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Evaluating Emerging Environmental Technologies: Strategic Planning and the Materials Supply Chain

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"Master of Science"

supervised by
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Affidavit

I, **CATHERINE BEALE**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Evaluating Emerging Environmental Technologies: Strategic Planning and the Materials Supply", 79 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 14.06.2011

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Signature

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List of Abbreviations

APS: American Physical Society

AWEA: Wind Energy Association

BGS: British Geological Survey

CREI: China Rare Earth Information Journal

DOE: Department of Energy (US)

Dy: dysprosium

EC: European Commission

EU: European Union

GAO: Government Accountability Office (U.S.)

GWEC: Global Wind Energy Council

GWEO: Global Wind Energy Outlook

HREE: Heavy Rare Earth Elements

IEA: International Energy Agency

IAGS: Institute for the Analysis of Global Security

IPCC: Intergovernmental Panel on Climate Change

LREE: Light Rare Earth Elements

MRS: Materials Research Society

NEA: National Energy Administration (China)

Nd: neodymium

NdFeB: neodymium-iron-boron

PBL: PBL Netherlands Environmental Assessment Agency

REE: Rare Earth Element(s)

RIC: Rare Earth Information Center (U.S.)

SDPA: State Development and Planning Commission (China)

SRREN: Special Report on Renewable Energy Sources and Climate Change Mitigation

TMR: Technology Metals Research

WTO: World Trade Organization

WWEA: World Wind Energy Association

WWER: World Wind Energy Report

U.S.: United States

USGS: US Geological Survey

Abstract

Rare Earth Elements are increasingly being used in a variety of emerging environmental technologies. It is therefore important to consider several interrelated issues involving the supply and demand for such materials and the relationship between them. These are complex and often not linear, requiring consideration of geostrategic as well as economic factors. The thesis examines why and how dominance of the industry shifted dramatically from the U.S. to China since the 1970s, focusing on the strategies pursued by Chinese leaders contributing to the significant migration of industries using REE along the technology supply chain to China. To gain insight into specific issues arising from the use of REE in emerging environmental technologies, the thesis teases out and scrutinizes key drivers for potential supply and demand problems, and classifies them according to three dimensions of resource scarcity to which they might contribute: physical, economic and political. It presents a table classifying key drivers for supply and demand problems involving REE according to these categories, and the potential impact of each driver: global, or on specific nations, industries, or REEs. The thesis then examines the use of REE in a specific technology: large-scale wind turbines. The thesis concludes that the development and implementation of long-term, comprehensive strategies on the national level has become increasingly necessary. If the widespread diffusion of such technologies is to be achieved, analysis along the entire material supply chain will play a crucial role in determining not only which strategies will ultimately bear fruit, but also whether the potential environmental benefits associated with these technologies will be realized. More broadly, however, the use of REE for environmental technologies illustrate increasing linkages between the use of various resources, and in this sense suggest the need for holistic policy approaches that address the underlying issues of escalating demand for energy and competing resource use.

1. Introduction: Basis for Research & Objectives of Study

In developed and emerging economies alike, rising energy demand, impending fossil fuel resource shortages, and growing concerns regarding the reality and effects of climate change have lead to a mounting consensus on the need for renewable energy technologies that are both affordable and feasible for widespread deployment.

There is thus a growing awareness that promoting and producing emerging energy technologies may yield significant benefits, for the reasons listed above, and also due to both economic and geostrategic fears of import dependence. Governments worldwide have initiated efforts to promote the use and diffusion of such technologies, and in response, private companies have increasingly sought to enter and dominate an emerging and potentially extremely lucrative market. Recognizing the economic potential as well, governments have sought to promote production of such technologies within their borders. In advanced economies in particular, the development of clean energy technologies is increasingly seen not only as a response to the threats of climate change and fossil fuel dependence, but also as a significant opportunity to revitalize local and national economies by creating new opportunities for jobs and growth.

Still, promoting and investing in emerging environmental technologies also bears potential risks. As is the case with all emerging technologies there is uncertainly regarding demand, since markets for specific technologies are unproven, as well as about feasibility for large-scale deployment.

Attempts to evaluate the promise of emerging environmental technologies have tended to focus on criteria such as costs, environmental impact, and technical considerations involving end-use, including lack of existing infrastructure required for widespread deployment and the intermittent nature of energy sources such as wind and solar. These analyses have thus largely neglected considerations involving the material constraints of specific technologies, or in other words, uncertainties regarding the supply side.

The role of material constraints and the material demands of various technologies, is an important topic, which has thus far received only limited attention from policy makers and the public, in part due to the complex and interrelated factors involved in the issue. In the United States in particular, the lack of a long-term, holistic strategy regarding the requirements and implications of increasing production and use of specific renewable energy technologies is already hindering the potential to reap economic benefits associated with producing these technologies for world markets, and may also have obscured awareness of which emerging technologies are feasible, and desirable or both.

Analyses that take the material demand into account are particularly important for emerging renewable energy technologies. Not only is there a critical need for such technologies, but “[m]any energy-related systems, such as wind turbines and solar energy collectors, are materials intensive” and thus “if new technologies like these are to be widely deployed, the elements needed to produce them will be required in significant quantities” (APS and MRS, 2011). Moreover, emerging environmental technologies increasingly employ critical materials, a measure determined by the relative importance of a particular material to an economy or sector, and risk of supply shortage or disruption (Bauer et al, 2010; EC, 2010). In particular, many emerging technologies require Rare Earth Elements (REE).

According to the U.S. Department of Energy clean energy technologies constituted about 20 percent of global consumption of critical materials in 2010. As these technologies are deployed more widely in the decades ahead, their share of global consumption is expected to grow. It is therefore necessary to consider several interrelated issues involving the supply and demand for such materials, and the relationship between the two, which particularly in the case of REE, is more complex than a cursory assessment might suggest.

Rare Earth Elements are seventeen chemically similar metallic elements, comprised the lanthanide family on the periodic table, with atomic numbers fifty-seven through seventy-one, along with and candium (atomic number 21) and yttrium (atomic number 39) which share similar physical and chemical properties. The group is typically subdivided into Heavy Rare Earth Elements (HREE) and Light Rare Earth Elements (LREE) and (see Table 1). The elements in the former group occur less abundantly, but are considered more valuable due to their numerous high technology applications.

Table 1: Heavy and Light REE by Group

Heavy rare earth elements (HREE)

Y yttrium	Gd gadolin-ium	Tb terbium	Dy dyspro-sium	Ho holmium	Er erbium	Tm thulium	Yb ytter-bium	Lu lutetium

Light rare earth elements (LREE)

Sc scan-dium	La lantha-num	Ce cerium	Pr praseo-dymium	Nd neo-dymium	Pm prome-thium	Sm samar-ium	Eu euro-pium

Source: Öko-Institut, 2011

Despite varying concentrations of the individual REEs, REE are not rare, and in fact are found throughout the earth's crust, in higher quantities and greater concentrations than many precious metals such as gold, and even common industrial materials such as copper. Due to difficulties involved with separation of individual REE, all of the individual REEs were not identified until the 20th century (BGS, 2010).

The electron structure of REE give them unique and desirable properties, such as the ability to form unusually strong, lightweight magnetic materials and resist very high temperatures. Increasing knowledge as to the metallurgical, catalytic, electrical, magnetic, and optical properties of the REE have lead to an ever-increasing variety of applications, many of which are characterized by high levels of specificity (Haxel et al, 2002). The rare properties which make REE useful, and in many cases necessary for emerging environmental and other technologies, however, also mean that they require advanced mining and processing techniques, and that good substitutes often do not exist or have yet to be developed, creating complex issues along the supply chain.

Sparse use of REE in the past, and hence a lack of incentives for mining and production, combined with the increasing number of applications for which they are seen as essential, make REE particularly vulnerable to supply shortages and disruptions. For industries and technologies requiring REE there is thus significant risk of supply/ demand mismatch, particularly in the short (0-5 years) and medium (5-15 years) term. Moreover, history suggests that shortages, price spikes, and abandonment of technologies can occur when the threat of shortages arises, even if the actual shortage never materializes" (APS and MRS, 2011). This presents particularly potent barriers to the development and deployment of the increasing range of emerging environmental technologies employing REE, for which final markets may be less developed that those for more established technologies using REE, creating high levels of risk on both the supply side and the demand side.

Table 2: Critical Materials in Clean Energy Technologies and Components

		CLEAN ENERGY TECHNOLOGIES AND *COMPONENTS*				
		Solar Cells	Wind Turbines	Vehicles		Lighting
	MATERIAL	*PV films*	*Magnets*	*Magnets*	*Batteries*	*Phosphors*
Rare Earth Elements	Lanthanum				●	●
	Cerium				●	●
	Praseodymium		●	●	●	
	Neodymium		●	●	●	
	Samarium		●	●		
	Europium					●
	Terbium					●
	Dysprosium		●	●		
	Yttrium					●
	Indium	●				
	Gallium	●				
	Tellurium	●				
	Cobalt				●	
	Lithium				●	

Source: Bauer et al, 2010

The second is that production is heavily concentrated in China, which currently produces 97 percent of REE, introducing political and geostrategic elements into the debate, which will be elaborated upon in the following sections. The recent attention to China's virtual monopoly on extraction is both warranted, and dovetails nicely with widespread fears regarding China's increasing dominance of key emerging industries.

Indeed, it is well established that extreme production concentration of a given resource is likely to contribute to supply shortages and price instability, which can have similar effects in terms of restricting the supply of final products using the resource. However, an exclusive focus on the mining and production of REE may obscure issues further along the supply chain with the potential to impact the diffusion of technologies employing them. A careful analysis of the whole supply chain for emerging environmental technologies employing REE can serve to identify risks associated with specific technologies, and in turn, reveal opportunities mitigate constraints of supply representing possible barriers to widespread deployment.

The use of REE in emerging environmental technologies thus involves significant potential benefits and unique risks, requiring consideration of geostrategic as well as economic factors. The implications arising from the use of REE in emerging environmental technologies thus represents fertile ground for future research and deserves further attention from policy makers and producers alike.

2. Research Questions & Structure of the Thesis

For the reasons elaborated above, in my thesis I will focus on the actual and potential impacts associated with the increasing use of REE in emerging environmental technologies. In order to do so I will attempt to provide some answers to the following questions: How might supply risks for REE determine which technologies are suitable for widespread deployment? Which strategies are being used, or may be used, to mitigate risks and constraints to supply of REE now and in the future? And, what specific issues arise from the use of REE in emerging environmental technologies?

In Chapter three, I will examine some key developments in the evolution of the REE industry, specifically focusing on why and how dominance of the industry shifted so dramatically from the U.S. to China since the 1970s. Specifically, I will examine the policies and other factors that have caused the supply chain for technologies employing REE to increasingly migrate to China. For the purpose of this thesis I will focus on the strategic polices Chinese leaders have pursued in regards to REE in general, and their use is emerging environmental technologies more specifically. My aim is not to provide a comprehensive history of the evolution of the REE industry, but instead to examine the extent to which China's current dominance can best be viewed as the product of deliberate and long-term policies and planning efforts, and if any strategies pursued might serve to illustrate the options available to governments wishing to secure supplies of REE or a share in markets of emerging environmental technologies employing them.

In Chapter four, I will examine some of the interrelated issues involving the supply and demand for REE, and the relationship between the two, which is more complex than a cursory assessment might suggest. To provide context and a framework for analysis, I will first include a brief general discussion in regards to defining material scarcity in the global context and identify three dimensions of scarcity: physical, economic, and political. I will then examine key drivers for demand and supply problems and using the framework described above, attempt to classify them according to which dimension of scarcity they are most likely to impact.

In Chapter five I will present a table classifying key drivers for supply and demand problems for REE according to both the categories discussed above and the potential impact of each driver. In a following discussion I hope to tease out the relationships between various drivers, and the impacts they might have, either individually, or in combination. Specifically I will attempt to determine and distinguish between potential global impacts, and impacts on individual nations, industries, and/or specific technologies, and suggest some strategies to mitigate potentially negative impacts.

In Chapter six, in order to gain insight into how the use of REE might impact the diffusion of specific emerging environmental technologies, I will look specifically at the use of REE in the permanent magnet technologies increasingly used in large-scale wind turbines. In this section I will elaborate on the advantages of wind technologies employing REE. Taking into account existing reserves of REE employed in these technologies, I will examine the potential for supply restrictions to inhibit large-scale deployment of such technologies under various scenarios, and highlight the importance of considering not only the potential promise of specific technologies in terms of environmental effects, but also potential material constraints associated with their use.

The thesis will conclude by looking at how the use of REE in emerging environmental technologies might play role in determining which technologies are feasible and desirable, and which strategies might be adopted to achieve widespread deployment. In addition I will attempt to provide some insight into the broader implications of the use of REE for environmental technologies, focusing on the increasing linkages among the use of different resources.

3. Evolution of the REE Industry: Strategic Planning and the Materials Supply Chain

Production of a given material generally occurs in countries with large resources and reserves. China holds around 36 percent of the REE reserves, and thus high production levels should be expected (Bauer et al, 2010). From 1950 to the late 1980s the U.S., which also holds significant reserves, around 13 percent of REE reserves worldwide, was in fact the world's dominant supplier of REE (Seaman, 2010).

Today, however, Chinese producers dominate mining and refining of REE, production along the materials supply chain for emerging environmental technologies employing these materials is increasingly based in China. In the U.S. by comparison, a 2010 Government Accountability Office (GAO) report identifies the absence of a U.S. presence at all stages of the global supply chain for REE, from extraction to the production of components. Although the report deals with REE for defense applications, its findings clearly also have implications for the use of REE for environmental technologies and for U.S. economic interest more broadly.

Both China and the U.S. are large, resource rich countries, with the worlds two largest energy markets, and thus leaders of each country face pressing needs to reduce the use of fossil fuels to satisfy energy needs. Each government has strong environmental incentives to promote widespread diffusion of emerging environmental technologies within their borders. In addition, within each nation country, leadership in industrial innovation is seen as a source of national pride and a basis of national identity. Producers along the supply chain within each nation have potentially huge gains to be realized from producing these technologies and securing a large share in growing markets. And the respective governments thus also each have economic incentives to promote domestic production, and keep producers within their borders. These similarities beg the questions: why is production of REE currently concentrated so heavily in China? Why is the U.S. nearly absent from the global supply chain of technologies employing REE? And how and why has this dramatic shift occurred?

In the following section I will explore some of the key reasons for China's rise to dominance vis-à-vis the U.S, focusing on the strategies, or lack thereof, pursued by the respective nations in regards to REE and emerging environmental technologies employing them. This is not intended to provide an exclusive interpretation of why and how the REE industry has evolved, but rather to suggest that far-sighted, strategic policies, and a focus on long-term goals indeed played a key role in establishing China's dominance of the REE industry, as well to explore the nature of those goals and policies, and possible implications for other governments wishing to secure supplies of REE for future use, particularly for use in emerging environmental technologies.

Of course, government policy cannot be seen as the exclusive reason for the dramatic evolution of the REE industry since the 1970s. As I will discuss below, Chinese policy decisions are at times opaque, and should not be viewed as the sole factor contributing to Chinese dominance of the REE industry. Governments are only one of many stakeholders with an interest in producing technologies employing REE, and various exogenous economic factors at least initially contributed strongly to the shift.

In particular, different levels of economic development in the U.S. and China certainly played a role. There is certainly an argument to be made that the rapid shift from US to Chinese dominance of mining and extraction, was due primarily not to policy decisions, but to the fact that lower levels of overall economic development provided Chinese producers with a comparative advantage by allowing them to produce these materials more cheaply. Beginning in the mid-1980s, "for environmental and cost reasons" (Fifarek et al, 2008), U.S. firms began purchasing REE from Chinese providers. This development need not have negatively impacted U.S. economic interests, and may in fact have provided U.S. producers with significant advantages, as well as reducing the negative environmental impacts of REE mining and refining within the U.S. Still, this practice also implied that U.S. firms "began to locate components of their business outside of the strong US national system of innovation" (Fifarek et al, 2008).

What is striking in terms of the evolution of the REE industry is the pace and extent of the subsequent migration of producers of industries using REE to produce technologies higher along the supply chain to China. Thus although economic factors clearly played a role in the process, for the purpose of this thesis I will attempt to illustrate the extent to which the specific policies and initiatives pursued by the Chinese government facilitated and reinforced this shift. Again, the development of the REE industry cannot be seen purely as the product of government policies; my purpose here however is to explore how policy has impacted the decisions and actions of various stakeholders and in doing so contributed to the current situation.

This is not intended to provide an exclusive interpretation of why and how the REE industry has evolved, but rather to suggest that far-sighted, strategic policies, and a focus on long-term goals indeed played a key role in establishing China's dominance of the REE industry, as well to explore the nature of those goals and policies.

As I will elaborate below, analyzing China's path to dominance of the REE industry in terms of the role of strategic planning suggests that Chinese leaders essentially recognized the future importance of what was at the time a minor resource, took action to consolidate production within it's borders, and have leveraged control of the industry to promote manufacturing higher along the supply chain and gain value added benefits associated with production within its borders. As discussed above, the market for emerging environmental technologies is expected to grow significantly, and China is currently "best positioned to benefit from this growth" (Cox, 2006).

As mentioned above, during the 1970s, the U.S. dominated the REE industry, with the Molycorp mine and refining facility at Mountain Pass producing as much as 40 percent of REE globally as late as the 1990's. Additionally during this period, intense research efforts in American Universities lead to the discovery of new commercial and military applications for REE (Hurst, 2010).

As early as the late 1950s, China began recovering rare earths during the process of producing iron from deposits at Bayan Obo in Inner Mongolia. From the 1960s onwards, as new deposits were discovered, Chinese leaders realized the potential strategic advantages of possessing vast resources of REE and initiated efforts to employ personnel throughout the country to research more efficient methods to recover REE and promote research and development on technologies using REE. Strategic investment in exploration and ways to improve refining techniques bore fruit. China's production levels of REE increased on tandem with rising global consumption levels. "Between 1978 and 1989, China's increase in production averaged 40 percent annually, making China one of the world's largest producers" (Hurst, 2010).

In 1990, the Chinese Government declared REE to be a protected and strategic mineral, prohibiting foreign investors from mining REE within China or participating in REE separation activities except in joint ventures with Chinese firms and requiring approval for all such projects from the Rare-Earth Office of the State Development and Planning Commission (SDPC) (Tse, 2011). Illustrating the far sighted and strategic nature of China's strategy towards REE, in 1992, Chinese leader Deng Xiaoping declared that "There is oil in the Middle East; there is rare earth in China" (Hurst, 2010), reaffirming and escalating China's desire to promote the REE industry and achieve global dominance within it. Seven years later, President Jiang Zemin wrote, "improve the development and application of rare earth, and change the resource advantage into economic superiority" (Hurst, 2010). Chinese policy and practice has subsequently pursued this strategic aim, with high levels of coordination and success.

Through the 1990s, China exported increasingly high levels of REE, causing

prices worldwide to drop and undercutting the business other producers. This undercut business for Molycorp and other producers, driving many out of business and significantly reducing incentives for new production projects outside of China. On the one hand, these developments were possible because Chinese producers overcame "technical issues of extraction from often low-grade deposits, using techniques enabled by low environmental standards and low labor costs" (APS and MRS, 2011). As mentioned above, the availability of low cost materials from Chinese producers, as well as domestic concerns as to the negative impacts associated with mining and refinement at home provided foreign producers with strong incentives to relocate parts of their business to China.

Yet seen in the historical context of China's current dominance of REE production, as well as increasingly the materials supply chain for environmental technologies employing REE, policies which facilitated sharp increases in production and the subsequent drop in REE prices on global markets can also be interpreted as part of a long-term strategy. Establishing China as the primary source for mining and extraction of REE has effectively enabled Chinese leaders to use extreme production concentration as leverage both in terms of raising prices in the long term, and attracting industries using REE to China. This in turn has provided significant economic advantages in terms of reaping the value-added benefits of becoming a global center for manufacturing and production higher along the supply chain. Both increasing use of REE in emerging environmental technologies and desire of governments worldwide to promote the deployment of these technologies are likely to enhance these benefits significantly.

As discussed above, though not all of the factors involved were necessarily under the control of the Chinese government, the long-term polices pursued by Chinese leaders have certainly played a key role in transforming China into a highly attractive center for manufacturing of final emerging environmental technologies and investment in such manufacturing. In November 2010, Ernst & Young's 'Renewable Energy Country Attractiveness Indices,' a well-respected guide for investors seeking to invest in renewable energy, rated China as the clear leader in renewable energy markets for the first time. The U.S. had topped the indices from November 2006 to May 2010.

China's dominance in terms of REE production is certainly a factor for industries relying on REE, but only as part of a suite of measures designed to keep China at the forefront of REE production, materials, technology, and research. Indeed, establishing China as a center of academic research on REE has been a key factor in enabling Chinese leaders to seize and maintain the upper hand in terms of production higher on the supply chain (Hurst, 2010; Cox, 2006, Fifarek, et al, 2006).

Since the initiation of the National High Technology Research and Development Program, so-called Program 863 in March 1986, China has pursued an explicit policy of pursing 'leapfrog' development in key high-tech fields by actively promoting research and innovation. "The use of rare earth elements can be found in each one of the areas in which Program 863 focuses" (Hurst, 2010). Program 973, announced in March 1997, provides massive funding to achieve those aims - projects supported by the program can last five years and receive tens of millions of RMB (Hurst, 2010). These programs and policies have successfully established China as a center for research on cutting edge REE applications. China boasts numerous university centers and labs dedicated to the study of REE, including the Baotou Research Institute of Rare Earths, which today is the largest research and development institution dedicated to REE in the world. As a result, "a large body of research is being provided by Chinese sources" (Cox, 2006).

Thus while the 1970s the US was a center for academic and technical research on REE, it has now far been surpassed in this area by China. The fate of the Rare Earth Information Center (RIC) at Iowa State University illustrates the dramatic shift that has taken place in terms of not only production, but also research and development activities. The RIC was established in 1966 by the U.S. Atomic Energy Commission's Division of Technical Information to be "a focal point for anyone interested in the rare earths" (Trout, 2006). It maintained an extensive database and library, and at it's peak handled as much as 500 inquiries a year. In addition, the RIC "kept the industry informed" (Trout, 2006) as to current events and new research through two newsletter, providing valuable information to producers of technologies employing REE. Today there are only two publications, globally, focusing almost exclusively on REE, the Journal of Rare Earth and the China Rare Earth Information (CREI) journal, both put out by the Chinese Society of Rare Earths (Hurst 2010). In 2002, however, the RIC closed due to a shift in funding from rare earths to pig research." The shift can be attributed to two main factors. On the one hand, dwindling interest by local firms due to the decline of the US REE industry, and equally important, the lack of a clearly defined national strategy to guide and support research on REE. As a result, "regional institutions such as Iowa State are forced to transfer funds to research more directly related to their local economy (pork)" (Cox, 2006). In this sense the closure of the RIC reveals the risks involved with failing to implement long-term strategic policies regarding REE for emerging environmental technologies.

In addition, a 2006 study entitled 'Offshoring Technology Innovation: A Case Study of Rare-earth Technology' shows that the Chinese have rapidly accelerated their number of rare earth patents (Fifarek et al, 2006). As a result of these two developments, promoting research on REE and securing patents on technologies and components that employ these materials, "non-Chinese firms are now faced with ever-increasing pressure to relocate closer to the Chinese REE resource" (Fifarek et al, 2006). Indeed, establishing a virtual monopoly on intellectual and increasingly legal resources necessary for cutting edge REE manufacturing, have been key factors enabling China to attract and retain foreign producers higher on the supply chain, and thus to gain value-added benefits associated with production of such technologies within China. The study, also notes that rare earth patent applications by US firms are in decline compared to the rest of the world, and from a US perspective concludes that, "As manufacturing moves overseas, it is inevitable that both engineering work and R&D will follow" (Fifarek et al, 2008). The implication, of course is that the inverse is true too as well. Policies establishing China as a center for research on REE applications provides powerful incentives for companies seeking to manufacture cutting-edge technologies employing REE. And snapping up patents provides China with a powerful legal tool to keep its dominant position as a center for manufacturing of these technologies.

In terms of final technologies, China can provide an additional and significant benefit to manufacturers of emerging environmental technologies: access to the worlds largest market for power equipment, with the government spending heavily on projects such as upgrading the electricity grid, committing $45 billion in 2009 alone. In terms of renewable energy, China has set ambitious targets, with wind, solar, and biomass intended to represent 8 percent of it's growing electrical generating capacity by 2020. As opposed to the United States, where significant energy infrastructure already exists, "in China, power companies have to buy lots of new equipment anyway, and alternative energy, particularly wind and nuclear, is increasingly priced competitively" (Bradsher, 2010a). Interest rates as low as two percent, state banks providing generous loans, a government policy of steering loans towards to renewable energy have all made China an attractive location for producers of emerging environmental technologies (Bradsher, 2010a). To name just one example, in 2010 Vestas of Denmark erected the worlds biggest wind turbine manufacturing complex in northeast China. Vestas uses the rare earth neodymium (Nd) in magnets for its V112 wind turbine, which enters production in 2012 (Biggs, 2011). Of course, illustrating the role of economic factors, for foreign companies China can also offer low tax rates, and low labor costs, although that is changing to some extent. Of course these factors are not purely the result of China's economic situation, but are also the result of economic policies pursued by the Chinese government. Lax environmental standards also play a role, although Chinese leaders say that they are trying to change this, an issue I will deal with in greater depth in later chapters.

While providing significant economic benefits, the influx of companies producing technologies employing REE will increase domestic demand for REE within China significantly. “Concerned with the sustainability of their current production trends” (Seaman, 2010) in addition to restricting exports of REE the Chinese government is currently taking action to consolidate control over its REE industry. China’s REE mining industry is large and spread out, including “over a hundred producers of varying sizes and capacities in the country as a whole” (Seaman 2010) and has historically been managed laxly, contributing to illegal mining and smuggling. Off the books mining and smuggling in turn have contributed to environmental devastation and artificially low prices. Concerned with impending supply shortages and seeking to “bring the industry under control, prevent overexploitation, and support prices to better serve mines that operate legitimately and responsibly” (Seaman, 2010), the Chinese government has begun to close down small and illegal operations and consolidate larger ones to gain more control. On the one hand, these developments have raised some concerns about further production concentration (APS and MRS, 2011), an issue I will elaborate on in the chapter on key drivers for supply and demand of REE. For the purpose of this chapter however, these policies also represent the ongoing evolution of China’s strategy regarding REE.

In addition to policies aimed at consolidating the REE mining industry, Chinese leaders have pursued a variety of policies to reduce exports of REE, most notably by imposing increasingly strict export and production quotas. Chinese leader say that these policies are aimed at reducing environmental impacts associated with extracting and processing of REE. In this sense, these policies represent a reasoned approach to legitimate domestic concern. Still skeptics argue that this position may also represent a strategic reaction to a World Trade Organization (WTO) dispute arising from China restricting supplies to Japan as a result of a maritime dispute and reducing supplies to Europe. WTO rules allow export restrictions for environmental reasons, but only if a country reduces domestic consumption, which China has not done (Bradsher, 2010a). In addition, some believe that China's primary goal may be to raise the financial return for the rare earth sector in order to attract still further foreign investment and value added extractive operations (Moran, 2010). In fact, until Autumn of 2010 Chinese leaders acknowledged as much, portraying their REE policies as a way to encourage high-tech companies to move production to China and retain supplies for industries within their borders (Bradsher, 2010a). Although it is impossible to say with certainly, these policies most likely represent a response to a combination of the issues and aims mentioned above.

Still, even if China's recent polices represent a reasonable policy approach to legitimate concerns, they pose potential threats to other nations and industries relying on REE. This is especially the case since China has seemingly shown the willingness to withhold supplies for geostrategic as well as economic reasons. In a September 2010 maritime conflict between China and Japan "Japanese officials claimed that Chinese officials held up rare earth shipments" (Humphries, 2010). Although Chinese officials denied doing so, if they did, the effect may have been counter intuitive, raising awareness among governments worldwide that securing supplies of REE is an issue that must be addressed. In other words, "If rare earths had been used to send a political message to Japan… this policy choice probably invited more unwelcomed, unintended consequences for China than expected" (Graham, 2011).

As a result of these interrelated developments in China's strategy, governments are growing increasingly concerned with China dominance of the REE industry. Particularly in the popular press, the focus has remained largely the implications of extreme production concentration in China for foreign industries relying on REE. Examining China's dominance of the REE industry from a perspective that takes the whole supply chain into account suggests that fears about China's ability to use its advantage to harm foreign industries may be warranted. Considering the extent to which

China’s rise can be viewed as the result of successful strategic planning suggests both that action must be taken with haste to address these concerns, and that appropriate strategies have the potential to have strong impacts in terms of doing so.

It should be noted that China’s relatively authoritarian system of government may provide distinct advantages in terms of implementing long term strategic polices. On the other hand, though, it is tempting to assign too much weight to this factor. According to Jane Nakano, a fellow in the Center for Strategic and International Studies in the Energy and National Security Program, “People in the United States or in Japan may think that China has a highly efficient, cohesive decision-making system. The reality may be more like in most other countries, however, in that there are many voices that must be coordinated in the decision-making process” (Webster, 2011). As this suggests, the specific strategies that are possible and appropriate will vary, depending greatly on factors such as the resource profile, level of development, and position on the supply chain of individual nations. There is no ‘one size fits all’ strategy in regards to REE for emerging environmental technologies, and governments and stakeholders will be required to evaluate both specific national interests, and the resources – economic, political, or otherwise- available to achieve those aims.

Still, I believe that taking a closer look at both the evolution of the REE industry and the policies which Chinese leaders have pursued regarding REE –particularly in terms of fostering innovation and value-added production within its borders – can prove valuable to any country seeking to promote the production of emerging environmental technologies. Doing so suggests both the need and potential for long-term strategic planning and cohesive strategies for critical materials, and highlights the value of investing in intellectual infrastructure and considering the entire materials supply chain.

4. Drivers for Supply and Demand Problems & Potential Impacts

4.1 Resource Scarcity: Materials in the Global Context

The fact that there are strong linkages among the use of different resources has become increasingly clear, adding new layers to the ongoing debate about scarcity (Kleijn and van der Voet, 2010). The issues involving the use of REE for environmental technologies thus in a sense represent a microcosm of a much larger debate involving the use and distribution of resources in an increasingly globalized and energy-hungry world.

In terms of defining material scarcity in the global context, a recent report produced by the PBL Netherlands Environmental Assessment Agency (PBL) and entitled 'Scarcity in a Sea of Plenty? Global Resource Scarcities and Policies in the EU and the Netherlands?' identifies a key aspect of the current discussion which applies especially well to the issues around REE: while in the past resource scarcity was viewed as primarily as issue of physical scarcity, "resources are more and more seen as strategic goods," (Slingerland, et al, 2011) adding a distinct geopolitical element to any discussion of scarcity. This emerging aspect to the debate over is particularly well illustrated by supply issues surrounding REE. The report identifies "three dimensions, or groups of drivers of scarcity," (Slingerland, et al, 2011) distinguishing between physical scarcity, relating to resource availability and demand; economic scarcity, focusing on the distribution of resources and functions of markets; and political scarcity, emphasizing the geopolitical considerations that influence the availability or affordability of resources in a certain place or country" (Slingerland, et al, 2011).

Clearly the three aspects of scarcity are "highly interdependent" (Slingerland, et al, 2011). Still, especially in discussions markets for REE, and particularly in terms of formulating workable national strategies, I believe that they represent a useful classification system. In particular, distinguishing between the first two categories and the third, political scarcity, provides a way to identify how particular constraints to supply might have an effect on a global level, while others might pose threats only to specific sectors and individual nations.

In evaluating the potential supply of REE for emerging environmental technologies, it is necessary to distinguish between resources and reserves, and the relationship among both and prices and production levels. The U.S. Geological Survey (USGS) defines resources as “a concentration of naturally occurring materials in such form that economic extraction of a commodity is regarded as feasible, either currently or at some future time,” (USGS, 2010) and reserves as “resources that could be economically extracted or produced at the time of determination” (USGS, 2010). In general, “the supply of a material is a function of resources, reserves, and production” (Bauer et al, 2010).

In terms of chemical elements such as REE, it is useful to remember that “past experience and a broad familiarity with the nature and distribution of mineral deposits indicates there is no absolute limit on the availability for any chemical element, at least in the foreseeable future” (APS and MRS, 2011). In general, increases in demand lead to price rise for a given commodity, incentives develop to identify and exploit new deposits, and as previously uneconomic resources become profitable, research yields new technologies for extraction and processing. In addition, lower-prices substitutes are developed and used, and recycling becomes profitable, reducing demand for new supplies. A “practical limit on availability” (APS and MRS, 2011) is reached, however, when the material is no longer available for a competitive price, i.e. when the energy or pollution required to produce the element from an increasingly dilute source become too great.

As an example of how resource linkages may contribute to other dimensions of scarcity in this context, water and energy are essential resources for mining of mineral resources. After rich and easily accessible deposits are depleted, mining will continue with lower grade and less accessible deposits, requiring substantially more of these resources. In addition, however, mining affects large areas of land, and often water, through waste-flows and emissions (Kleijn and van der Voet, 2010). These linkages are further complicated when the mineral extracted is used to produce energy, as is the case with REE, particularly if those affected by mining are not those that benefit from the energy produced. In the case of renewable energy, the issues become more complex because there is an argument to be made that renewable energy represents a global public good.

Despite the fact that REE are not geologically scarce, they may well become scarce according to one or all of the three dimensions mentioned above. REEs' unique properties mean that their extraction and refinement require advanced mining and separation techniques that entail risks and costs, both financial and environmental. In the production of REE, there are two stages that threaten other resources. One is the mining process. Nearly all rare earth deposits contain the radioactive material thorium, which in the absence of effective environmental regulations is generally discarded as a byproduct and can cause serious environmental harm to land and water resources, as has already been the case in northern China. Next there is the refining process where toxic acid is generally used in China (Webster, 2011). Nevertheless, illustrating the complexity that resource linkages introduce, producers of wind turbines requiring REE argue that the environmental benefit afforded by the end technology outweighs the harm caused by recovering the necessary materials (Bradsher, 2009). Adding another layer, to the extent that adequate protection of other resources is possible it also can represent a significant operating cost and thus "is an important factor in evaluating the economics of a potential mine," (U.S.DOE, 2010) and perhaps a limiting factor in developing new sources of production. Thus REE may be subject to physical scarcity if demand is too large, and incentives to increase production are too low, or disincentives too high.

There is also the possibility that resource linkages could create political scarcity, if the impact of production on competing resources is deemed too high by producing countries. As mentioned above, China has already given the negative environmental impacts associated with extracting and processing as a reason for tightening export quotas.

Therefore, due to both the characteristics of known reserves of REE and the aforementioned concentration of production in China, REE may become scarce in terms of their availability for certain applications or nations, even despite seemingly adequate levels of resources. Threats of political scarcity have contributed to growing fears on the part of governments worldwide, epitomized in a recent National Geographic article entitled ‘Replacing Oil Addiction With Metals Dependence?’

For emerging environmental technologies, these problems may be exacerbated for reasons of economic scarcity related to the peculiarities of markets for both REE and end-use technologies as had been touched upon above and will be elaborated below.

Research and innovation can increase the total amount of known reserves available for physical exploitation, and reduce environmental impacts, and diversify supplies of REE by fueling increased production, but both require time and money, and therefore incentives. Thus there is potential for supply –demand mismatch in the short to medium term, even despite adequate quantities of a given resources and reasonable expectation that barriers to developing new reserves will not be technically or economically prohibitive given current state of knowledge. These factors suggest the need for long-term planning strategic planning and likely government intervention if supply disruptions are to be minimized, both on a global level, and particularly for individual industries and nations relying on REE. In other words, governments and industries that wish to use REE now and in the future would be wise to develop long term strategies that address all three dimensions.

Having offered above a general discussion of the ways in which resource linkages might contribute to supply shortages and constraints for REE in the face of growing demand for these materials, I will now discuss specific drivers for supply and demand of REE, and attempt to classify them using the categories described by the PBL report.

For the purpose of this thesis, when I discuss physical scarcity, which relates to resource availability and demand, I will focus on technical characteristics of REE production, looking at geological, scientific, and technological issues that may contribute to scarcity, and assume relatively functioning markets – to the extent that this is possible for REE. Under the category of economic scarcity, which deals with the distribution of resources and functions of markets, I will deal primarily with the specific peculiarities of markets for both REE and emerging technologies, and investigate the interplay between the two. In the section on political scarcity, emphasizing geopolitical considerations that influence the availability or affordability of resources in a certain place or country, I will examine political and social aspects of REE production and use, including geostrategic concerns, environmental issues, and legal issues which could constrain supply for particular regions or countries. Some drivers may impact more than one kind of scarcity. In these cases, I will discuss specific aspects of the particular driver according to the type of scarcity to which they are likely to contribute. An example is the complicated effects of joint production, which contribute to the potential for both physical and economic scarcity.

I believe that looking at different drivers in terms of the specific dimensions of scarcity to which they relate provides a valuable lens through with to analyze the specific causes and potential effects of supply and demand shifts. Nevertheless, the inherent difficulties in precise categorization indicate the linkages between the various dimensions of scarcity, and the extent to which all are interconnected. This is an important issue in its own right, which I will return to in the discussion on potential impacts.

4.2 Supply and Demand Problems: Drivers for Scarcity

4.2.1 Physical scarcity: resource availability and demand

In general, the two majors drivers of demand for mineral commodities are the rate of overall economic growth, and "the state of development for principle material applications (e.g. clean energy technologies)" (Bauer et al, 2010). As increasing applications for REE have been discovered, demand for these materials has grown sharply, with steep increases predicted over the next decades. The primary driver for sharply escalating demand for REE is the widespread deployment of the growing number and variety of technologies and applications employing these materials, but other factors may play a role in rapidly escalating demand.

World demand for REE was estimated at 134,000 tons per year in 2010, with global production around 124,000 tons annually and the difference covered by above-ground stocks or inventories. World demand is projected to rise to 180,000 tons annually by 2012, and may exceed 200,000 tons per year by 2014 (Humphries, 2010).

In terms of supply, China's output may reach 160,000 tons per year in 2014 (up from 130.000 tons in 2008), a significant increase but not sufficient to cover rising demand in the short term (Humphries, 2010). The Technology Metals Research (TMR) Advanced Rare-Earth Projects Index tracks REE projects currently underway around the world, which have been either formally defined as a mineral resource or reserve under the guidelines of a relevant scheme, or are subject to past mining campaigns, and for which reliable historical data is available. As of May 7, 2011 the index lists 20 projects, being worked on by 19 different companies and located in 8 different countries.1 Still, TMR founder and technology metals expert Jack Lifton emphasizes that these projects are currently in various stages of development and large uncertainty exists as to when or if they might make a significant contribution to global supply (Lifton, 2011).

The figures mentioned above for projected supply and demand are of course, projections, but there is widespread agreement that steep increases in worldwide demand for REE will occur, with some analysts suggesting that total REE demand will double over the next five years, meaning that "the projected near-term demand is expected to outstrip supply" (Ventner, 2009). In the long run the USGS expects that reserves and undiscovered resources of REE are large enough to meet demand. (Humphries, 2010). Due to several issues that may distort the usual relationship between scarcity, price, and the possibility of increasing production which will be discussed below, it is likely that available reserves may be unable to meet rising demand quickly enough and there appears to be real potential for supply disruptions in the short and medium term. Industries relying upon REE are thus likely to face physical scarcity during this timeframe. Hey

[1] http://www.techmetalsresearch.com/metrics-indices/tmr-advanced-rare-earth-projects-index/

As discussed above, REE, are increasingly being used in a variety of emerging environmental technologies. Increases in demand from these applications alone have the potential to be extensive, as governments worldwide seek to promote production and use of such technologies, both in order to reduce emissions and to reap the economic gains associated with securing greater market share in an already fast growing sector. Large-scale diffusion of environmental technologies using REE could therefore significantly affect worldwide demand for REE.

REE are also used increasingly in a variety of non-environmental applications, however, including military applications and consumer products, many with more established markets than environmental technologies, such as flat screen TVs among many others. This issue could be of critical importance in terms of the diffusion of emerging environmental technologies because "demand for key materials in clean energy technologies compete for available supply with demand for the same materials in other applications" (Bauer et al, 2010) creating distinct possibility for inter-industry competition. Indeed, this has already proved the case with solar technology, which uses the critical materials indium, gallium, and tellurium. Rechberger and Zuser show that inter-industry competition is particularly likely to create material constraints for emerging environmental technologies, because in many cases other competitors can afford higher prices because the added value for the material in question may be higher in a more developed industry (Rechberger and Zuser, forthcoming). Supply shortages could be particularly damaging for technologies and industries with less established markets, and which therefore face risk in terms of demand for final products as well as supply of materials they employ.

Moreover, physical scarcity of REE caused by large growth in demand without a comparable increase in supply may be further exacerbated due to the fact that "substitutes for REE are unknown or inferior, and the recycling of rare earth is extremely problematic" (Verrax, 2011). As described above, the availability of cheap substitutes and effective recycling would generally act as a buffer against runaway demand growth. Until these materials and programs are developed, their absence could contribute to skyrocketing demand and thus threats of physical scarcity.

In the case of REE, specific geological and mineralogical characteristics create significant barriers to increasing production quickly or with ease. Thus despite the USGS's expectation that reserves and undiscovered resources of REE are large enough to meet demand in the long run, there are several reasons why these resources may not become available in tandem with rising demand, i.e. supply will not keep pace with demand, leading to physical scarcity in the short to medium term.

The most obvious potential constraint to increasing production is geologic availability, with regards to where and in what form both deposits themselves, and the infrastructure for production and extraction exist. In the first place, although REE are distributed around the globe, unlike precious and base metals, they don't tend to occur in concentrated or easily exploitable deposits. REE do not occur naturally as metallic elements, and are rather 'hosted' by various minerals, particularly in rock-forming minerals where they substitute for major ions, with higher concentrations required to form their own minerals (BGS, 2010). Although around 200 minerals are known to contain REE, vast majority of resources are associated with just three, bastnäsite, monazite and xenotime. Over 90 percent of economically recoverable REE are found in bastnäsite ores (Humphries, 2010). Individual deposits can vary greatly, however, "in general each rare earth ore body is unique and requires site specific processing" (Bauer et al, 2010). Deposits are complex to evaluate and pilot studies are thus required to evaluate potential mines and site specific processing is generally required (Lusty, 2010). Due to the physical characteristics of deposits of REE, advanced mining techniques are required, introducing technical constraints. Therefore even economically viable deposits may fail to become available due to problems with metallurgical extraction, absence of infrastructure (APS and MRS, 2011), or other issues that will be dealt with below.

In addition, due to their chemically similar nature in terms of their ionic radii and oxidation states, REEs can easily substitute for each other in crystalline structures, meaning that all REE must be recovered as a group and separated (Lusty, 2010). Essentially, all REE can be regarded as co-products or by-products of each other (APS and MRS, 2011). In terms of processing, the fact that multiple REE occur within a single mineral makes refinement to pure metal technically difficult. In comparison to metals such as gold, REE tend to be more costly and complicated to extract from the mineral in which they are found. First, ore containing a variety of minerals is extracted via mining. The bastnaesite must then be removed from the ore through a complicated series of chemical and physical procedures (Seaman, 2010). REE mines inevitably produce ore containing some amount of all REEs. REE must therefore be recovered as a group and then separated into their respective pure forms in a separation plant, using acid and various solvent-extraction separation steps. Each element has its own unique extraction steps and chemical processes and some require reprocessing to achieve the purity level desired. (Seaman, 2010) This is a technically challenging and thus costly process due to their chemical similarity (Lusty, 2010), yet necessary because as mentioned above the applications for individual REE tend to be very specific The total process takes approximately 10 days from the point when the ore is taken out of the ground to the point at which the rare earth oxides are actually produced and entails significant costs due to the numerous steps involved and thus relatively long time-frame required compared to other metals (Seaman, 2010).

The fact that REE can only be recovered as a group also raises challenges in terms of matching available supply to current demand. Since some REE have much higher economic value than others, even if rare earth supply and demand were in equilibrium on average, some REEs would always be in oversupply and others would always be in undersupply" (APS and MRS, 2011). This is particularly problematic because the value ascribed to individual REEs have tended to change as scientific knowledge has developed, technological needs have shifted and new applications have been discovered. For example, before 1965 there was no market for europium. In 1965, the US began to use europium as a red phosphor in color televisions, creating a new market and leading to steep increases in demand (Hurst, 2010.) Thus, "matching geological ratios to demand is a challenge" (Lusty, 2010) Relating to and compounding these issues, deposits of REE are generally made up of between 80-99 percent of the lighter REEs, (LREE) which tend to be more abundant and concentrated, but are also less "desirable," and therefore priced lower than heavy REE (HREE) (Humphries, 2010). There is therefore potential for oversupply of LREE, and undersupply of HREE (Lusty, 2010), although as I will explore below, complicated market dynamics for REE could reverse this equation.

In the case of REE, the relationship between resource availability and demand is complex. Geological characteristics of deposits, mineralogical characteristic of REE, and technical and scientific constraints contribute to capital costs typically in billions of US dollars and lead times up to 10 years required to bring new mines on line (Bauer et al, 2010). As a result, suppliers are unable to respond quickly to changes in demand. While increasing demand – and fears of impending physical scarcity -have led to renewed interest in initiating extraction and production around the world, for reasons described above, as well as several others which I will discuss below, there is likely to be a significant time lag before planned projects produce significant quantities of REE. The probable result will be that at least some industries and applications will face physical scarcity in the short to medium term.

4.2.2 Economic scarcity: the distribution of resources and functions of markets

The specific dynamics of markets for REE suggest significant potential for market failures to contribute to the economic scarcity of these materials.

In the first place, price signals for REE tend to be unclear. In markets, tensions between resource demand and supply are generally indicated by the price of a resource, with a rising price indicating that the resource is becoming scarcer. “Markets clear as prices equalize quantity supplied and quantity demanded” (Slingerland, et al, 2011). In the case of REE, however, market dynamics mean that interactions between demand, supply and prices, “are not captured by traditional economic models or simple economic analyses” (Bauer et al, 2010). Unlike traditional commodities, REE are not traded on structured commodity exchanges. Instead, prices are generally negotiated between individual suppliers and manufacturers via long-term, bilateral contracts (Ventner, 2009). The length and variability of these contracts result in a lack of standardized prices and thus “reliable price information for supply- and demand-side players to incorporate into business decisions” (Bauer et al, 2010). In other words, “price signals for key materials tend to be muted by the lack of price transparency,” (Bauer et al, 2010) and for REE this has been shown to be the case. Weak pricing signals distort markets and mean that the relationship between increased demand and increased production may not be linear.

On the supply side, price increases may fail to provide sufficient incentives to increase production of REE. As a result of traditionally small markets and difficulties involved with extraction and refinement, REE have tended to be extracted as by-products or co-products of other mining operations, “creating complex relationships between availability and extraction costs, which may cause supply curves and market prices to vary in ways not captured by simple supply and demand relationships” (Bauer et al, 2010).

In the first place, “the availability of an element produced as a by-product is constrained by the amount of the by-product contained in the main-product ore” (APS and MRS, 2011) In addition, incentives for increased production of the by-product itself are limited because “a by-product plays a relatively minor role in a project’s commercial appeal” (APS and MRS, 2011) Thus even if cases where it could be possible to increase production of the main product to levels high enough to significantly increase the quantities of the by-product as well, owners of mines and processing facilities have little incentive to do so. Since revenues from the by-product represent only a very small fraction of the value of the project this is likely to be the case even if market price of the by-product increases significantly. In other words, co-production creates the potential for the supply of REE to be “completely or partially independent of demand or price levels for these materials” (Bauer et al, 2010).

Even when REE are extracted as a main-product, uncertainty as to future demand and price levels may create disincentives to increase production, even when it could be highly profitable to do so. As mentioned above, the process of bringing additional supplies to markets is both long and costly. Even if current price levels would justify increasing supply, suppliers are likely to be reluctant to do so in the absence of certainty in regards to future demand and price levels.

On the demand side, even steep price increases are unlikely to significantly reduce demand for REE. REE often make up only a small fraction of the total cost of the environmental technologies in which they are employed. Due to their low value share in the cost of producing final technologies, price increases for these materials may not have a significant impact of prices of final products, and ultimately, on worldwide demand for these technologies themselves. Moreover, lack of both effective substitutes and economic incentives to develop them means that price increases of REE have little effect on end-use demand. While research may identify substitutes in the future, developing good substitutes has thus far proven technically difficult, carrying cost, and in turn, risk, that producers may be hesitant to take on. "Individual firms on the demand side will be challenged to justify the expense. Only under high prices and certainty about sustained high prices for end technologies will firms actively pursue R&D into substitutes" (Bauer et al, 2010). In the absence of these conditions, which seem unlikely due to the factors discussed above, demand for REE from producers of technologies employing them will remain inelastic with respect to price.

This lack of responsiveness to price signals on both the supply side and the demand side – the apparent disconnect between supply and demand - indicates the distinct possibility of supply constraints due to economic scarcity. As material demand outstrips reserves, yet prices fail to provide incentives to increase production, in is probable that some or all REE will become economically scarce.

This is particularly the case because even assuming some level of price responsiveness, future price levels for REE are highly uncertain for a several reasons. One important reason is uncertainty as to the policies that governments will pursue, and the large effects that these policies may have.

One the supply side, extreme production and market concentration in China may play an important role in contributing to the potential for economic scarcity. In the first place concentration in any producer creates risks for global markets, enabling a monopolist or near-monopolist to reduce global supply in order to drive up prices, and thus contributing to price volatility. Indeed, China has introduced various instruments to reduce the available supply of REE on global markets. These include not only export quotas, but a comprehensive raft of polices introduced in 2003 including production quotas, tax policies, and stockpiling. Export quotas in 2010 declined 40 percent since 2009, as compared to 20 percent between 2005 and 2009, causing sharp price increases for REE and raising international concern (Chan, 2011). What is particularly interesting in terms of teasing out specific drivers for economic scarcity is the specific and in some cases unexpected effect that the particular form such policies take can have on markets. For example, the cuts from 2009 to 2010 were based on tonnage and applied to all REE together. The result was a spike in prices of for the lower priced LREEs, as traders preferred the higher valued HREEs, which provided higher profit margins. Due to the specific way the quota worked, the ironic effect was that the scarcer HREEs remained relatively available, while the more physically abundant LREEs became economically scare (Areddy, 2011). In December 2010, however, the Ministry of Finance and State Administration of Taxation announced a new resource tax on domestic REE miners, which became effective 1 April 2011, with rates depending on the type of rare earth mined. According to the new policy, medium and HREE are taxed at 30 yuan per ton, while LREE are taxed at 60 yuan per ton (Yuan, 2011). While the tax is primarily designed to drive small and medium producers out of business by increasing production costs (Irvine, 2011), some analysts predict that it will increase the economic burden imposed disproportionately for HREE producers, because heavy rare earth has a lower grade (Chan, 2011). If this is the case, the policy could make HREE more economically scarce.

As the examples above show, the specific policies China pursues in the future could contribute to economic scarcity by raising prices and restricting supplies, but could also affect the available supplies of particular REEs necessary for specific applications. Neodymium, for example is a LREE, and is critical for the permanent magnets used in wind turbine generators and electric vehicles. Dysprosium, a HREE, which allows magnets to retain their magnetism at high temperatures, is also increasingly used in permanent magnets (Bauer et al, 2010), The US DOE's Critical Materials Strategy 2010 assigns dysprosium the highest level of criticality in both the short and medium term.

On the demand side, however, uncertainly as to the future polices governments pursue also contributes to uncertainty regarding future price levels. Due to reasons elaborated above, governments worldwide are seeking to promote the widespread deployment of emerging environmental technologies. As I will show in the case study on wind power, vastly different rates of deployment are projected, with much of the actual outcome dependent on the policies which governments choose to pursue. Emerging environmental technologies are expected to represent an increasing share of demand for REE. And since, “deployment, not materials intensity, is the biggest driver of demand (Bauer et al, 2010) these policy choices will heavily influence future demand. Uncertainty as to future policies thus contributes significantly to uncertainty regarding future demand for REE. Investing in such technologies entails significant cost and risks and governments have the resources to help overcome these obstacles. Government support will be necessary to achieve widespread deployment of beneficial technologies, but such investment is also largely a policy decision rather than an economic decision, and thus exacerbates the disconnect between supply and demand by decoupling demand for final technologies from costs and available supply considerations (Bauer et al, 2010).

The complex yet opaque dynamics of markets for REE introduce additional uncertainly as to the economic feasibility of emerging environmental technologies that require them. Introducing another layer of uncertainty, producers of final technologies could well face shortages further up the supply chain if supply risks or threats of supply risks make manufacturers of components unwilling to produce at adequate levels. Thus while the use of REE may confer significant technical benefits, it also implies added economic risk, compounding the already significant risks associated with markets for emerging technologies. In this sense economic scarcity of REE both as a group and individually should be viewed as an important factor in evaluating the feasibility of such technologies.

4.2.3 Political scarcity: geopolitical considerations that influence the availability or affordability of resources in a certain place or country

In addition the physical and economic drivers for potential supply problems discussed above, which largely relate to increasing production on a global level, geostrategic concerns will play an increasingly important role in terms of individual nations ability to secure material supplies, with countries such as the US and Japan already facing what the PBL Report calls political scarcity. In the first place, concentration of production in any supplier creates risks for global markets and geopolitical dynamics with the potential to affect the strategic interests of other nations seeking to produce technologies requiring the materials in question (Bauer et al, 2010). Production concentration in China introduces not only market distortions that may lead to economic scarcity, but also introduces the threat that REE and will become politically scarce in other nations seeking to develop technologies that employ them.

Even from a purely economic standpoint, emerging economies such as China are facing growing domestic demand for critical materials, and realizing the benefits of associated with satisfying growing worldwide demand for technologies employing REE. According to the European Commission’s Ad-hoc working group on Defining Critical Rare materials, governments are thus increasingly pursuing development strategies aimed to reserve their resource bases for their exclusive use. Although of course these policies has a strong economic dimension, particularly in the case of China, they can also be viewed as a geostrategic strategy to control a key industry and thus improve their geostrategic position vis-à-vis more developed nations. As described above, Chinese leaders have pursued a cohesive, long-term strategy designed to consolidate Chinese dominance of the REE industry and gain value-added benefits by producing components and technologies using REE higher up the supply chain within China.

Speaking at the annual Minor Metals and Rare Earth Conference in Beijing on 2 September 2009, former Ministry of Industry and Materials official Wang Caifeng stated that China would limit the export of semi-finished goods, but encourage the sale of finished REE products. While Wang's ostensible intent was to calm fears over China's export quota reductions, her statement raised new fears as to the potential to increase foreign dependence on China for finished goods (Hurst 2010). Already, as result of China's tax policies since 2007, the OECD estimates that non-Chinese REE producers pay at least 31 percent more for rare materials than Chinese processers (Seaman, 2010). China's geostrategic agenda thus has real potential to restrict supply along the entire supply chain for other nations requiring REE for their industries. This is particularly critical for countries such as Japan and South Korea who rely heavily on a steady supply of REE for the competitiveness of their own commercial industries (Bauer et al, 2010).

Perhaps more troubling, however, is Chinese leaders apparent willingness to leverage their ability to restrict exports in response to seemingly unrelated geostrategic issues. As mentioned above, the September 2010 maritime conflict in which Japan claimed that China held up REE shipments to Japan as political retaliation received widespread attention, highlighting potential for geostrategic concerns to lead political scarcity for particular nations.

Still, highlighting the complexity of the debate, China has consistently claimed that restrictive policies are necessary for resource conservation and environmental protection. As mentioned previously, many in the international community have received this claim with considerable skepticism. Still, whether this particular case represents an attempt to circumnavigate WTO rules, the environmental damage caused by REE mining is real and demonstrable. Environmental concerns represent a key driver for political scarcity on several fronts. China has shown signs of getting serious about implementing environmental policies, including but not limited to the tax described above which will be imposed on Chinese miners, rather than foreign importers.. While these rules could decrease global supply by limiting production in China, it is also true that Chinese producers and investors are seeking to expand production capacity worldwide (Humphries, 2010). The impact of that these initiatives will have supplies available to other countries is ambiguous. On the one hand, Chinese investment or loans to small independent producers could help expand global supply and by making the industry more competitive. On the other hand, Chinese investment in major producers "that puts the Chinese owners (and Chinese government) in a position to control production" (Moran, 2010) could decrease access for other countries, exacerbating current threats of political scarcity. In this sense it is critical to distinguish between global supply of REE and the supply available to particular countries, regions, and industries.

While concerns about Chinas drive to secure supplies around the globe may be overemphasized in terms of global supply, "Beijing's willingness to invest where others won't," raises serious political questions (Moran, 2010). There is a always the danger that even as China tightens and enforces environmental regulations, production will be moved to places with lax environmental laws, passing the problem along but not eliminating it.

This aspect raises more general issues around mining and resource production in general. Although China's current dominance of REE production is largely a result of a long-term strategy pursued by Chinese leaders, the lack of production in the US and other developed countries is also a result of the fact that wealthier nations "remain less than eager to play host to the refineries that produce [REE]" (Bradsher, 2011), due to the environmental impacts associated. While it is true that a major reason for the 2002 closure of the Molycorp mine at Mountain Pass, California was that Chinese producers had undercut prices of REE, making production uneconomical, this was due in part to the mine's growing ecological costs. Chemical processing at the mine was stopped In 1998 after a series of wastewater leaks spilled hundreds and thousands of gallons of water carrying radioactive waste into Ivanpah Dry Lake (Margonelli, 2009), an impact that was seen as environmentally and socially unacceptable in the US context. (APS and MRS, 2011) Indeed, the social and legal requirements for environmental protection, including extensive permitting systems, are a major factor contributing to long lead times and high costs of extraction and refinement in developed nations in particular. These political constraints may thus contribute to scarcity by discouraging production in developed nations such as the U.S. which have significant reserves. Indeed, these issues pertain not only to extraction, but along the materials supply chain. For example, radiation concerns helped force the closing of rare earth refineries in Japan (Bradsher, 2011).

In terms of mitigating the potential for political scarcity, the issues mentioned above illuminate the necessity of considering not just extraction of REE, but issues along the supply chain. For example, higher along the supply chain, not only environmental issues, but legal issues involving intellectual property or national legislation may play a key role in driving scarcity for particular nations. For example, master patents on NdFeB magnets required for large wind turbine applications are currently controlled by just two firms: Japanese firm Hitachi Metals, and Magnequench, the former US firm sold to Chinese interests in 1995. "Hitachi has used this intellectual protection to capture a large portion of the market for high-quality magnetic materials" (Bauer et al, 2010), while the Magnequench acquisition provided Chinese companies with the intellectual property and technology necessary to "establish production plants and further increase supply chain integration" (Bauer et al, 2010). As a result, production of high performance sintered magnets required for electric cars and large wind technology applications is limited to just 10 firms in Japan, China, and Germany, creating distinct risks of political scarcity for industries elsewhere requiring these components. These patents may expire in 2014 (Bauer et al, 2010), however, presenting a potential opportunity revealed through analysis of the materials supply chain.

While diversifying supply of REE could alleviate some of the geopolitical issues caused by production and market concentration, doing so on a global basis will require delicate balance. On the one hand, there is certainly an argument to be made for promoting production in countries which as less developed, and can have a competitive advantage in terms of supplying world markets with raw commodities. On the one hand, such initiatives could provide poor countries with access to foreign investment and world markets. Securing cheap supplies comes at the expense of negative environmental and social impacts for producing countries, however, could contribute to political scarcity by destabilizing the host country, leading to reliance on unstable suppliers. History has shown that “when sources of rare commodities are discovered, and subsequently developed in underdeveloped countries, the result is sometimes increased hardship and political instability rather than improved living standards for a majority of citizens” (APS and MRS, 2011) Both the US and the EU include the political and economic stability of producing countries as a key measure of criticality. Political and/ or economic instability can lead to an unreliable supply of REE and must thus be regarded as a key driver for political scarcity.

Malaysia’s history in respect to REE production illustrates some of the complications surrounding the issue of increasing production in developing countries. Prompted by fears of impending scarcity and Chinese control, Australian mining company Lynas is currently building a refinery in Malaysia that it says will be able to meet nearly a third of global demand for REE, not including China, within two years. The plant will be the world’s largest refinery for REE and is the first to be built outside of China for nearly 30 years. The refinery could significantly benefit the Malaysian economy. If REE prices remain at current levels it could generate 1.7 billion US dollars in exports, nearly one percent of Malaysia's economy. Realizing these potential benefits, the Mayalsian government actively courted investment from Lynas, offering the company a 12-year tax holiday. According to Lynas executives, all measures have been taken to insure that local environmental risks will be minimized, and that building such a refinery in Australia would cost four times as much due to higher labor and construction costs. Although public opinion in Malaysia as to weighing potential risks and benefits appears divided, the project has attracted weekly public protests Malaysia's last rare earth refinery, operated by Japanese company Mitsubishi Chemical, is currently on of Asia's largest radioactive waste cleanup sites. The Malaysian government announced in April, 2011 that it would appoint a panel of international experts to review the safety of Lynas's plans, with Lynas officials saying that the company welcomes the move (Bradsher, 2011). Still, the controversy over the Malaysian refinery, particularly in terms of the historical context, illustrates both risks and opportunities inherent in promoting production of REE in developing countries.

Both the US and the EU explicitly note that any efforts to increase production must be coupled with promoting environmentally sound mining techniques. In these sense, expanding production in developing countries provides an opportunity to promote the spread of high standards and environmentally sound mining practices. Doing so, however, will entail costs that could put producers at a competitive disadvantage, particularly in the short term. (APS and MRS, 2010) Promoting socially and environmentally sound mining and production will thus likely require policies offering sustained support from governments in developed countries. Policies to promote research and development on such techniques and their application in new projects need not be viewed as altruistic: "environmentally sound mineral extraction and materials processing can contribute to local acceptance of these activities, as well as reduce costs over the long term" (Bauer et al, 2010).

A comprehensive strategy to secure necessary supplies of REE for emerging environmental technologies must therefore take political, social and regulatory into account, as well as needs to increase and diversify production. On the one hand, this includes the risks that political instability within a producing country will threaten extraction and production projects or lead to erratic and unpredictable access to REE, on the other hand issues with permitting and regulation processes which could delay the start of new projects. Developing effective strategies will thus require both minimizing hurdles associated with permitting and regulation, while not losing sight of the aim that in many cases these processes were designed to achieve, to ensure an environmentally sound and socially acceptable production process and well as a secure and sustained source of future supplies.

5. Impacts: Potential Problems and Opportunities for Emerging Environmental Technologies

As illustrated above, the relationship between supply and demand for REE and the emerging technologies in which they are used is complex and often not linear. In the first place, the relationships between the various dimensions of scarcity are highly interrelated, In the specific case of emerging energy technologies employing REE, strong linkages among the use of different resources add an additional layer of complexity in terms of determining and classifying specific impacts. In the discussion above, in some cases, in as attempt to maintain logical consistency, I have examined specific drivers, or groups of drivers in terms of the dimension of scarcity that I determined that they were likely to impact most strongly. For example, constraints to global supply of REE, relating to production capacity, which I have classified as a driver for physical scarcity, could also act as a driver for economic scarcity for specific applications and technologies, particularly if other phenomena such as inter-industry competition are also at play. For this reason, in Table 3, in situations where I believed that there was significant potential for overlap I have listed both categories of scarcity where a particular driver could have an impact. In addition, one reason I have chosen to classify drivers according to the specific dimensions of scarcity with which they are most strongly connected is to determine the specific causes and potential effects of supply and demand shifts- i.e. how a driver might affect not only global supply or demand for REE, but also for particular applications, technologies, industries, nations or regions. In order to tease out these specific impacts, I have added a column in which I attempt to predict the type of impact that a particular driver might have. When identifying potential risks to a specific application I mean potential barriers to widespread deployment vis-à-vis other technologies, applications, or industries requiring REE. Scarcity risks for certain REE may of course also affect particular technologies and applications, for example those requiring HREE. I chose to create a separate category, however, since I believe that these potential risks are more specific, and could thus play a key factor in evaluating the feasibility of specific technologies. In other words, although the categories are connected, the specific risks involved may require different policy actions. I hope that this will provide a useful tool for policy makers and producers to get a sense of how key drivers might affect nations, industries, and specific technologies, and thus provide an idea as to where policy intervention might be most useful and appropriate. For example, looking at relative scarcity risks for particular REEs could indicate the most profitable ways to channel funding for research and development into substitutes.

The interrelated nature of resource use more generally and among the dimensions of scarcity more specifically, therefore introduces complications in terms of identifying and categorizing individual drivers for scarcity. Moreover, the impact that a specific driver will exert cannot be predicted with surety. In the first place, a key driver has potential to exert an effect in either direction. For example, increases in worldwide demand for REE could have two potential impacts: to increase scarcity, or simulate efforts to increase production. In the second place, the relationships among various drivers is complex. Certain drivers serve as sub-drivers for other drivers. To continue with the previous example, increased in global demand could be attributed to a variety of more specific factors including policies which contribute to shifts in energy demand, policies which promote the deployment of emerging environmental technologies to satisfy an uncertain potion of this uncertain increase on demand, demand from other technologies and/or industries, and lack of substitutes, among others. On the supply side, efforts to increase production could be driven by market incentives, policies to fund research for more efficient extraction and refinement technologies, efforts to fund new projects worldwide, or others.

In addition, the relationships between and among individual drivers are dynamic, and in some cases may be circular. For example, increases in global demand for REE could lead to increases in production of REE, facilitating the use of REE in environmental technologies, the widespread deployment of these technologies, and development of stable markets for final technologies, thus creating a cycle by contributing to further increases in global demand. On the other hand, however, increases in worldwide demand for REE could contribute to physical scarcity on the global level, or when coupled with effects of inter industry competition, could lead to economic scarcity for emerging environmental technologies using REE. This in turn, could lead to decreased production of these technologies, and ultimately, if they were indeed a key driver for initial increases in demand, a reduction in global demand. Illustrating the value of examining the relationship between and among individual drivers and their specific impacts, the price of stabilizing skyrocketing demand could well be the abandonment of specific and potentially promising technologies. The above example highlights the complex and circular nature of supply and demand issues for REE the extent to which an exclusive focus on traditional market dynamics may fail obscure in terms of their potential impact in terms of emerging environmental technologies.

For these reasons I have chosen to list both ‘major’ drivers for potential supply and demand problems, such as overall increase in global demand for REE, as well as the specific drivers which may fall under this broad category but I also deemed important in their own right. My hope in taking this approach is that I provide the reader with insight as to the major drivers for supply and demand problems, as well as highlighting specific risks associated with the drivers that contribute to them, and thus underline potential opportunities for policy intervention to mitigate these risks. The table below represents my personal interpretation as to the major drivers for supply and demand problems for REE and an attempt to categorize the potential impacts that these drivers might have in terms of the widespread deployment of emerging environmental technologies. It should be regarded not as an exclusive and comprehensive of all potential problems and issues involved with the use of REE in these technologies, but as a starting point for analysis of these complex issues. In the discussion below I will elaborate on what I see as specific potential impacts in terms of both deployment of these technologies globally, and for individual nations, industries, and/or specific technologies. In addition, I will attempt to identify some potential policies and strategies to address these impacts.

REE have recently received increased attention from policy makers and the mainstream media for two main reasons. The first is their escalating use in a variety of applications, and particularly those which are considered essential such as military technologies, and increasingly, promising emerging environmental technologies. REE are currently used in a variety emerging environmental technologies including but not limited to Wind Turbines, Vehicles, and Efficient Lighting. (See Table 2).

Table 3: Key Drivers for Supply and Demand Problems and Potential Impacts

Driver	Impact: Economic Category	Impact: Dimension of Scarcity	Impact: Type
Global demand for REE	Demand	Physical	Global
Global energy demand	Demand	Physical	Global
Domestic demand (China)	Demand	Physical, Political	Global, Specific Nations
Deployment rate of emerging environmental technologies employing REE	Demand	Physical	Global
Deployment rate of other applications employing REE	Demand	Physical	Global
Development of economically viable substitutes for REE	Demand	Physical	Global
Recycling and recovery	Demand	Physical	Global
Inter-industry competition	Supply	Physical, Economic	Specific Applications
Intra-industry competition	Supply	Physical, Economic	Specific Applications
Global supply of REE	Supply	Physical	Global
Production capacity	Supply	Physical	Global
Geological characteristics of deposits	Supply	Physical	Global
Mineralogical characteristics of REE	Supply	Physical	Global

Scientific and technical constraints	**Supply**	**Physical**	**Global**
Market dynamics: weak price signals	**Demand, Supply**	**Economic**	**Global**
Market dynamics: low value share	**Supply**	**Economic**	**Global**
By- production	**Supply**	**Economic, Physical**	**Global**
Co-production	**Supply**	**Economic, Physical**	**Global**
High capital outlays for new projects	**Supply**	**Economic**	**Global**
Development strategies aimed to reserve resource bases for exclusive use	**Supply**	**Political, Economic**	**Specific nations**
Production concentration	**Supply**	**Economic, Political**	**Specific Nations**
Restrictive financial polices	**Supply**	**Economic, Political**	**Specific Nations, Applications, Specific REEs**
Uncertain markets for REE: price volatility	**Supply**	**Economic**	**Global**
Uncertain markets for final technologies employing REE	**Demand**	**Economic**	**Global, Specific Nations, application**

Reliance on unstable suppliers	**Supply**	**Political**	**Global, Specific nations**
Using REE supply as leverage for political issues	**Supply**	**Political**	**Specific nations**
Environmental issues	**Supply**	**Political, Physical**	**Global, Specific Nations**
Social issues	**Supply**	**Political**	**Specific Nations**
Legal issues: intellectual property	**Supply**	**Political**	**Specific Nations**
Legal issues: permitting and regulation process	**Supply**	**Political**	**Specific Nations**

Source: Own creation based on research noted in accompanying text

As described above, steep increases in worldwide demand could represent a key driver to physical scarcity on the global level. Examining the specific drivers for increased demand reveals the extent to which many of them are policy-driven. Rising global energy demand has stimulated governments worldwide to implement policies to promote the widespread deployment of energy efficient technologies, thus contributing to rising demand for REE that many of these technologies employ. As I will illustrate in the case study on REE for large-scale wind applications, both the extent to which energy demand rises, and the proportion of this demand that technologies using REE ultimately satisfy can have large impacts on demand for REE. Due to the market dynamics for emerging environmental technologies discussed above, the policies and strategies that governments pursue represent a key factor in determining deployment rates for these technologies. These related issues highlight several important issues. In the first place, even well-intentioned policies to increase the amount of energy produced from renewable and less environmentally damaging technologies may be jeopardized if not coupled with policies to address the underlying issue, escalating demand for energy. Underscoring the need for long-term, comprehensive strategies, governments could of course promote the deployment of technologies that do not require REE, but would be wise to do so before pursuing the costly alternative of increasing production and securing supplies. Second, while the issues surrounding the use of REE for emerging environmental technologies are in some senses unique, they also highlight the critical role that serious consideration of material constraints of any technological solution must play in determining effective policies. Illustrating the complexity of the issue, the use of REE in large wind turbine applications is particularly advantageous in that it reduces the size and weight of the application, making wind power more economically competitive because less conventional materials are required.

As mentioned above, however, increases in demand could have various impacts besides physical scarcity. Increases in global demand could lead to increases in production-which in turn could be driven by market incentives, policies to fund research for more efficient extraction and refinement technologies, and efforts on the part of governments to fund new projects worldwide. Defining a specific impact of increased worldwide production is complicated by the fact that China not only dominates production of REE, but that domestic demand within China represents a key driver for overall increases in demand. While providing significant economic benefits for China, the ongoing influx of companies producing technologies using REE will have the consequence of increasing domestic demand for REE significantly. It is estimated that by 2012 China's domestic consumption for REE will outpace domestic production (Humphries, 2010; Seaman 2010). As a result, Chinese producers are actively seeking to expand production capacity in areas around the world, and Chinese investors have been actively seeking to acquire equity stakes in new rare-earth element producers particularly in Australia (Humphries, 2010; Moran, 2010). However, if Chinese political and producers represented the main driver for new projects worldwide, it is possible that global supply for REE could increase overall, yet fail to reduce risks of physical scarcity in other nations seeking to produce technologies employing REE.

Illustrating both the linkages between the dimensions of scarcity, and the importance of considering the entire supply chain for REE, the actual impact of rising domestic demand in China – if the bulk of comparable increases in supply go towards satisfying these increases- may vary greatly for individual depending on both their position on the supply chain in terms of producing emerging environmental technologies, and their geostrategic relationship with China. In other words, although all nations seeking to produce emerging environmental technologies may be impacted by growing domestic demand in China, "the degree of reliance depends upon where each economy sits along the supply chain. Clean energy and advanced electronics manufacturers such as Japan and South Korea are closer to the rare earth refining stage in the supply chain than other economies, such as the United States" (Webster, 2011). This example illustrates that individual national strategies must consider not only the likelihood of particular impact occurring, but also of its strength, and in doing so underscores the need for specific tailored strategies on the part of both governments and industries.

Similarly, due to the geostrategic aspects driving the supply and demand of REE, the potential impact of a particular driver may vary strongly according to the specific nation or region in question. Production concentration in China may contribute to economic scarcity in a general sense, but also pose particular risks to specific nations such as Japan, which both depends of REE for its domestic industries and shares a complicated and historically fraught relationship with China. Jane Nakano, the fellow in the Center for Strategic and International Studies in the Energy and National Security Program, writes that, “in surveying Japanese stakeholders, [she determined] there was a sense that something they wished would stay in the economic domain—Japan’s reliance on Chinese rare earth supplies—had reached into the political domain” (Webster, 2011). Comparing the relationship between Japan and China as the Japan and the US in the 1980’s, when trade relations were also strained, but economic issues did not cross over into the political realm, she concludes that, “different bilateral relationships may have a different level and type of threshold separating the divide between economic and political ties” (Webster, 2011). This analysis provides valuable insight into the differentiated impact that key drivers may exert on specific nations, and thus highlights the need for tailored national or regional strategies.

In terms of impacts on specific industries or technologies, even the effects of demand from competing industries may also be ambiguous. Of course, inter-industry competition has the potential lead to physical or economic scarcity for specific applications or technologies. As described above, REE generally make up only a small part of the cost of producing environmental technologies that employ them, still if these materials become physically scare in relation to overall demand, there is potential that extreme price spikes, or sheer lack of availability could cause producers to abandon these technologies. Illustrating the mutually reinforcing nature of various drivers, the lack of stable final markets for specific technologies could exacerbate the potential for this potential impact to occur.

Still, use of REE in other industries and application could alternatively lead to increases in global supply of REE and thus also available supply for emerging environmental technologies. This is particularly the case because REE are essential for various defense applications including fighter engines, missile guidance systems, and space-based satellites (Humphries, 2010). If securing supplies of REE is perceived as a vital national security issue this could well spur efforts on the part of governments to increase production worldwide, both increasing global supply and mitigating the geopolitical and economic impacts of extreme production concentration. Similarly, the existence of established and growing markets for non-environmental technologies and applications using REE has the potential to provide REE producers with economic incentives to initiate new projects, particularly if coupled with policies to reform permitting processes and regulatory barriers contributed to the long lead times and high capital outlays associated with bringing new mines online. On the demand side, policies to fund research into the development of effective substitutes and efficient recycling and recovery projects could have significant impacts in terms of curbing runaway demand, reducing the potential for supply-demand mismatch.

The use of REE in more established technologies thus contributes to both risks and opportunities in terms of achieving the widespread deployment of environmental technologies employing REE. On the one hand, as discussed above, national security concerns have already contributed to increasing awareness as to risks of both potential for supply shortages on the global level, for individual nations, extreme production and market concentration in China. Sill, inter-industry competition has the potential to contribute to scarcity for specific industries and technologies. For nations seeking to promote the production and deployment of the dynamics of markets for REE, and in particular the fact the REE are not traded on spot exchanges as conventional materials may exacerbate this impact. Since applications for individual tend to be very specific, this impact may have strong consequences for technologies requiring specific REEs.

On May 27th 2010 it was announced that China's first rare earth spot exchange will be established as early as August this year, led by the Inner Mongolia Baotou Steel Rare-Earth Hi-Tech Co Ltd, the world's largest rare-earth producer. Modeled after the China Iron and Steel Association, the exchange will assist companies in exports and international cooperation and lead price talks with foreign buyers, limiting the role of individual traders. As reported in China Daily, former Ministry of Industry and Materials official Wang Caifeng said the exchange, which will be established on August 8, 2010, will help increase the transparency and regularization of the rare-earth trading market. If the exchange represents a step toward developing a nationwide exchange, it could thus represent a step towards more transparent global markets for REE, potentially alleviating some of the impacts associated with unclear price signals in REE markets. Still the overall impact on specific nations requiring REE is unclear. Yuan Zhibin, an industry analyst with the CIC Industry Research Center notes that "Recognition of the exchange could gain Baotou Steel, as well as the whole Chinese rare earth industry, a bigger voice in the international rare-earth market" (Fei, 2011) increasing the impacts related to market concentration, and thus China's ability to effect prices, and use industry control as leverage on other issues. In this sense, the implications of potential impact of the exchange reveals both the need to diversify supplies of REE, but also the potential for market reforms to mitigate supply constraints resulting from the dynamics of markets for REE, particularly in regard to available supplies of specific REE.

The preceding discussion has focused on opportunities for government polices to mitigate supply risks for emerging environmental technologies employing REE. In addition however, producers of such technologies have the potential to reduce the potential for scarcity of specific REEs. For example, according to TMR founder Jack Lifton, "a straightforward solution would be for an end user to buy the critical heavy rare earths, and all of its needs for the light rare earths, from the heavy-rare-earth producer. This might necessitate paying more than the market price for the light rare earths, but it would secure the supply of the critical heavy rare earths" (Lifton, 2011). Still, particularly due to the often-uncertain markets for final environmental technologies, government policies will remain a key factor promoting the production and deployment of such technologies. As discussed above, this is especially the case due to the potential environmental and social impacts associated with extraction and refinement of REE. Environmentally sound mining and refining techniques entail additional costs. Market dynamics fail to provide producers with incentives to cover these costs. As discussed above, these impacts may contribute to reliance on unstable suppliers, and thus risks of supply disruptions even despite increases in production overall.

As mentioned previously, the complicated relationship between various drivers for supply and demand for REE for emerging environmental technologies presents serious challenges in terms of determining the impact of a particular driver with certainty. In addition, various drivers either independently or in combination may exert differential impacts on various nations, industries, and applications. The above analysis therefore represents not an exclusive interpretation of the specific impacts of various drivers, but rather an attempt to illustrate the complexity of the issues surrounding the use of REE for emerging environmental technologies, investigate the possible impact of various drivers, and identify possible opportunities to mitigate disruptions and constraint to supply of REE for these technologies. Policy makers will increasingly be required to weigh the economic and environmental benefits associated with the use or REE against attendant risks and develop cohesive long-term strategies. I hope that this analysis provides a useful starting point from which to do so. In the following section I will present a case study of a specific application for REE, generators for large-scale wind turbines, and attempt to analyze how the use of REE might impact the potential for widespread deployment, and in evaluating the feasibility and desirability of these technologies.

6. Case Study: REE & Emerging Wind Energy Technologies

6.1 Basis of Study

In the preceding chapters I have focused on key drivers for supply and demand problems for REE in general and emerging environmental technologies more specifically. In the following section I will look specifically at the use of REE in the permanent magnet technologies increasingly used in large-scale wind turbines, and how the use of REE in these applications might impact the extent to which they could satisfy rising energy demand. To provide context, I will first discuss the promise of wind power, and the specific advantages conferred by the use of REE in large-scale wind applications.

Rechberger and Zuser have calculated the material demand for four different photovoltaic technologies and shown that because these technologies use rare metals, certain scenarios envisioning PV installations supplying a significant portion of increase in global energy demand by 2050 cannot be achieved. In will attempt to build on their research to determine the extent to which material constraints could influence the ability of wind power technologies employing REE to represent a viable way to satisfy energy demand under various scenarios. In order to do so I will examine two scenarios based on data from the International Energy Agency's (IEA) 2010 World Energy Outlook, a more conservative 'Current Policies Scenario' (replacing the 'Reference Scenario' in previous World Energy Outlook reports), taking into account only polices and measures currently in place, and a '405 Scenario' that assumes governments implement measures necessary to stabilize greenhouse gases as 450 ppm by 2030 as mandated by the Copenhagen Accord, as well as "other policies currently under discussion or announced but not yet implemented" (IEA, 2010).

However, as I have attempted to illustrate above, the use of REE in emerging environmental technologies involves significant uncertainty on both the supply and demand side. In particular the unique characteristics of REE and peculiarities of markets for REE mean that the degree to which increases in production take place will be based to a large degree on policy decisions, introducing additional uncertainty into predicting increases in global supply. The analysis will therefore not attempt to make a conclusive prediction as to possible future deployment rates for wind technologies employing REE based on future supply, but instead use the example of a specific technology to illustrate the extent to which the polices governments pursue may have unintended effects in terms of demand for materials required to execute them. Using the example of REE for wind applications I hope to show that while the use of REE confers significant benefits in terms of the technical and economical viability of large-scale wind applications, rising energy demand in particular has real potential to impose constraints in terms of widespread deployment of these technologies, particularly in the short to medium term. In doing so I hope to show the necessity of strategies taking material constraints into account.

6.2 The Promise of Wind Energy: potential to satisfy raising energy demand

The Current Policies Scenario predicts a steep rise global electricity demand, i.e. total electricity generated, from the baseline 20,183 TWh in 2008, reaching 34,716 TWh by 2030 powered by a total installed electric capacity of 8,056 GW. The more optimistic 405 Scenario anticipates a less dramatic, but still significant rise in demand to 30,170 TWh in 2030 powered by a total installed electric capacity of 7,689 GW (IEA, 2010).

To put these figures in perspective, in terms of the purely energetic potential for wind energy technology, the theoretical limit for energy production is 6,000 EJ, or 1,666,670 TWh (Resch et al, 2008), a figure several orders of magnitude greater than current or projected electricity demand to 2030. Moreover, there is general consensus that the technical potential for wind-based technologies – a measurement which takes into account practical boundary conditions such as the efficiencies of conversion technologies and area available to install wind turbines, as well as environmental and regulatory limitations – is still more than enough to cover current and projected increases many times over (Edenhofer et al, 2011; GWEC, 2010; Resch et al, 2008). For example, a 2009 study by Harvard University and Finland's VTT Technical Research Centre, Global Potential for Wind-Generated Energy, concludes that "Wind could supply more than 40 times current worldwide consumption of electricity, and more than five times total global use of energy in all forms" (Lu et al, 2009.) In is also important to note that, "the technical potential must be seen in a dynamic context" (Resch et al, 2008). In the case of wind power, new technologies have the potential to drastically increase the technically usable fraction of wind potential, particularly those that make off shore wind more feasible and politically palatable (GWEC, 2010). As I will discuss below, technologies employing REE have strong potential to fulfill this requirement. Even if technological development were to stagnate, however, which given the current market trends appears unlikely, neither the technical potential of wind as a resource or constraints as to current technology can be seen as limiting factors in the widespread deployment of wind technologies.

Compared to current and projected global electricity demand under either scenario, wind power offers a potentially enormous energy resource. Like the resource 'sunlight,' wind is "supplied all over the world, for free, and with no emissions" (Rechberger and Zuser, forthcoming). Thus response to concerns surrounding climate change and rising energy demand, wind energy offers an initially promising alternative to dwindling and polluting fossil fuel resources.

In addition, wind energy is increasingly seen as an economically as well as environmentally viable option. For the first time, the 2010 edition of the IEA's Projected Costs of Generating Electricity has onshore wind power replacing oil to join coal, gas and nuclear as the main technologies which will compete for market share in the power sector of the future (GWEC, 2010). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) shows that the medium range of recent levelized cost of wind for selected commercially available technologies is slightly higher than, but comparable with the range of non-renewable energy cost (Edenhofer et al, 2011).2 Illustrating the growing consensus that wind technology offers a particularly promising alternative to fossil fuels, global wind markets have grown steadily over the last decade, by an average 28% per year in terms of total installed capacity (GWEC, 2010). Indeed, the Ernst & Young "Renewable Energy Country Attractiveness Indices" mentioned above include an 'All renewables indice' as part of which specific technologies are scored out of a hundred based on their attractiveness in terms of future investment opportunities. Wind power tops the list at 68 percent, far higher than the second highest scoring technology, solar, which receives a rating of just 15 percent (Ernst & Young, 2010).

It is also worth noting that wind currently supplies a small percent of current energy demand, but relatively larger portion than other emerging technologies excepting hydropower and biomass, both of which have significant environmental drawbacks which wind does not. The significant increase in wind power is attributed improvements in technology, but also reductions in costs and barriers to obtaining finance for new projects, especially for offshore wind. Even in the Current Policies Scenario the share for wind power is projected as significantly higher - 4.7 percent- than the share for the solar, which is projected to supply less that 1 percent of total electricity generated in 2030 (IEA, 2010). These figure indicate that markets for wind technology are more

[2] The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer; the cost of integration; or external environmental or other costs. Subsidies and tax credits are also not included.

established than those for other promising emerging renewable environmental technologies, a key driver for the further growth of market share.

This is especially the case due to the key driver of domestic demand within China. Even despite the fact that growth rates3 of installed capacity have slowed, the World Wind Energy Report 2010 showed the second lowest growth rate of the last decade, 23,6 %, numerous studies predict that installed capacity will continue to increase significantly. (WWEA, 2010; GWEC, 2010; IEA, 2010) This may largely be due to domestic growth in China. In 2009 alone, China added 13.8 GW of new wind power capacity, compared with 6.3 GW the previous year, "making it a world leader in terms of new installations in 2009" (GWEC, 2010). In 2010, the Chinese wind market added 18,9 GW, representing a market share of 50,3 % (WWEA, 2010). These figures are significant not only because they demonstrate the Chinese government's commitment to promote the diffusion of wind power and economic wherewithal to do so effectively, but also because the Chinese political system is less dependant on political fluxuations which may affect future government funding for renewable technologies and certainly introduce greater uncertainty in terms of future market demand. In this sense China stands in stark contrast to the second largest market for wind technology, the United States. While the past decade saw enormous growth in US wind power – from slightly more than 2.5 GW installed capacity in 2000 to a "world-leading" installed capacity of more than 35 GW by the end of 2009 – that growth has never been steady, with "reasons that often seem to have more to do with Washington politics than political will, national policy has been short-term and inconsistent, with the industry either speeding to catch the green light, or braking hard" (GWEA, 2010). Still, despite the impact of the financial crisis, installed capacity reported to be under construction in the

[3] growth rate = relation between new installed wind power capacity and the installed capacity of the previous year.

US as of the end of the first quarter of 2011 was 5,600 MW more than twice the amount under construction at the comparable point in 2009 or 2010 (Grey, 2011). However, China is likely to play a increasingly pivotal role in the overall diffusion of these technologies. China not only now accounts for over fifty percent of the global market for wind technologies, but “given the sheer scale of China’s domestic market, its push to increase the share of new low-carbon energy technologies could play an important role in driving down their costs through faster rates of technology learning and economies of scale” (IEA, 2010). Taken together, these two facts suggest that China’s leading role in the wind sector will be a key driver for sustained growth of the wind industry in coming decades.

The extent to which market growth will be realized is uncertain. The actual growth of markets for wind technologies will depend strongly on both financial supports by governments and investor confidence, and are thus difficult to predict accurately. Still, a result of the factors elaborated above, wind power seems poised to play an increasing role in the move to replace fossil fuels with renewable energy sources.

6.3 Wind Technology and REE: Applications and Advantages

REE based magnet technologies are increasingly used in the generators of wind turbines, with the most widely employed type consisting of an alloy of neodymium, iron, and boron (NdFeB). In a 2008 report on increasing wind energy’s contribution to US energy supply, the US Department of Energy includes the use of Rare Earth permanent magnets as a key trend in wind technology: “Rare-earth permanent magnets are now taking over the market with Asian suppliers offering superior magnetic properties and a steady decline in price” (U.S. DOE, 2008).

As touched upon above, due to their unique properties, REEs such as neodymium and dysprosium can be used to make magnets that are not only more powerful, but also much lighter and smaller than traditional Ferrite magnets, which "have long been the staple in permanent-magnet generators for small wind turbines…this enables more compact and lighter weight generator designs" (U.S. DOE, 2008) In addition, using permanent NdFeB magnets in generators allows "relatively high temperatures (U.S. DOE 2008) and high remanence flux (Kurronen, 2011) or level of magnetization retained after an external magnetic field is removed. Both factors are indicative of the relative strength and durability of NdFeB magnets, and thus the advantages they confer over traditional magnets.

Moreover, turbines using NdFeB can operate without gearboxes, increasing reliability and thus significantly reducing the need for and cost of maintenance. These so-called 'direct drive' systems replace high-speed generators used in traditional systems with low-speed generators, eliminating the need for a gearbox. In conventional wind turbines, gearboxes increase the speed of the wind driver rotors several hundred-fold, reducing the size and weight of the generator required. Direct-drive generators operate at the same speed as the turbine's blades and therefore would generally required to be much larger. Normally this would be problematic because it would increase the size, weight of each unit significantly, and thus the amount of conventional materials required and the cost of each unit. The use of REE permanent magnets, however, can reduce size and weight dramatically, as well as affording other advantages mentioned above. Illustrating the differences in the amount of materials required for the battery aolne, a 15-millimeter-thick segment of permanent magnets can generate the same magnetic field as a 10- to 15-centimeter section of copper coils (Fairly, 2010).

In addition to eliminating much of the weight associated with generators relying on copper-based magnets, the high energy density of REE magnets eliminates problems associated with insulation degradation and shorting, and thus reduces electrical losses. “Parasitic losses” (U.S. DOE, 2008) in gears, and other electrical devices are individually quite small but can add up to significant numbers. Technological improvements that remove or reduce losses therefore have the potential to have an important impact on raising the capacity factor – the ratio of the actual output of a power plant over a period of time and its potential output - and thus reducing costs. The US Department of Energy includes switch to direct drive systems as a key means to achieve these goals through eliminating energy losses associated and reducing reliability issues with gearboxes, which are expensive to replace (U.S. DOE, 2008).

Significantly, due to the advantages elaborated above, the use of REE in wind turbine generators have facilitated the development of more larger, higher capacity turbines, and thus promoted development of, and investment in, offshore wind installations. As mentioned above, the ability to build larger turbines requiring less conventional materials offers considerable benefits in terms of improving technical and thus economic efficiency. In the first place, “the higher the turbine is mounted, the better the wind resource. Further, higher turbines are less prone to be affected by turbulence caused by obstructions, topography, surface roughness or thermal effects” (GWEC, 2010) As a result, “turbines have also grown larger and taller. The generators in the largest modern turbines are 100 times the size of those in 1980. Over the same period, their rotor diameters have increased eight-fold,” according to the Global Wind Energy Council. “In 2006 alone, average turbine size increased by more than 11 percent over the 2005 level to an average size of 1.6 MW” (U.S. DOE, 2008). In addition, large turbines are particularly well suited to offshore wind applications. Because the potential energy produced by wind is directly proportional to the cube of the wind speed, and wind speeds tend to be stronger and more sustained offshore, an offshore turbine should be able to produce significantly more electricity than a similar turbine located on land.

These two trends towards larger turbines and interest in offshore wind applications have reinforced each other, with the offshore market representing “a main driver for larger capacity machines [since] placing turbines on the seabed demands the optimum use of each foundation” (GWEC, 2010). The 2011 IPCC SRREN includes “foundation and turbine designs for offshore wind energy” as an example of important areas of potential technological advancement that could reduce costs of these technologies significantly, and thus promote greater potential deployment. The advantages associated with these technologies could thus have potentially significant effects in terms of the efficiency and cost effectiveness of wind power. As a result, he latest generation of large wind turbines, and offshore turbines in particular depend increasingly on REE, and projections suggest that this trend will continue (Seaman, 2010).

6.4 Wind Technology and REE: The Role of Material Constraints

In terms of the amount of REE demanded by wind technologies, these interrelated developments are significant in several senses. In the first place, as discussed above, turbines currently under development are larger and taller than their predecessors (GWEC, 2010). Secondly, due to both the benefits associated with offshore wind and the technological improvements that have made these applications increasingly feasible, offshore wind capacity is expected to grow dramatically. Demand for large wind turbines, and thus for REE, are therefore also likely to increase further.

By addressing some of the technical problems associated with large turbines in general and offshore installations in particular, the use of REEs has also seemingly reduced the perceived risk in investing seriously in these technologies. For example, while noting that the market for large wind turbines using permanent magnets in their generators is still relatively small, the U.S. DOE predicts that, “their share is likely to grow as purchasers increasingly choose larger turbine for wind projects” (Bauer et al, 2010).

The largest turbine currently in operation as of 2011 is the Enercon E126, an onshore turbine manufactured by the German wind turbine producer Enercon. with a rotor diameter of 126 metres and a power capacity of 6 MW, but efforts develop 10 MW turbines are underway (Jacobson and Delucchi, 2011). According to the Global Wind Energy Council's (GWEC) website, though the offshore wind farms installed so far have used turbines in the capacity range up to 3.6 MW, a range of designs of 5 MW and above are now being deployed and are expected to become the 'standard' in the coming years.4 In Europe in particular, offshore wind "is set to become a mainstream energy source in its own right" (GWEC, 2010) with the offshore wind power market exhibiting strong growth and steadily increasing installed capacity throughout 2009-2010, even despite the financial crisis. In the United States, which had yet to enter the offshore market as of October 2010, there are various projects under development, and China, the world's largest market for wind power, the National Energy Administration (NEA) has required all coastal provinces to compile provincial offshore wind development plan up to 2020 (GWEC, 2010).

By facilitating interconnected trends towards large-scale, large-capacity turbines and offshore wind systems, the use of REE has therefore acted as a driver for technological advances in the wind energy sector. The proliferation of such technologies, has in turn acted as a key driver for demand of REE. "Vestas, a Danish company that has become the world's biggest wind turbine manufacturer, said that prototypes for its next generation used dysprosium. Goldwind, the biggest Chinese turbine maker, has switched from conventional magnets to rare-earth magnets" (Bradsher, 2009). As of January 2011, fourteen percent of newly installed wind turbines on the market already used NdFeB magnets (Öko-Institut, 2011), and due to the advantages above, the industry is increasingly switching from geared electromagnetic induction turbines to direct drive permanent magnet turbines employing REE (Seaman, 2010).

[4] http://www.gwec.net/index.php?id=31&L=0

Advantages gained from REE are already leading to more investment in and production of specific technologies, particularly by facilitating development of larger, higher capacity turbines, suitable for offshore wind. In other words, the advantages conferred by the use of REE have a cyclical relationship with demand for emerging wind technologies employing these materials, and this for demand for REE. In addition to promoting higher deployment rates for wind power technologies, the larger and more powerful turbines that are likely to increasingly dominate the market will require higher quantities of REE for each unit. To provide a sense of the potential impact in terms of demand for REE, according to Jack Lifton, Co-founder and Director of Technology Metals Research, LLC, current estimates indicate that building the latest and most efficient one MW capacity wind turbine powered electric generator requires one ton of neodymium (Lifton, 2009). Ten MW gearless wind turbines currently under development will probably use about 5 tons of permanent NdFeB magnets per unit (Graeme, 2010).

Still, even as turbines become larger, wind farms proliferate, and installed capacity continues to increase worldwide constraints imposed by conventional materials should not limit the growth of wind power. Pointing to a 2008 study by the US Department of Energy, Jacobson and Delucchi conclude that the availability of bulk materials for wind turbines such as steel and concrete should not serve as a limiting factor, that "there do not appear to be significant environmental or economic constraints on expanded production of these bulk materials." Moreover, the bulk of these materials can be reused and recycled, for example, "the steel used to make towers, nacelles, and rotors for wind turbines should be virtually 100% recyclable" (Jacobson and Delucchi, 2011). In the U.S. in 2008, for example, 98% of steel construction beams and plates were recycled (USGS, 2010).

Instead, Jacobson and Delucchi suggest that for wind power "the most problematic materials" (Jacobson and Delucchi, 2011) are likely to be REE like neodymium. Growth in wind market in expected to represent a key driver for higher demand for neodymium and dysprosium and several projections suggest that this increase could strain supplies and that that the use of REE could act as the limiting factor in the proliferation such technologies. (Lifton, 2009; Margonelli, 2009; Bauer et al, 2010).

Determining future market shares for wind technologies in general, and technologies that employ REE more specifically, however, is difficult to predict with certainty. The two scenarios mentioned above predict stark differences in overall energy demand, itself an important driver for demand for REE. Each scenario predicts an increase in installed capacity of wind energy but also at different level. The IEA Current Policies Scenario predicts increase in wind-generated electricity from 219 TWh in 2008 to 1,635 TWh in 2030, powered by an increase in installed capacity to 662 GW, from baseline level of 120 GW installed capacity in 2008. The 405 Scenario envisions that wind energy will provide 3,197 TWh, powered by an increase in installed capacity to 1,148 GW in 2030. Both scenarios, however, are intended primarily to examine the environmental effects of potential policy paths. The 405 Scenario represents an optimistic projection of the potential impact of governments pursuing policies to both reduce overall energy demand, and satisfy an increasing proportion of this demand with renewable energy sources, while the Current Scenarios envisions a less proactive and more pessimistic course of action. However, as discussed above, producers and individual nations have not only environmental, but also economic incentives to increase production of emerging environmental technologies such as large scale wind turbines. There is thus significant possibility for a scenario in which sharp increases in energy demand are combined with large increases in wind share, creating greater demand for REE than either IEA scenario envisions. While the IEA scenarios do not address the potential for demand for REE to constrain the development of wind technologies employing them, several other studies have examined the relationship between deployment levels for wind technologies and supply constraints for REE.

For example, Jacobson and Delucchi envisions a scenario in which 3.8 million 5 MW wind turbines supply 50 percent of projected total global power demand in 2030, a highly ambition projection for the growth of wind share in power generation. He calculates that building 19 million installed MW (19000 GW) of wind power would require 3.8 million metric tons of neodymium (Nd) or about 4.4 million metric tones of neodymium oxide (Nd oxide), which is "the commercial feedstock from which neodymium metal is refined and NdFeB magnets are fabricated" (USDOE, 2010). In 2008, the world produced about 22,000 metric tons of Nd oxide (Jacobson and Delucchi, 2011). Under Jacobson and Delucchi's scenario, which assumes a given partitioning of demand among plants or devices, with rated power of one plant or device equaling 5 MW, the demand for Nd oxide from wind technology would amount to approximately 100,000 metric tons of Nd oxide per year over a 40–50 year period. Annual world production of Nd therefore would have to increase by a factor of more than five to accommodate the demand only for production of permanent magnets for wind-turbine generators. Jacobson and Delucchi's scenario represents a highly ambition projection for the potential of wind power to supply future energy demand (tellingly, it appears in an paper entitled, 'Providing all Global Energy with Wind, Water, and Solar Power.') Still it highlights the necessity of considering not only the potential environmental benefits of widespread deployment of emerging environmental technologies, but also potential constraints in terms of the materials they require.

The U.S. DOE's Critical Materials Strategy describes several possible trajectories for future demand of REE in magnet technologies, taking into account various scenarios in terms of deployment, market share for specific technologies, and material intensity in those technologies. Showing the difficulties in predicting actual market shares for specific technologies, for offshore wind turbines using REE, the report predicts penetration rates between 10 and 75 percent for off-shore wind technologies using REE in 2025, depending on the scenario chosen. While the report notes that there is no concrete data available on market share for wind technologies employing REE, the high market share prediction is based on "the preference for NdFeB permanent magnet generators in larger wind turbines (in the 2-3+ MW range) and the trend towards the use of larger turbines in new wind projects, particularly for offshore applications" (U.S. DOE, 1020). Although the report concludes that, "the basic availability of Nd oxide is adequate in the short term" (Bauer et al, 2010) projected non-clean energy demand alone will exceed projected 2015 supply before 2025. Under high penetration scenarios, clean energy technologies represent an increasing proportion of overall Nd oxide demand. These projections suggest significant potential for inter-industry competition to create scarcity for clean energy technologies employing REE. In addition, "Nd demand in vehicles contributes roughly five times higher demand in wind turbines," illustrating the potential for intra-industry competition among various emerging environmental technologies to create scarcity for wind applications in specific.

In addition, as mentioned previously, supply risks for dysprosium, which is also increasingly used in permanent magnet technologies are predicted to be still more likely. The report shows that not only is the availability of dysprosium "tight in the short term," but that "global demand exceeds projected 2015 demand under all four trajectories in the beginning of the medium term" (Bauer et al, 2010).

In the case study above I have attempted to show that not only does wind power offers a promising alternative to fossil fuel use, but that the use of REE in wind technologies provides significant advantages in terms of improving the technical and economic efficiency of these technologies. In doing so, the use of REE has the potential to reduce serious barriers to achieving the widespread deployment of these technologies. The extent of actual future deployment rates, and thus the extent to which promise of these technologies is realized is difficult to predict and will depend heavily on the policies pursued by governments worldwide. Still, even under conservative scenarios, the use of REE introduces material constraints that could make widespread production and deployment unfeasible. Material constraints associated with the use of REE are therefore likely to play a significant role in the potential for the widespread deployment of wind technologies. In some cases, efforts to increase production of REE, develop substitutes, and implement effective recycling and recovery programs may be sufficient to mitigate these constraints, but these efforts are unlikely to be adequate if not implemented with haste. As mentioned above, developing effective substitutes has proven difficult, and therefore achieving the widespread technologies of certain technologies may be deemed unfeasible. In this sense the issues surrounding the use of REE in wind technologies highlight the importance of long-term, comprehensive policies that take into account not only the potential promise of specific technologies in terms of environmental effects, but also potential material constraints associated with their use.

7. Conclusion

This thesis has attempted to illustrate that the use of REE in emerging environmental technologies involves both significant potential benefits and unique risks, and therefore may play a critical role in determining which technologies are feasible and desirable, as well as in guiding what strategies may usefully be adopted to achieve widespread deployment.

The relationships between key drivers for supply and demand for REE in general, and for emerging environmental technologies in particular, are complex and often not linear. I have attempted to tease out and explore the potential impacts of many of these complexly entwined variables by examining how they might impact various dimensions of resource scarcity: physical, economic, or political. While the dimensions of scarcity are clearly interrelated, I believe that this framework provides a valuable lens through which to analyze the specific causes and potential impacts of supply and demand shifts, and moreover, how they might impact individual nations, industries, or technologies. Viewing drivers in terms of how they might impact various dimensions of scarcity underscores the need for tailored yet comprehensive strategies on the part of both governments and industries.

The use of REE for emerging environmental technologies requires consideration of geostrategic, as well as economic and environmental factors. Therefore the development and implementation of long-term, comprehensive strategies that consider material constraints seriously will be increasingly necessary in order to take timely measures to mitigate risks that could represent barriers to the future use of promising technologies.

China's current dominance of the REE industry and apparent willingness to use its position as leverage on geostrategic issues has raised concerns worldwide. However, an exclusive focus on production concentration obscures issues further along the supply chain. What is most striking about China's current dominance of the REE industry is not current production concentration in China, but the pace and extent of the subsequent migration of producers of industries using REE to produce technologies higher along the supply chain to China. In this sense examining policies that Chinese leaders have pursued in terms of fostering innovation and value-added production within its borders provides prove valuable insight into the need for long term strategies to any country seeking to promote the production of emerging environmental technologies. Doing so suggests both the need and potential for long-term strategic planning and cohesive strategies for critical materials, and highlights the value of investing in intellectual infrastructure and considering the entire materials supply chain rather than any limited to isolated aspects.

An analysis of the materials supply chain also, however, highlights a significant risk associated with the use of REE and energy technologies more broadly: the material constraints and material demands of various technologies. The electron structure of the REE lends them the ability to form unusually strong, lightweight magnetic materials and resist very high temperatures, unique characteristics that have the potential to improve the efficiency of wind technologies significantly. In my Case Study I show how wind turbines alone may be called on to provide an increasingly significant portion of the worlds energy demands and that in the long-term the raw potential supply of wind power could far exceed the projected demand. But under various scenarios the projected demand for wind turbines alone for the year 2030 would likely far outstrip any projected supply of the REE they would require. This underscores the importance of considering not only the environmental promise, but also the material constraint associated with technologies employing REE.

As I have attempted to illustrate by looking at the example of wind technologies employing REE – a promising alternative energy source environmental source from both an environmental and economic standpoint- even well-intentioned policies to increase the amount of energy produced from renewable and less environmentally damaging technologies may be jeopardized if not coupled with policies to address the underlying issue, escalating demand for energy.

More broadly, however, the issues involving REE represent a microcosm of a much larger debate involving the use and distribution of resources in an increasingly globalized and energy-hungry world. In particular, the environmental impacts of REE production illustrate the linkages between resource uses. In this sense the use of REE for environmental technologies illustrate the extent to which any technological solutions to current dependence on fossil fuels imply trade-offs and require an ecologic mode of thinking which assesses a web of relationships in addition to linear cause and effect. As resources are seen more and more as strategic goods, governments and industries that wish to use REE now and in the future would be wise to develop long-term strategies that address all three dimensions of scarcity and address them in mutual context. In this sense, the thesis points towards the conclusion that a long term view that is also broad in scope, allowing holistic synthesis of apparently disparate aspects will be increasingly needed and will yield the most effective outcomes.

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