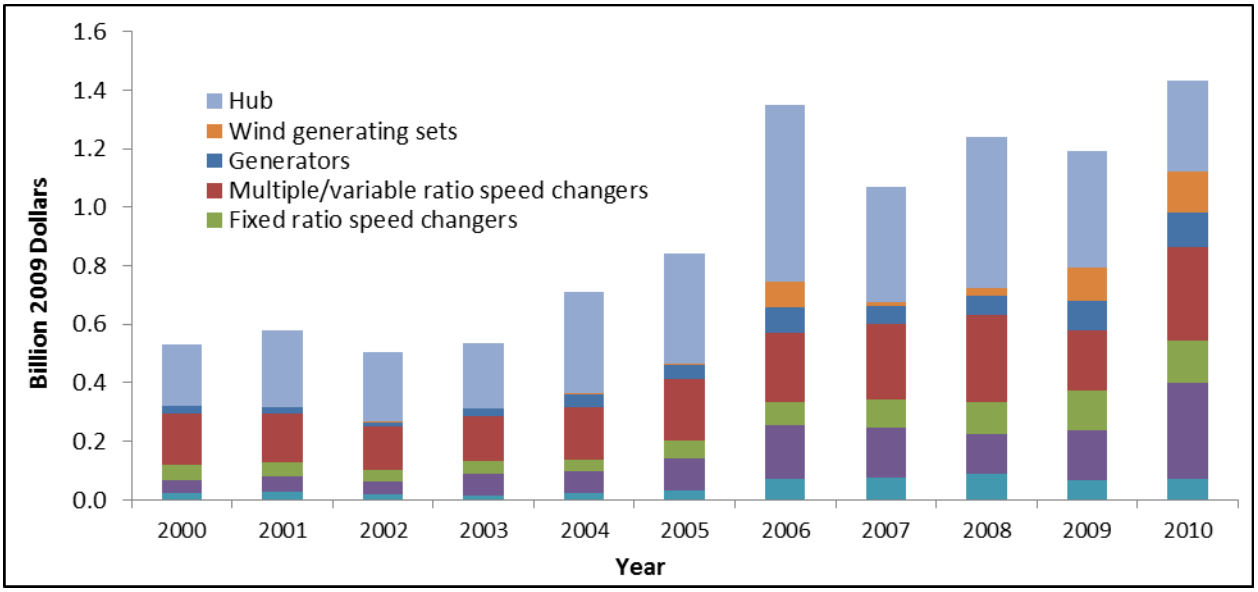
Notes and Sources: Data sources are the same as in Figure . Data are reported by U.S. HTS code.

Figure 11. Annual U.S. Wind Exports, by Country



Notes and Sources: Data sources and HTS codes are the same as in Figure . The chart shows the total value of exports across all codes, which may include products that are not used in wind turbines. ROW, rest of the world.

Figure 12. Annual U.S. Wind Exports, by Component



Notes and Sources: Data sources and HTS codes are the same as in Figure. Imports are shown by component rather than by country.

4.3.4 Predicted Employment in the Wind Industry

Because we are interested in the implications for U.S. employment of vertical integration and potential changes in the location of the PMDD supply chain, it would be desirable to have estimates of future employment levels given expected levels of wind investment and cumulative wind capacity. A sizeable literature has examined U.S. employment under particular policy scenarios (e.g., a renewable portfolio standard). The most common approach is to use input–output tables that link the consumption of final goods (i.e., wind turbines) to employment in various industries based on data collected over a specified time period. The basic idea is to compute, from the input–output tables and other data sources, the ratio of total employment to total wind investment. The employment effect of a hypothetical policy is then calculated by multiplying this ratio by the amount of wind investment expected under the policy. This approach assumes that the relationship between final goods and employment scales with wind investment. Some reports analyze total employment effects, whereas others also analyze regional effects.

The data used in most studies are privately maintained, but NREL has made its Jobs and Economic Development Impact (JEDI) model publicly available.[29] The model permits an analysis of the regional employment effects of particular wind investment projects. For example, according to the model, a hypothetical 200-MW wind project in Iowa would be associated with about four construction and manufacturing jobs per megawatt of capacity. Importantly, only a small number of jobs are associated with operating the wind turbines, so wind industry employment is more closely associated with wind capacity investment rather than with cumulative wind capacity.

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[29] The JEDI model estimates the economic impact and number of jobs generated by installing and operating wind turbines. The model uses an input–output methodology, where user-specified inputs are translated into expected economic outputs.

We note that considerable caution should be used when interpreting estimates generated by this approach (i.e., this is not specific to the JEDI model, but applies generally to analyses using the input–output approach, such as Kammen et al. 2004). The first issue is that these estimates represent gross rather than net job effects. For example, the construction workers at a wind farm may have otherwise been employed at a different job. In that case, the net employment effect is zero. Classical economic theory suggests that, in the long run, the economy is at full employment, and the net employment effects would only be positive in the short run; however, short-run effects are of particular interest given current high levels of unemployment.

The second issue is that the estimates are based on the assumption that wind policy does not affect the ratio of employment to wind investment. This relationship is usually based on average investment and employment levels over a particular period of time, and the relationship does not necessarily represent the change in employment caused by a change in investment (in economic terms, the ratio of employment to investment represents the *average* effect of wind investment on employment, and it is really the *marginal* employment effect that is relevant to the analysis). For example, a construction establishment that participated in a single project in one year may be able to participate in two projects in the following year if the establishment had spare capacity in the first year—in that case, marginal and average are not the same. It is also possible that, even if average and marginal are the same, the marginal effect changes with the overall level of wind investment in a way that is not captured by the model. However, we are not aware of employment analyses that suitably address all of these issues, and we use the input–output-based estimates to provide a sense of the scale of wind industry employment under alternative scenarios.

4.4 Forecasts of Future Wind Investment and Employment

4.4.1 Baseline

Above, we discuss EIA projections of future wind investment, which we treat as the baseline scenario. The baseline scenario contains an estimate of about 17 GW of investment between the years 2010 and 2035. Most of the investment is expected to occur in the early 2010s, and nearly all of the investment is expected to be onshore. The overall estimate corresponds to an average of 1 GW/year. By comparison, as Figure shows, annual investment has been 5–10 GW over the years 2007–2010. Thus, unless U.S. exports of wind components exhibit major growth, the EIA analysis implies a significant decrease in wind industry employment over the next 25 years.

4.4.2 High Wind Investment Case

In an alternative case, a DOE report discusses future scenarios with cumulative investment between 2010 and 2035 of about 260 GW (DOE 2008). According to the study, in 2035, wind generators would account for about 20 percent of total electricity generated in the United States. In the scenario, which includes about 54 GW of cumulative offshore wind investment, DOE assumes investment of about 16 GW/year from about 2018 to 2028. Using the JEDI model, the report estimates about 73,000 jobs per year in the wind industry, which represents about a three-fold increase compared to estimates of current wind industry employment as discussed above. This job count is significantly smaller than estimates of a few million jobs that were more widely reported from this study. The difference is because we focus on manufacturing and construction jobs, as opposed to indirect jobs, to maintain consistency with the recent reports discussed above.

4.5 Effects of PMG Vertical Integration and Manufacturing Location on the U.S. Wind Industry and Electricity Consumers

A quantitative analysis of the effects on the U.S. wind industry and electricity consumers of PMG vertical integration and manufacturing abroad would require an integrated model of employment and electricity generation, which is beyond the scope of the study. Instead, based on the structure of the industry and technologies, we discuss the conditions that would have to hold to cause a large, long-run negative effect on the U.S. wind industry and electricity consumers. The specific case we consider is one in which the cost of manufacturing RE PMGs in the United States increases compared to the cost of manufacturing RE PMGs in China (or elsewhere). For example, Chinese export quotas could increase the cost of manufacturing RE PMGs in the United States. In the extreme, the manufacturing cost could increase to infinity if the policy makes it impossible to manufacture RE PMGs in the United States. Note that, to simplify the exposition, we do not distinguish between direct-drive and hybrid PMGs—in general, the effects related to hybrid turbines are smaller but the analysis is qualitatively the same.

An important distinction exists between manufacturing employment and the welfare of electricity consumers. Assuming that electricity suppliers earn zero economic profits in the long run, their welfare is not affected; in other words, we assume, consistent with standard economic theory, that costs are passed through fully to consumers in the long run. Therefore, only electricity consumers are affected by such policies in the long run, and they are affected only to the extent that a policy raises the overall cost of electricity. For example, if Chinese policy causes the manufacturing of RE PMGs to shift from the United States to China, U.S. electricity consumers are worse off only to the extent that the Chinese-produced RE PMGs are more expensive than the U.S.-produced RE PMGs would have been in the absence of the policy. In contrast, Chinese policy could adversely affect manufacturing employees if electricity consumers are not harmed. In the example, manufacturing workers in the United States would lose their jobs but U.S. electricity consumers may not be greatly affected.

Following is a list of the conditions that must hold if the PMG vertical integration and manufacturing location is to adversely affect U.S. wind manufacturing and the welfare of U.S. electricity consumers in the long run.

1. *U.S. policies, technological change, or market conditions cause more wind investment than is currently expected.*

In the absence of major policy changes, EIA forecasts much lower average investment in new wind turbines over the next 25 years than has been experienced over the last 4 years. If these forecasts prove to be accurate, U.S. wind industry employment would probably decrease.

However, there are several conditions under which wind investment could be greater than currently projected levels. First, a policy could specifically target wind, such as a production tax credit (i.e., an extension of or increase in the tax credit). Second, a policy could encourage cleaner technologies, and wind may turn out to be one of the main options used to comply with the policy. For example, a clean energy standard or a renewable portfolio standard could significantly increase wind investment. The third possibility is a change in market conditions, such as an increase in natural gas prices above current forecasts, which improves the economics of wind compared to alternatives. Finally, increased use of “smart grid” technologies may facilitate the use of nondispatchable, intermittent generation sources, such as wind or solar.

2. *RE PMGs become less costly than other wind turbine technologies.*

If considerable wind investment occurs, the increased production of RE PMGs in the United States would significantly affect U.S. manufacturing jobs and electricity consumers only if much of the investment were in PMGs. We did not find evidence that either direct-drive or hybrid technologies currently enjoy a significant cost advantage over geared technologies (see section 4.2.2). This may change with improvement in the RE technologies, which are newer than the geared technology and may, therefore, have more room for improvement. If the costs of RE PMGs fall compared to the geared technology, and the first condition is met, considerable U.S. investment in RE PMGs could occur.

3. *RE PMGs become less costly than other electricity generation technologies.*

Raising the cost of manufacturing RE turbines in the United States would raise the cost of installing RE turbines in the United States, at least initially. The cost increase would not affect U.S. electricity consumers if close substitutes for wind generators—either imported or domestically produced—are available. What matters for electricity consumers is whether the overall cost of generating electricity in the United States increases. For example, under a renewable portfolio standard, this condition implies that wind continues to be more profitable than solar and other renewable technologies even in the presence of the increase in U.S. RE PMG manufacturing costs. Likewise, with a clean energy standard, wind must be competitive with natural gas and other low–carbon dioxide technologies. In other words, there must not be close substitutes for wind turbines—if there are, the effect on electricity prices would be small.

Note that this condition is relevant only for electricity consumers. Wind manufacturing employees could be adversely affected even if close substitutes for wind generators are available; in that case, investment would shift from wind to other technologies, which would decrease U.S. wind industry employment.

4. *The production of wind generators or turbines changes location.*

Even if the first three conditions are met, it is entirely possible that, in the absence of a cost increase, turbines would have been produced outside of the United States anyway. Such a policy change could affect U.S. employment at turbine manufacturing firms if significantly more production would otherwise have taken place in the United States.

5. *The change in wind generator/turbine production location affects the location of other manufacturing jobs.*

As noted above, manufacturing jobs account for just a fraction of total wind industry employment. Furthermore, generators and turbines account for just a fraction of total wind manufacturing jobs. If generator or turbine manufacturing moves to China (or elsewhere), the effects on U.S. employment would be magnified if other manufacturing jobs relocate as a result. Whether this occurs depends on the transportation costs of intermediate goods used in wind turbines and the economies of scope—whether it is more efficient to manufacture parts in the same area (in the same plant or city, perhaps) as the wind turbine.

5. Conclusions

We have focused on two RE elements, Nd and Dy and described the supply chain, from their mining to their use in the production of PMs for wind turbines. We have examined the industrial organization of suppliers along the chain, both horizontally and vertically, and the relationship between the supplies of the elements and the performance of the wind industry, including employment and overall national welfare. Our work contributes to the ongoing public discussion about critical materials (for example, see DOE 2010) by providing a basis for understanding some of the key physical and economic factors influencing the RE market—currently and prospectively—and, in turn, the effects on the producers and consumers of the final products that embody these elements. Much of our discussion draws from the MFA of supply chains and the economics of industrial organization.

In undertaking this study, we have faced a number of key challenges. First—and this has been acute—is the lack of systematically collected and reasonably verifiable data, particularly on physical quantities in mining and refining, international trade, the amount of Nd and Dy contained in commodities, and employment in the wind industry. Another challenge has been rapid changes in the relationships among domestic and international suppliers along the supply chain, with frequent acquisitions of companies, new joint ventures, and provisions for sharing of intellectual property during the course of our six-month study. A third important challenge has been the inability to determine, from a distance, the extent to which firms operating in China act independently or collectively, whether through explicit central control or implicit understandings. These challenges complicate analysis. The rapid changes in the industry also lead us to caution that the patterns in industrial organization and the consequent effects on the quantities and prices of Nd and Dy that we observe at present may be very different from those in even the near future.

We point out that vertical integration may reduce transparency but can also improve operating efficiency and reduce costs, much like long-term contracts. In special cases, vertical integration can increase market power through evasion of regulation, elimination of potential entrants along the supply chain, or changing strategic interactions in the market. None of these appears to be an important factor in the RE supply chain, however, based on the data available to us. Furthermore, over the longer run, new raw material supplies, technological change, the development of substitutes in the supply chain, and recycling could erode the market power of any supplier and further reduce potential harm to consumers in the wind power market.

A specific finding along these lines is that, because the United States does not, at present, rely much on wind power generated by RE PMs, U.S. consumers do not appear to be vulnerable to the exercise of market power along the supply chain. The relative advantage of direct-drive turbines with RE PMs over conventional geared technologies may be greatest in offshore wind applications, but the cost of offshore wind, regardless of turbine technology, remains significantly higher than the cost of onshore wind (not including subsidies). Total employment in the U.S. wind industry may have been around 25,000 to 30,000 in 2010. Absent a dramatic increase in exports of wind turbine components, EIA's baseline forecast of cumulative new investment in wind generators suggests a significant employment decrease in the U.S. wind industry compared to current levels.

Nevertheless, practices by other countries—China, most notably—may have a longer-run effect, particularly if wind power deployment were to significantly exceed the baseline forecasts. Much of our report has centered on the role that China plays, at present, in the REs market. Our understanding is that China currently does not limit the exports of domestically produced PMs or wind turbines. If domestic producers can obtain REs in China under more favorable prices or with a greater assurance of supply than can magnet or turbine manufacturers outside of China, then they will have a competitive advantage over the outside manufacturers. This advantage creates an incentive to relocate production facilities to China, benefitting that country over the longer term if it is able to combine the experience of these separate producers in such a way as to innovate in manufacturing along the supply chain.

It is crucial to note that China's market power over REs, and any strategy to build an advantage in innovating in the future, depends on how mining and manufacturing firms are governed within China. If nominal separation implies independent decisionmaking, neither of the outcomes noted above is likely. However, corporate governance may not operate in China as it does in the United States. Further study of the extent to which Chinese firms operate independently or in a coordinated manner, particularly through state controls, would be important for gaining more authoritative knowledge regarding these possibilities.

We conclude by noting that, in other experiences, other would-be exercisers of market power have had their advantage competed away by new raw-material supplies, technological change, and the development of substitutes. In congressional and other expressions of concern about RE dependency, needs related to national security and the U.S. Department of Defense have been recurrently underscored.[30] We do not know whether it is premature to suggest that REs will continue to be long-term issues of strategic concern. We do note, however, that foreign supply uncertainty often leads to steps for the protection of domestic interests. For instance, intermittent turbulence in world oil markets often has led to concern over energy security (including, frequently, the goal of "energy independence"), even if such intermittent upheavals have rarely turned out to have damaging long-term macroeconomic consequences. That said, it is understandable why, in the RE markets, where short-term supply options are far more limited than in the oil industry, a prolonged impasse over matters with substantial implications for the U.S. economy and industry strengthens policymakers' search for effective ways to respond.

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[30] For example, see Title I, Section 1010, U.S. Senate Legislative Counsel, Critical Materials Policy Act of 2011, draft copy, April 15, 2011—legislation proposed in April 2011 by Sen. Murkowski—and U.S. Government Accountability Office (2010, 14).

6. Appendices

6.1 Appendix A: The Future Demand For Wind Power

Wind turbines, though just one of multiple ways to generate electricity, attract widespread global interest as one of the clean and renewable alternatives—or, at least, complements—to the fossil and, conceivably, nuclear systems that are likely to endure for some years to come. How rapidly wind power can achieve a significant stake among the array of viable electric-generating modes depends on a variety of factors: the growth of electricity overall, comparative cost, dispatchability to the grid, siting constraints, technological progress, and supportive public policies (e.g., mandated renewable standards or tax credits). Because assumptions about the evolution of one or more of these factors will often vary among those doing the projecting, it is no surprise that estimates about the status of U.S. and global wind power 20 or 25 years hence can, correspondingly, coexist within a wide range of possibilities, as will quickly become apparent. Similar to the U.S. orientation in much of this report, our focus here will be on the United States as well.[31]

6.1.1 U.S. Perspectives.

We have chosen to deliberately take an agnostic view about which projection(s) are most likely to materialize, being content instead to show how a particular set of underlying assumptions determines a future outcome. The reason for adopting that approach may be best appreciated by looking at the so-called U.S. “reference case” projections contained in EIA’s *Annual Energy Outlook* (AEO; e.g., EIA 2011a). Those projections (also loosely referred to by some as “base case” or “business-as-usual” conditions) are the ones—frequently the only ones—picked up by the media and in public discussions as the most appropriate guide to future trends. In fact, though they may serve satisfactorily as an initial “point of departure” in the process of developing conjectures about future electricity (or other) trajectories, reference case projections are conspicuously insufficient to satisfy that objective.

To elaborate on that point, consider that EIA’s U.S. reference case projection, shown as the lower end of the ranges in Table 17, basically rules out fundamental changes in existing U.S. public policies, in prevailing energy production costs, and, except for the assumption of modest continuing improvements, in the basic state of technology.[32] Among such expected improvements, for example, are steadily rising wind capacity factors associated with taller towers and more reliable equipment.

Aside from the reference case, EIA explores a large number of supplementary cases that quantify the effect of different economic growth rates, fossil-energy production costs, and market-penetration rates of known technologies. For the most part, however, these supplementary projections—reflecting, as in the reference case, an absence of major discontinuities—show fairly modest differences from the 55-GW wind power capacity for 2035 in the reference case. Thus, one such

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[31] With respect to the U.S. focus, it is important not to conflate two equally important, though interrelated, considerations: the prospect for wind power installations, whether of foreign or American origin, in the U.S. electricity mix, and the prospect for a U.S. wind power manufacturing capacity, whether intended for domestic or foreign markets. Although the former aspect has significant implications for the country’s environmental conditions, the latter aspect has particular salience for job and income growth in the United States.

[32] Consistent with what might rightly be viewed as a conservative approach, the projections accept the “sunset” provisions of policies (e.g., the wind power production tax credit, set to expire in 2012) even when near-predictable renewals of previous expirations have often been the case.

supplementary exercise—labeled a “low renewable cost” variant—raises the 55-GW reference case to 84 GW. Only in a scenario that assumes an economy-wide carbon dioxide price (starting at $25/ton in 2013 and rising to $75 in 2035, with prices in 2009 dollars) does wind power capacity show appreciable expansion, rising to 106 GW in 2035.

In effect, the counterpart to the weak growth for wind power in EIA’s reference case is the substantial growth foreseen for natural gas, decisively influenced by the increase of estimated shale gas reserves in recent years. (Detailed projections of all energy sources appear in EIA [2011].) Of the overall net growth in electric-generating capacity of 117 GW during the next 25 years, natural gas combined-cycle units account for more than 50 percent, compared to a prevailing share of less than 20 percent. Coal’s absolute level of generating capacity is projected to be virtually flat over that time span. Clearly, EIA’s model points to gas as the economic energy source of choice in incremental electric capacity, at least some of whose spare gas-based capacity dates from the 1990s. But one should not assume that an absence of the gas bonanza would clear the way for wind: a resurgence of coal could frustrate that option. An AEO (EIA 2011a) table of the estimated levelized cost of new generation in 2016 shows gas at 6.6 cents/kWh and onshore wind at 9.8 cents/kWh (expressed in 2009 prices). (Offshore wind comes in at a hugely uncompetitive 24.3 cents/kWh.)

Of course, regarding wind power’s competitively poor showing in the U.S. reference case projection, it is important to consider circumstances that could produce a more favorable outcome. Accelerated technological progress or a narrowing of the cost spread between wind and its competitors (including fossil fuel competitors as well as other renewable energy competitors)—conceivably spurred by externality add-ons, widespread enactment of renewable energy portfolio standards, and pro-wind subsidies—could all contribute to such a result. Yet even a more favorable cost prospect for onshore wind could prove problematic: wind tends to blow more at night and during spring when electricity prices tend to be relatively low. This could prompt investors to perhaps still prefer gas.

Thus, in contrast to the essentially “no-major-discontinuity” assumption on which the EIA reference case and most EIA supplementary projections are predicated, two (non-EIA) DOE reports, released several years ago, pointed to a prospective level of U.S. wind power capacity by 2030 of, respectively, 210 GW and 300 GW—that is, significantly higher than the AEO estimates for 2035, cited above. The first of these two estimates, exploring “the consequences of producing 20% of the nation’s electricity from wind technology by 2030” is an outgrowth of the Wind Energy Deployment Model developed by NREL (see Thresher et al. 2008, 5). The 300-GW figure comes from a report released by the DOE Office of Energy Efficiency and Renewable Energy (DOE 2008, Figure 1-4). It is the more expansive vision embodied in these and similar reports that serves as the broad backdrop to—and justifies explorations and analyses in—the present report.

6.1.2 International Perspectives.

The worldwide wind power projections shown in Table 17 are not, in every detailed methodological and conceptual respect, comparable to the U.S. part of the table, but for present purposes, they are sufficient to highlight essential differences between the U.S. and global outlooks. Consistent with the U.S. reference case, the largely conservative character of the international projection is reflected in an EIA (2011c, ii) explanatory note: “The Reference case projection is a business-as-usual trend estimate, given known technology and technological and demographic trends…. The [*International Energy Outlook 2011* generally assumes] that current laws and regulations are maintained throughout the projections. Thus, the projections provide policy-neutral baselines that can be used to analyze international energy markets."

In terms of wind power's share in total electric-generating capacity, there are fairly modest differences between the U.S. and worldwide recent picture, and that is the case as well in the respective reference case projections. In 2010, those shares were 3.9 percent (U.S.) and 3.7 percent (global); by 2035, the numbers are 5 percent (U.S.) and 7 percent (global). However, just as alternative U.S. scenarios were shown above to suggest shares rising to the 20–30 percent range, so, too, do alternative global scenarios envisage substantially expanded wind power shares. Indeed, successive reports by the International Energy Agency (IEA) over the last several years signal a steadily diminishing disposition to credit the utility—or even to publish—a reference case projection, shifting instead to a normative indicator of *what should be* rather than what present thinking judges to be *what is most likely*.[33]

Table 17. Electricity and Wind Power Projections, 2010–2035

	Capacity and generation		% Total electricity		Average annual % change
	2010	**2035**	**2010**	**2035**	**2010–2035**
World					
	GW				
Total electricity	4,907	7,272	100.0	100.0	1.6
Total wind	180	533–1,062	3.7	7.3–14.1	4.4–10.7
	Billion kWh				
Total electricity	20,345	35,175	100.0	100.0	2.2
Total wind	314	1,462–2,814	1.5	4.2–8.0	6.3–9.2
United States					
	GW				
Total electricity	973.4	1,090.4	100.0	100.0	0.5
Total wind	37.49	54.83–200	3.9	5.0–18.3	1.5–6.9
	Billion kWh				
Total electricity	3,804	4,485	100.0	100.0	0.7
Total wind	91.25	160.88–680	2.4	3.6–15.2	2.3–8.4

Sources: EIA 2011a,c; IEA 2009.

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[33] See, e.g., IEA (2009). *World Energy Outlook 2010*, Executive Summary, p. 4.

6.2 Appendix B: Commercial Wind Turbine Models and Technologies

Wind turbine model	Generator size	Technology	Type
Acciona/AW1500	1.5 MW	Gearbox	-
Acciona/AW3000	3 MW	Gearbox	
Areva/M5000	5 MW	Hybrid	Synchronous PMG
Clipper/Liberty 2.5 series	2.5 MW	Hybrid	Synchronous PMG
Coemi/G3	55 kW	Gearbox	Asynchronous
Dewind/D8.2	2 MW	Gearbox	Synchronous
Dewind/D9.0	2 MW	Gearbox	Induction
Dewind/D9.1	2 MW	Gearbox	Synchronous PMG
Dewind/D9.2	2 MW	Gearbox	Synchronous
Enercon/E–101	3 MW	DD	Synchronous
Enercon/E–126	7.5 MW	DD	Synchronous
Enercon/E–33	330 kW	DD	Synchronous
Enercon/E–44	900 kW	DD	Synchronous
Enercon/E–48	800 kW	DD	Synchronous
Enercon/E–53	800 kW	DD	Synchronous
Enercon/E–70	2.3 MW	DD	Synchronous
Enercon/E–82	2 MW	DD	Synchronous
Enercon/E–82	2.3 MW	DD	Synchronous
Enercon/E–82	3 MW	DD	Synchronous
Fuhrlaender/FL 1250	1.3 MW	Gearbox	Asynchronous
Fuhrlaender/FL 1500	1.5 MW	Gearbox	Asynchronous
Fuhrlaender/FL 2500	2.5 MW	Gearbox	Asynchronous
Fuhrlaender/FL 3000	3 MW	Hybrid	
Fuhrlaender/FL 600	600 kW	Gearbox	Asynchronous
Gamesa/G128, G136	4.5 MW	Hybrid	Synchronous PMG
Gamesa/G52, G58	850 kW	Gearbox	-
Gamesa/G80, G87, G90, G97	2 MW	Gearbox	-
Gamesa/Made AE–59	800 kW	Gearbox	Synchronous
Gamesa/Made AE–61	1320 kW	Gearbox	Synchronous
GE/1.5–77	1.5 MW	Gearbox	Asynchronous
GE/1.6–100 & 1.6–82.5	1.5 MW	Gearbox	Asynchronous
GE/2.5–100	2.5 MW	Hybrid	-
GE/2.75–100	2.5 MW	Hybrid	-

Wind turbine model	Generator size	Technology	Type
GE/2.75–103	2.5 MW	Hybrid	-
GE/4.1–113	4.1 MW	PMDD	-
Goldwind/GW70, GW77, GW82, GW87	1.5 MW	PMDD	Synchronous PMG
Goldwind/GW90, GW100, GW106, GW109	2.5 MW	PMDD	Synchronous PMG
HZ Windpower/H56	850 kW	Gearbox	Synchronous
HZ Windpower/H82 ,H87, H93	2 MW	Gearbox	Asynchronous
Largerwey/L 82	2 MW	PMDD	Synchronous PMG
Largerwey/L 90	2.6 MW	PMDD	Synchronous PMG
Largerwey/L 93	2.5 MW	PMDD	Synchronous PMG
Mitsubishi/MWT62	1 MW	Gearbox	-
Mitsubishi/MWT92	2.3 MW	Gearbox	Asynchronous
Mitsubishi/MWT92, MWT94, MWT100, MWT102	2.4 MW	Gearbox	Asynchronous
Nordex/ N117	2.4 MW	Gearbox	Asynchronous
Nordex/N100	2.5 MW	Gearbox	Asynchronous
Nordex/N150	6 MW	PMDD	Synchronous PMG
Nordex/N80, N90	2.5 MW	Gearbox	Asynchronous
Nordex/N82, N77	1.5 MW	Gearbox	Asynchronous
Northern Power/100	100 kW	PMDD	Synchronous PMG
Northern Power/2.3	2.3 MW	PMDD	Synchronous PMG
REpower/MM100	1.8 MW	Gearbox	Asynchronous
REpower/MM92	2.02 MW	Gearbox	Asynchronous
REpower/3.2M114	3.2 MW	Gearbox	Asynchronous
REpower/3.4M104	3.4 MW	Gearbox	Asynchronous
REpower/5M	5 MW	Gearbox	Asynchronous
REpower/6M	6.15 MW	Gearbox	Asynchronous
Siemens/SWT–2.3–113	2.3 MW	PMDD	Synchronous PMG
Siemens/SWT–2.3–82	2.3 MW	Gearbox	Asynchronous
Siemens/SWT–2.3–93	2.3 MW	Gearbox	Asynchronous
Siemens/SWT–3.0–101	3 MW	PMDD	Synchronous PMG
Siemens/SWT–3.6–107	3.6 MW	Gearbox	Asynchronous
Siemens/SWT–3.6–120	3.6 MW	Gearbox	Asynchronous
Suzlon/S52	600 kW	Gearbox	Asynchronous
Suzlon/S66, S64	1.25 MW	Gearbox	Asynchronous

Wind turbine model	Generator size	Technology	Type
Suzlon/S82	1.5 MW	Gearbox	Asynchronous
Suzlon/S88	2.1 MW	Gearbox	Asynchronous
Suzlon/S88 Mark II DFIG	2.25 MW	Gearbox	Asynchronous
Vestas/V100	2.6 MW	Gearbox	
Vestas/V112	3 MW	Hybrid	
Vestas/V164	7 MW	Hybrid	Synchronous
Vestas/V52	850 kW	Gearbox	Asynchronous
Vestas/V60	850 kW	Gearbox	Asynchronous
Vestas/V80	2 MW	Gearbox	Asynchronous
Vestas/V80 GridStreamer	2 MW	Hybrid	-
Vestas/V90	1.8 & 2 MW	Gearbox	
Vestas/V90	3 MW	Gearbox	
Vestas/V90 GridStreamer	1.8 & 2 MW	Hybrid	
WinWinD/WWD1	1 MW	Hybrid	Synchronous PMG
WinWinD/WWD3	3 MW	Hybrid	Synchronous PMG
XEMC Darwind	5 MW	PMDD	Synchronous PMG

Notes: DD, direct drive.
Source: Compiled by Resources for the Future.

6.3 Appendix C: 2011 Allocation of RE Export Quotas to Individual Companies in China

Exporting company: Chinese-owned	H1 (tonnes)	H2 (tonnes)
Baotou Huamei Rare Earth Hi-Tech Company[a]	954	1,112
Inner Mongolia Baotou Steel Rare Earth Hi-Tech Company[a]	740	979
Inner Mongolia Baogang Hefa Rare Earth Company[a]	750	858
Leshan Shenghe Rare Earth Technology Company	750	840
Shandong Pengyu Industrial Company	709	802
China Minmetals Nonferrous Metals Company[b]	747	773
Gansu Rare Earth New Materials Company	689	746
Sinosteel Corporation	584	666
Yiyang Hongyuan Rare Earth Company	594	664
Xuzhou Jinshi Pengyuan Rare Earth Materials Company	410	502
China Nonferrous Import-Export Company Jiangsu Branch	493	483
Jiangxi Rare Earth Tungsten Industry Group Company		461
Guangdong Rising Nonferrous Metals Group Company	431	449
Ganzhou Chenguang Rare Earth New Materials Company	374	424
Jiangxi South Rare Earths Hi-Tech Company[b]	401	396
Funing Rare Earth Industry Company	327	351
Grirem Advanced Materials Company	333	346
Ganzhou Qiandong Rare Earth Group Company	329	303
Baotou Tianjiao Seimi Rare Earth Polishing Powder Company[a]	251	271
Jiangsu Geo Quin Nano Rare Earth Company	251	262
Changshu Shengchang Rare Earth Smelting Company	196	189
Guangdong Zhujiang Rare Earth Company	166	186
Ganxian Hongjin Rare Earth Company[b]	102	158
Jiangsu Golden Century Advanced Materials Co., Ltd.	432	
Baotou Huaxin Smelting Co., Ltd.	93	

(Continued on next page.)

Exporting company: Foreign-owned	**H1 (tonnes)**	**H2 (tonnes)**
Baotou Rhodia Rare Earth Company	867	935
Zibo Jiahua Advanced Material Resources Company	805	835
Jiangyin Jiahua Advanced Material Resources Company	481	475
Yixing Xinwei Leeshing Rare Earth Company	440	431
Liyang Rhodia Rare Earth New Materials Company	324	319
Huhhot Rongxin New Metal Smelting Company	296	301
Baotou Santoku Battery Materials Company	127	146
Pingyuan Sanxie Rare Earth Smelting Company		75
Subtotal: Chinese-owned	**11,106**	**12,221**
Subtotal: Foreign-owned	**3,340**	**3,517**
Total for 2011	**14,446**	**15,738**

Notes: H1 and H2, first and second half of the year.

[a] Part of Baotou Steel Group Corporation, which was allocated a total of 5,915 tonnes. [b] Part of China Minmetals Corporation, which was allocated a total of 2,577 tonnes.

Sources: Ministry of Commerce, People's Republic of China 2011; Shanghai Metals Market 2011.

6.4 Appendix D: PM Producers

Company	Country	Product	Capacity (tonnes)	2010 Output (tonnes)
Beijing Zhongke Sanhuan High-Tech Co., Ltd.	China	NdFeB	12,000	10,000
Beijing Jingci Magnetism Technology Co.	China	NdFeB		
Advanced Technology & Materials Co. Ltd.	China	NdFeB	2,000	
Thinova Co., Ltd.	China	NdFeB		
Ningbo Yunsheng Co., Ltd.	China	NdFeB	1,000/300	
Ningbo Konit Industries Inc. Ltd.	China	NdFeB		
Tianjin San Huan Lucky New Materials Inc. Ltd.	China	NdFeB		
SANVAC Magnetics Co., Ltd	China	NdFeB		
Zhaoqing San Huan Jingyue Magnetic Materials Inc. Ltd.	China	NdFeB		
Baotou Yunsheng Strong Magnet Material Co., Ltd	China	NdFeB	3,500	3,500
Ningbo Yunsheng Strong Magnet Material Co., Ltd.	China	NdFeB		
Baotou Showa Rare Earth High-Tech New Material Co., Ltd.	China	NdFeB	1,000	950
Beijing Sanjili Rare Earth Co., Ltd.	China	NdFeB	5,000	4,000
Yantai Zhenghai Magnetic Material Co., Ltd.	China	NdFeB	5,000	5,000
Constant Magnetic Materials Technology Group Co., Ltd.	China	NdFeB	6,000	6,000
Ganzhou Huajing Rare Earth New Material Co., Ltd.	China	NdFeB	3,000	2,500
Ganzhou Dongci Rare Earth Co., Ltd.	China	NdFeB	2,000	1,500
Ningbo Yunsheng High-Tech Magnetics Co., Ltd.	China	NdFeB	5,000	5,000
Ningbo Zhongshi	China	NdFeB	600	

Company	Country	Product	Capacity (tonnes)	2010 Output (tonnes)
Shenzhen Shengli Magnetic Products Co., Ltd.	China	NdFeB	5,000	5,000
Ningbo Co-Star Material High Tech Co. Ltd	China	NdFeB, AlNiCo, SmCo		
Nanjing Chuangken Magnetism Co. Ltd	China	NdFeB, AlNiCo, SmCo, Ferrite		
Ningbo Ninggang Permanent Magnetic Materials Co. Ltd	China	NdFeB, AlNiCo, SmCo, Ferrite		
Beijing San Huan New Material High-Tech Inc.	China	NdFeB		
Xinchang Magnet Industry Co.	China	NdFeB AlNiCo SmCo Ferrite		
Chengdu Magnetic Material Science & Technology Company	China	SmCo		
Zhejiang Tinnau Group	China			
Ningbo Strong Magnet	China	NdFeB AlNiCo SmCo Ferrite	1,000, 500, 40, 8,000	
Fellermagnets	China	NdFeB AlNiCo SmCo		
Neo Materials (Magnequench)	China	NdFeB		
Langfang GANS Magnetic Material Co., Ltd.	China			
Taiyuan Gangyu	China	NdFeB	3,000	
Shougang Company	China	NdFeB	500	
Tianjin Jinbin Advanced magnet Co.	China			

Company	Country	Product	Capacity (tonnes)	2010 Output (tonnes)
Shin Etsu	Japan	SmCo, NdFeB		
Sumitomo Special Metals Corp	Japan	NdFeB		
TDK	Japan	Ferrite, SmCo, NdFeB		
Hitachi Metals	Japan	NdFeB		
Advanced Material Japan Corporation	Japan			
Arnold Magnetic Technologies	USA	AlNiCo, SmCo		
Thomas and Skinner	USA	AlNiCo		
TDK	USA	Ferrite		
Permanent Magnet Co.	USA	AlNiCo		
Electron Energy Corp.	USA	SmCo		
Hitachi Metals America	Japan	Ferrite		
Vacuumschmelze GmbH	Germany	SmCo, NdFeB		
Magnetfabrik Schramberg	Germany	Ferrite, SmCo, NdFeB		
Kolektor Magnet Technology	Germany	AlNiCo, Ferrite		
The Morgan Crucible Company plc	U.K.	NdFeB		
SGM	U.K.	AlNiCo		
Neorem Magnets Oy	Finland	SmCo, NdFeB		
Arnold Magnetic Technologies	Switzerland	AlNiCo, SmCo		

Notes: blank cells indicate missing data.
Source: U.S. Magnetic Materials Association 2011; Shanghai Metals Market 2011.

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