# EVALUATING UNITED STATES AND WORLD CONSUMPTION OF NEODYMIUM, DYSPROSIUM, TERBIUM, AND PRASEODYMIUM IN FINAL PRODUCTS

by

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# ABSTRACT

This paper develops scenarios of future rare-earth-magnet metal (neodymium, dysprosium, terbium, and praseodymium) consumption in the permanent magnets used in wind turbines and hybrid electric vehicles. The scenarios start with naïve base-case scenarios for growth in wind-turbine and hybrid-electric-vehicle sales over the period 2011-2020, using historical data for each good. These naïve scenarios assume that future growth follows time trends in historical data and does not depend on any exogenous variable. Specifically, growth of each technological market follows historical time trends, and the amount of rare earths used per unit of technology remains fixed. The chosen reference year is 2010.

Implied consumptions of the rare earth magnet metals are calculated from these scenarios. Assumptions are made for the material composition of permanent magnets, the market share of permanent-magnet wind turbines and vehicles, and magnet weight per unit of technology. Different scenarios estimate how changes in factors like the material composition of magnets, growth of the economy, and the price of a substitute could affect future consumption. Each scenario presents a different method for reducing rare earth consumption and could be interpreted as potential policy choices.

In 2010, the consumption (metric tons, rare-earth-oxide equivalent) of each rare-earth-magnet metal was as follows. Total neodymium consumption in the world for both technologies was 995 tons; dysprosium consumption was 133 tons; terbium consumption was 50 tons; praseodymium consumption was zero tons. The base scenario for wind turbines shows there could be strong, exponential growth in the global wind turbine market. New U.S. sales of hybrid vehicles would decline (in line with the current economic recession) while non-U.S. sales increase through 2020. There would be an overall increase in the total amount of magnetic rare earths consumed in the world.

Total consumption of each rare earth in the short-term (2015) and mid-term (2020) scenarios could be between: 1,984 to 6,475 tons (2015) and 3,487 to 13,763 tons (2020) of neodymium; 331 to 864 tons (2015) and 587 to 1,834 tons (2020) of dysprosium; 123 to 325 tons (2015) and 219 to 687 tons (2020) of terbium; finally, zero to 871 tons (2015) and zero to 1,493 tons (2020) of praseodymium. Hybrid vehicle sales in non-U.S. countries could account for a large portion of magnetic rare earth consumption. Wind turbine and related rare earth consumption growth will also be driven by non-U.S. countries, especially developing nations like China. Despite wind turbines using bigger magnets, the sheer volume of hybrids sold and non-U.S. consumers could account for most future consumption of permanent magnets and their rare earths.

## TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

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# CHAPTER ONE

# INTRODUCTION

In the last two decades, rare earth elements have become vital components used in advanced electronics systems, military applications, and emerging green energy technologies like the hybrid electric vehicle (HEV) and wind turbines. Amplified demand for rare earth-containing products throughout the 1990s, coupled with the 2002 closure of Molycorp's Mountain Pass mine in California, have led to a reliance on imports from foreign entities. Rare earths are primarily supplied by China and to a lesser extent Australia, South Africa, Canada, and India. Cheaply-priced Chinese exports and subsequently historically low prices resulted in the decline of U.S. dominance in all stages of rare earth production, with the majority of up and downstream value-added production becoming located in China (Haxel, Hedrick and Orris 2002).

Export tariffs and quotas for rare earth products, ranging from raw ore to metals and powders, previously existed in China. A 2009 draft of new government legislation regarding their mineral exports was released. It recommended full bans on the export of some rare earth products and that export quotas for others be reduced (Bradsher 2009). Chinese authorities announced the official establishment of price-fixing mechanisms and a 72% cut in exports as of July 2010 (Humphries 2010, 4). The former action streamlines industrial output while the latter encourages local production of final goods. These issues remain prominent in 2011 and 2012; China's government "shut down its rare earth industry for three months [in 2011]" (REUTERS 2012) and "recently handed out additional quotas to 12 companies" (Savitz 2012). After more than two decades of rare earth mining by companies operating with few, if any, environmental or regulatory constraints, China has reversed course and begun implementing measures to take hold of their domestic resource economy and environmental quality.

There is a tentative sense of relief regarding supply concerns among North American, European, and Japanese companies that produce rare earth components and final products. This is the result of several factors, first of which is the re-opening of Molycorp's Mountain Pass mine and the resumption of extraction, separation, and refinement processes in 2011 (Molycorp 2011). A large portion of this production is comprised of light rare earths such as lanthanum, neodymium, and praseodymium. Planned expansion will result in the production of "commercially significant quantities of heavy rare earths like europium, terbium, dysprosium, and yttrium" (Molycorp 2012). Molycorp achieved "mine-to-magnet" vertical integration in June 2012 after purchasing Neo Materials and their subsidiary Magnequench (Harden 2012). Renewed production by Molycorp at every stage of upstream supply will help contribute a small supply of non-Chinese rare earth materials to Western producers of downstream goods (Molycorp 2012).

Another factor contributing to this sense of relief is the new production of rare earth materials from Lynas Corp.'s Mt. Weld in Australia. Lynas Corp. has not recently been mining their deposit, instead focusing on the separation and concentration of previously-mined rare earth ore stocks. They conducted studies recently that served to increase the quantity of resources and reserves believed to be contained within the Mt. Weld deposit (Lynas Corporation Ltd. 2012, 12). These new estimates of resources "confirm [Mt. Weld's] status as the richest known deposit of Rare Earths in the world … at 1.9 million tonnes of rare-earth-oxide (REO)" (Lynas Corporation Ltd. 2012, 12), while it was found that the deposit's reserves are now "260% higher than the 2005 estimate" (Lynas Corporation Ltd. 2012, 12). It is highly enriched with light rare earths (primarily lanthanum, cerium, and neodymium) and does not contain notable quantities of heavy rare earths. Lynas is attempting to vertically integrate by building a Malaysian processing facility; the firm is currently engaged in a legal battle with local opposition groups (Berube 2012).

Both of these mines are thought to be the ‘best’ alternatives to Chinese rare earths due to their advanced operational nature and the quality and quantity of their in-situ resources. Even with both sites producing at full capacity, China will remain the primary source of both light and heavy rare earth materials (Bauer et al. 2011, 51-52). New sources of rare earths may benefit producers in the short term but will not alleviate long-term supply issues as global demand for rare earths expands. Other sources like Canada’s Thor Lake (Avalon Rare Metals Inc. 2011) and South Africa’s Steenkampskraal (Great Western Minerals Group Ltd. 2010) remain in exploratory and developmental stages and are not projected to be operational until 2015 at the earliest. Also, rare earths have unique physical and chemical properties that are difficult to replicate; adequate material substitutes are virtually non-existent.

With the U.S. and global economies facing an uncertain future and an ever-changing landscape of geopolitical alliances, the rare earth supply situation has caused concern among government and private entities. Government reports paint a grim picture of a weakening national defense (U.S. Government Accountability Office 2010) while news outlets print stories emphasizing the importance of rare earths in alternative energy technologies and consumer electronics (Bradsher 2009) (Gorman 2009). Framed in this light, concerns over rare earth supplies are not based on a fanciful desire to stockpile shiny metals. They are predicated on the idea that demand for rare-earth goods will increase in coming years.

Many estimates find that United States (U.S.) and world demand of rare-earth goods will see growth in several areas. There is a projected 482% increase in U.S. wind power capacity between 2008 and 2014 (Smith 2010) and a projected doubling of hybrid electric vehicle sales from 2012 to 2020 (Molycorp 2011). From 2011 to 2016, the share of rare earth demand (in terms of overall tonnage) held by permanent magnets (PM) will slightly increase (Figure 1.1 and 1.2). The total quantity of permanent magnets consumed will increase substantially; the cumulative annual growth rate of permanent magnet demand is projected to be 11% from 2011 to 2016 (Molycorp 2011). World use of rare earths is assumed to grow at an annual rate of 8-11% over that same period (Hocquard 2010).

These statements assume a specific rate of growth based on historical cumulative growth rates. Moreover, they are vague, referring only to total REO tonnage and fail to mention specific factors affecting demand. They do not provide deep insight into the full nature of rare earth magnet element demand and potential growth. Relatively few studies have been produced which fully examine in detail the demand from U.S. and global consumers for end-products containing rare earth elements.

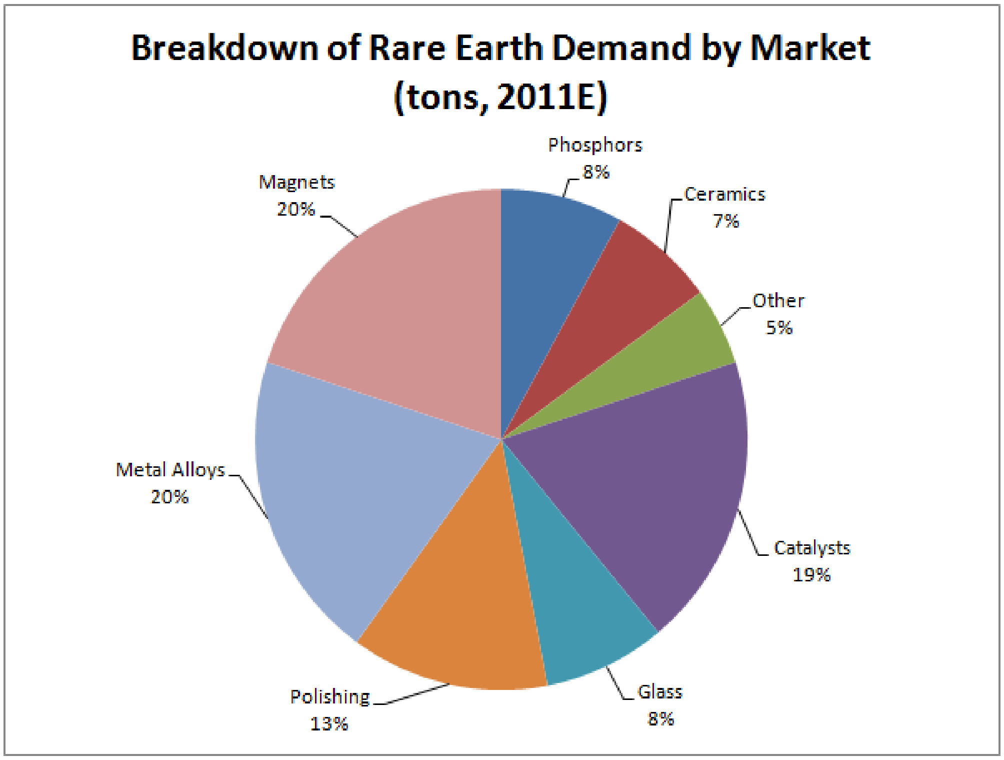

Figure 1.1 Breakdown of rare earth demand by market (2011, est. tonnage) (Kingsnorth 2012).

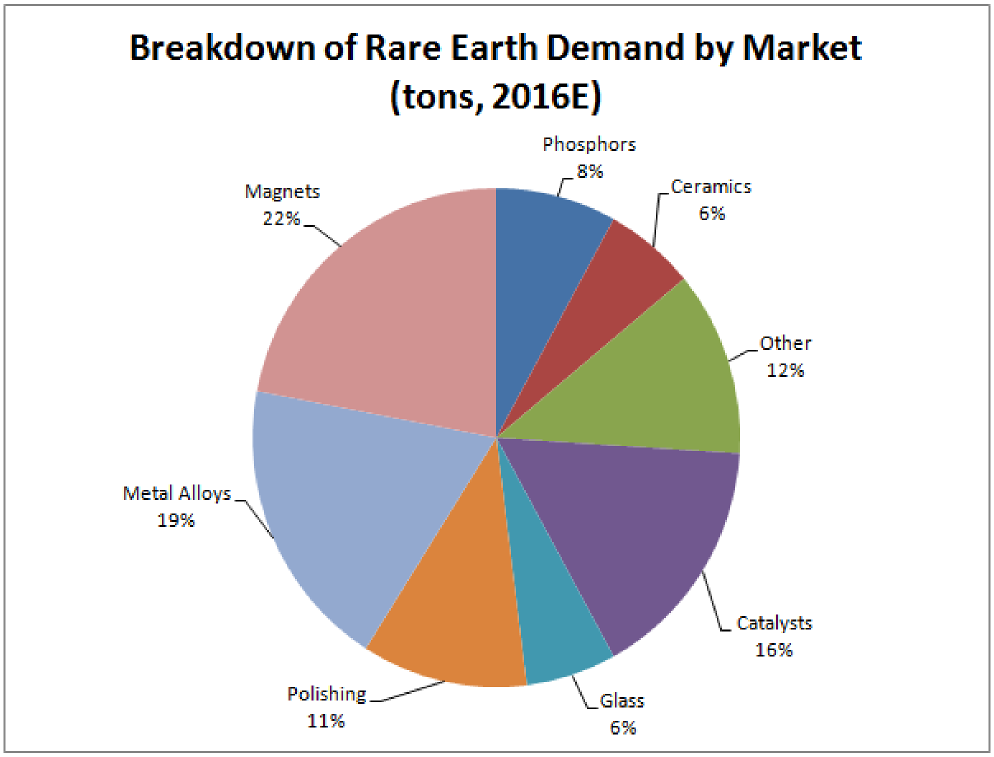

Figure 1.2 Breakdown of rare earth demand by market (2016, est. tonnage) (Kingsnorth 2012).

One such study was produced by the U.S. Department of Energy (DOE) and is titled *Critical Materials Strategy* (CMS) (Bauer et al. 2010, 2011). This study examines different scenarios of domestic U.S. demand for rare earths deemed critical to green energy technologies like wind turbines, hybrid vehicles, and photovoltaics. A similar study is Alonso et al.'s report, "Evaluating Rare Earth Element Availability" (Alonso et al. 2012), which creates demand scenarios similar to those produced by Bauer et al. Further analysis of relevant literature can be found in chapter three, "Literature Review."

Additionally, most common and precious metal markets are well documented with a vast array of economic data being available. Gold and copper companies, for example, have a basic framework for how their industry's demand is driven – rare earth market participants do not. Conducting a study, rooted in economic principles, into historic and potential levels of rare earth "magnet metal" demand for desired applications could help verify estimates produced in other publications and provide vital insight about demand-side market dynamics for market participants and national policy-makers.

Supply-side issues of the rare earth market are well-documented despite limited supply data from the primary production in China. Demand drives supply; according to industry experts (Smith 2010) (Hatch, "Critical Rare Earths" 2011) (Hykawy, Thomas and Casasnovas 2010) (Gibson and Parkinson 2011), as well as different government agencies (U.S. Government Accountability Office 2010) (Bauer et al. 2010, 2011) (Humphries 2010), demand for end products (and thus the supply of precursor rare earth materials) is exploding. This contradicts current events that negatively affect demand for these goods including widespread economic depression, faltering climate change policies, and a shifting geopolitical landscape – it appears vitally prudent to examine potential demand growth if these claims are to be justified.

The purpose of this thesis is to answer the following question: how will United States and world consumption of rare earth magnet metals evolve in the short to medium term (2011 – 2020) and why? Rare earth magnet metal demand will be evaluated for the most recent period of available data (2010)[1] and then scenarios will be constructed for U.S. and rest of the world (RoW) demand in the short to mid-term (2011 to 2020). Specifically, these calculations will focus on the demand for rare earth magnet metals found in two final consumer products: hybrid electric vehicles and wind turbines. It is important to note that demand generally refers to the quantity demanded of a good as a function of its price and other factors. Consumption represents the intersection of supply and demand at a given point of time; it is a single point of demand (or supply) calculated for a given set of prices and values. Since this paper does not estimate an actual demand function, the term consumption will be used in place of demand.

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[1] At the time of writing, the most recent data available was for 2010. Data from 2011 became available during the final revisions of this paper.

The primary scope for this discussion will be final U.S. and world consumption of four magnetic rare earths, embodied in two final products. These goods will be wind turbines and hybrid electric vehicles, which are both green energy technologies. Neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb) are the four rare earths found in neodymium-iron-boron (Nd-Fe-B) permanent magnets. There are two reasons that this paper will focus on these specific rare earths and end-uses.

First, rare earth magnet metals are projected to have the largest market growth of all the rare earths while permanent magnets will account for the biggest portion of total final rare earth demand (as discussed on pages four and five and in section two). Second, hybrid electric vehicles and wind turbines are both clean energy technologies, which are important for their potential role in reducing future pollution emissions. They also use one of the largest quantities of rare earth magnets relative to other magnet technologies such as magnetic resonance imaging systems and computer hard drives. Thus, the focus of this paper will be on the consumption of these value-added goods.

Plug-in and full-electric vehicles (PHEV and EV, respectively) will not be covered in this paper. According to (Constantinides "The Elements of Magnetics" 2012), hybrid electric vehicles accounted for 94% of total electric vehicle sales in 2011 (plug-ins were ~6%) and 91% in 2012 (estimated, with plug-ins the other 8-9%). Full-electric vehicles like the Tesla Roadster and Nissan Leaf have only recently been made available to automotive consumers and will not provide a significant contribution to electric vehicle sales through 2020. In addition, it is unclear as to how much, if any, rare earth magnet metals are used in full-electric vehicles. Hybrid electric vehicles currently represent a majority of electric vehicle sales and it is believed that this will hold true in the short to mid-term. For these reasons, the contribution of plug-in and full-electric vehicles to rare earth magnet metal consumption is presumed to be negligible.

This paper's methodology employs the statistical modeling program SAS and historical deployment and sales data to create baseline ("naïve") scenarios for future consumption of each technology. These scenarios assume that (a) future growth rates for the number of new wind turbines and hybrid vehicles follow a SAS-generated best-fit growth through 2020 and that (b) the amount of rare earths per turbine and vehicle remains fixed over time. The next step is to create different scenarios of future consumption by applying two types of changes: ones that affect the number of new turbines or hybrid vehicles deployed, such as changing national and global economic growth, and ones that affect the quantity of rare earths found in each technology like improved technological efficiencies.

Conducting this analysis will help determine how factors such as technological improvements or increasing substitute good prices could affect future consumption of these technologies and the rare earth metals they utilize. The results from these scenarios may suffer from high levels of uncertainty due to risk both known and unknown. This type of risk is inherent to the modeling of non-ideal, real-world markets and it is possible that unforeseen circumstances could lead to inaccuracies in this paper's scenarios.

The primary difference between this study and other similar publications is that it will develop its future scenarios of rare earth consumption using base scenarios that were generated in-house. Baseline scenarios are created for hybrid vehicles and wind turbines using historical sales and installation data and the SAS statistical software. Other publications use a "top-down" approach to analyzing future growth in the rare earth market, employing external forecasts in their analysis and breaking them into more manageable factors of technological and rare earth consumption. They do not create their own baseline scenarios, instead choosing to use projections from the International Energy Agency's (IEA) *World Energy Outlook 2010* and *Energy Technology Perspectives 2010*. The present thesis generates and uses its own base scenario in an attempt to shed new light on the potential future of the rare earth market.

Two other differences between this thesis and other reports are the scope and assumptions used for each scenario. First, this thesis examines all four of the rare earth magnet metals including terbium and praseodymium, as opposed to documents such as (Bauer et al. 2010, 2011) and (Hatch, "Critical Rare Earths" 2011) that focus on neodymium and dysprosium. Second, while there are overlapping assumptions used for the scenarios in this paper and other publications, the economic approach used in this paper results in new assumptions that were not used by other analysts. This includes estimating the impact of gasoline prices on hybrid vehicle sales and the effect of national economic growth on wind turbine installations. Despite differences with other reports, a lack of critical economic analysis in this fashion makes it a relevant methodology to use.

The main body of the paper will be split into seven chapters. Chapter two will focus on the general background of rare earth elements as a whole and specifically the magnet elements (Nd, Dy, Tb, Pr). It will also describe the historical background for and recent usage of hybrid vehicles and wind turbines. Chapter three will provide a review of relevant literature that also conducted analyses of clean-energy technology and rare-earth magnet consumption. Chapter four provides the methodology and data source limitations.

Chapter five will discuss historical consumption and present baseline and alternate scenarios of short to mid-term consumption (2011 – 2020) for wind turbines in the U.S. and world. Chapter six will present the same analysis as chapter five but for hybrid electric vehicles.

Chapter seven will present the final results of this analysis and link these conclusions to potential government policies for reducing the consumption of magnetic rare earths. Chapter eight summarizes the paper’s primary conclusions.

# CHAPTER TWO

# BACKGROUND: RARE EARTHS, WIND TURBINES, HYBRID VEHICLES

The average person utilizes rare earths on a daily basis. A cellular phone rings and people pull out a Google Android or an Apple iPhone. When people check their email, it is done on a high-tech laptop or desktop computer. At home, people sit on the couch and turn on their television - it is probably a flat-screen plasma or liquid crystal display. Even something as simple as the flint in a lighter requires rare earths. No matter where people turn, many common technologies have components made from rare earths.

## 2.1 General Background

There are a total of fifteen rare-earth elements, known by their chemical classification as lanthanides, though some have little to no practical application. Each of these elements and their periodic-table classification can be found in Table 2.1. Scientists place the rare earth elements into two primary classifications based on an arbitrarily decided atomic weight value. Light rare earths range in weight from approximately 139 to 150 (these values are unit dimensionless), while heavy rare earths range in atomic weight from 151 to 173. It is important to note that while they are not lanthanides, scandium and yttrium closely resemble rare earth elements and display similar physical and chemical properties. This is why they are included on the list of rare earth elements and are sometimes used in conjunction with rare earths in certain technologies.

Several rare earths are becoming increasingly important for many applications due to their unique magnetic physical properties. The three properties that are relevant for this paper are coercivity, remanence, and Curie temperature. Coercivity is a material’s ability to resist demagnetization – higher values mean that it is more difficult for external magnetic forces to

Table 2.1 Rare earth elements (Brown, LeMay and Bursten 2005).

| **Atomic Number** | **Name** | **Symbol** |
|---|---|---|
| 21 | Scandium | Sc |
| 39 | Yttrium | Y |
| 57 | Lanthanum | La |
| 58 | Cerium | Ce |
| 59 | Praseodymium | Pr |
| 60 | Neodymium | Nd |
| 61 | Promethium | Pm |
| 62 | Samarium | Sm |
| 63 | Europium | Eu |
| 64 | Gadolinium | Gd |
| 65 | Terbium | Tb |
| 66 | Dysprosium | Dy |
| 67 | Holmium | Ho |
| 68 | Erbium | Er |
| 69 | Thulium | Tm |
| 70 | Ytterbium | Yb |
| 71 | Lutetium | Lu |
| 57-62 = Light rare earths<br>63-71 = Heavy rare earths<br>21, 39 = Chemically similar to rare earths | | |

break down the magnetic charge of a permanent magnet (Coey 1995, 2). Remanence represents a magnet’s strength. Rare earth permanent magnets have high remanence values, as evidenced by numerous cautionary tales that even small permanent magnets can break fingers (Swain 2009).

Finally, a material’s Curie temperature is the point where it begins to lose magnetic charge as the temperature gets too hot and the magnet becomes increasingly demagnetized (Cullity and Graham 2009, 125). Each of these properties is important when producing rare earth permanent magnets because they enable the magnets to function properly under the considerably extreme conditions present in most applications.

Despite the fact that rare earths have only recently come into prominent use, they have been known to scientists for over two hundred years. The first rare earth element to be discovered was yttrium in 1787; it was found in a mine near the town of Ytterby, Sweden. This mineral went unidentified by its discoverer, Lieutenant Carl Arrhenius, and Professor Johann Gadolin, but it was eventually separated from the original ore. Cerium was then discovered in 1794 at a site near Riddarhyttan, Sweden. Lanthanum, erbium, and terbium were discovered by 1842 (Cappelen and Gschneider 1987, 6-7).

Other rare earths were identified years later as a result of continued chemical analysis on previously discovered ore samples. Commercial applications were initially limited and largely revolved around incandescent gas-light mantles and alloys used for lighter flints. New ore separation and purification techniques such as the ion-exchange method, developed by scientists working on fissile radioactive material separation for the Manhattan Project, enabled the wide-spread commercialization of rare earths. Improved prospects for technologies bearing rare earth-components in turn lead to increased exploration ventures by geologists and mining companies hoping to cash in on these potentially profitable elements (Colorado Rare Earths Inc. 2011).

There is a common misconception in the public arena that the rare earth elements' namesake results from a physical geologic scarcity. This is not true. As the United States Geological Survey (U.S.G.S.) states, "the more abundant rare earth minerals are similar in crustal concentration to commonplace industrial metals such as chromium, nickel, copper, zinc, [and others]… even the least two abundant rare earth minerals are nearly 200 times more common than gold" (Haxel, Hedrick and Orris 2002). Metals like gold and copper are generally found clustered together in massive, readily-exploitable deposits; however, the geologic chemistry of rare earths tends to result in sparse distribution within mineral deposits. Some rare earths are produced as by-products of iron and precious metal extraction while most stand-alone deposits consist of light or heavy elements in varying qualities and quantities. This results in an irregular global distribution of resources.

There are several different types of geologic mineralizations found at rare earth deposits. Of these different formations, the two most prominent are monazite and bastnäsite. Most of the earliest discovered deposits and mining operations were comprised of thorium-containing monazite placer sand [ $(Ce,La,Nb)PO_4$ ] (Monecke 2010, 4). These deposits include those found in Sweden (1880s), Norway (1880s), Brasil (1887), and India (1911), which often pose a moderately hazardous radioactive danger to workers because of the thorium content (Naumov 2008, 14). While many of these sites still produce small quantities of rare earths, South Africa's Steenkampskraal mine (owned and operated by Great Western Minerals Group Ltd.) is currently poised to take the lion's share of global monazite production after having been a major producer of thorium concentrates during the 1950s and 1960s (Great Western Minerals Group Ltd. 2010).

Production of rare earths from bastnäsite ore [ $(Ce,La)CO_3F$ ] (Monecke 2010, 4) was non-existent until the 1949 discovery of California's Mountain Pass deposit. The Molybdenum Corporation of America (now Molycorp) began producing small quantities of rare earth ore, particularly europium, in 1952 and ramped up operations throughout the 1960s as the number of color televisions in U.S. and European homes exploded. Europium is a key ingredient for the red phosphors used to generate the color picture in televisions and the development of Mountain Pass enabled this technology to replace black and white sets (Hocquard 2010, 21). Mountain Pass allowed the United States to become the major global producer of rare earths, feeding most of the world's demand until the discovery of massive deposits in China in the early 1980s.

China's biggest discovery of bastnäsite was at the Bayan Obo iron-ore deposit located in the Inner Mongolia region near the Mongolian border. This deposit is believed to be one of the largest in the world in terms of overall tonnage. Throughout the 1990s, production from Bayan Obo and several smaller mines in China's Sichuan province displaced most of the production from Western operations (Naumov 2008, 15). Rare earth prices were greatly depressed during this time due to the low-cost production that Chinese firms enjoyed (Haxel, Hedrick and Orris 2002). Low rare-earth prices, coupled with the expiration of permits and an accidental leak of radioactive waste into the surrounding desert, forced the closure of Mountain Pass in 2002. This is why China now maintains a hefty 95-97% share of the global rare earth market (Naumov 2008, 15). Figure 2.1 is a historical (1956-2008) timeline for REO production.

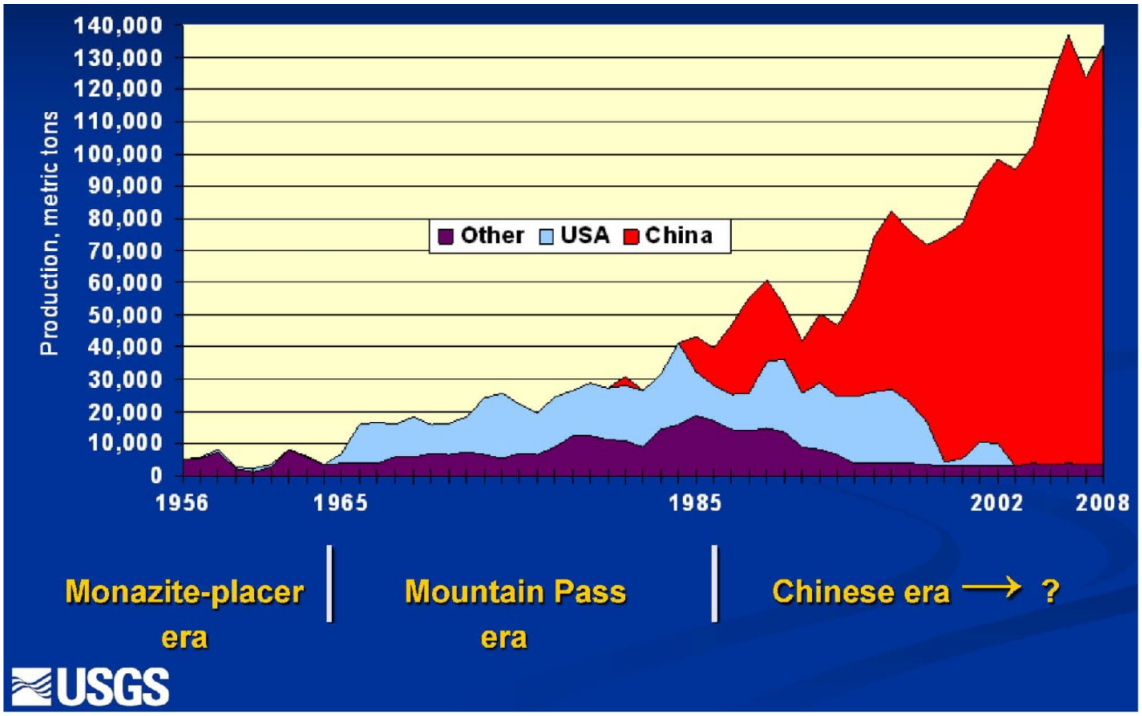

Figure 2.1 Historic rare-earth-oxide production (Tse 2011).

As stated previously, rare earth elements can be found in many modern technologies, including those listed on the following page (Hocquard 2010, 42-56). Table 2.2 presents the most-used rare earth elements and their various applications. The next section gives a brief history of Nd-Fe-B permanent magnets and the rare earths crucial to their production – neodymium, dysprosium, terbium, and praseodymium.

The following list highlights a few of the modern technological applications using rare earths:

- Phosphors in light-emitting-diodes (LEDs) and computer monitors
    - Medical field for certain radiological processes
- Advanced power systems such as the nickel-metal-hydride (NiMH) battery
- Catalytic processes such as automotive catalytic conversion, which removes excess carbon from emissions, and fluid catalytic cracking for oil refinement
- National defense items such as tanks, radar systems, missiles, and night vision goggles (U.S. Government Accountability Office 2010, 28-30).

Table 2.2 Primary applications of rare earth elements (Kara et al. 2010).

| La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy |
|---|---|---|---|---|---|---|---|---|
| NiMH batteries | Catalysts | NdFeB magnet | NdFeB magnet | SmCo magnet | Phosphors | Microwave apps. | Green phosphor | NdFeB magnet |
| Petroleum refining | Polishing | Color glass | Color glass | Carbon-arc lighting | Red phosphor | Phosphors | NdFeB magnets | Lasers |
| Glass | Glass |  | Enamel colorant | CaF crystal doping | Neutron absorbers | Enhance MRI images | Fuel cells |  |
| Cast iron additive | Carbon-arc lighting |  | Lasers | Catalysts |  |  |  |  |
| Alloys | Plastic pigments |  | Auto catalyst enhancer | Misch metal |  |  |  |  |
| Misch metal | Misch metal |  | Misch metal |  |  |  |  |  |

### 2.2 Historical Background of Rare Earth Magnets

There are two types of rare earth permanent magnets: samarium-cobalt (Sm-Co) and neodymium-iron-boron. Two non-rare-earth permanent magnets exist; aluminum-nickel-cobalt (Al-Ni-Co) and ferrite (ceramic) (Shih et al. 2012, 24). Each type uses different rare earths and can be found in vastly different applications. Samarium cobalt ($SmCo_5$) was the first non-ferric, non-ceramic permanent magnet put into commercial use after its discovery in the 1960s by researchers at the Air Force Materials Lab, Wright-Patterson Air Force Base, and General Electric's Research and Development Center (Cappelen and Gschneider 1987, 19). This type of magnet rose to prominence as a stronger, lighter, smaller alternative to the iron and ceramic-based magnets previously used. Samarium-cobalt magnets are known for their high coercivity and Curie temperature (727°C), making them ideal for applications such as military equipment that functions at full capacity over long periods of time under stressful operating conditions (Cappelen and Gschneider 1987, 22).

Unfortunately, there are several issues with samarium-cobalt magnets that led to the development of the neodymium-iron-boron alloy. First, samarium was a scarcely mined element and thus was expensive and in short supply. Second, cobalt has also been relatively expensive and there are concerns regarding its continual supply. Zaire, the main supplier of cobalt, has faced continual violence and civil unrest, particularly in the late 1970s. This caused the price of cobalt to spike "by a factor of 8 [in 1978] and [remained] up by a factor of 5 a year later" (Cappelen and Gschneider 1987, 19) and began the quest for substitute materials to replace cobalt (Eggert 2009, 12).

In 1983, the $Nd_2Fe_{14}B$ (neodymium-iron-boron) magnet alloy was discovered during joint research being conducted in Japan and the United States (Cappelen and Gschneider 1987, 19). Although it has a lower Curie temperature than samarium-cobalt, the Nd-Fe-B material is relatively cheap as world supplies of each element are much more plentiful. These permanent magnets are comparable to samarium-cobalt magnets due to their similar coercivity (Hcj) and remanance (Br) values and are just as powerful.

Neodymium is not the only rare earth in these magnets. Dysprosium and terbium are also used while praseodymium may also be added, depending on the application. Many Nd-Fe-B magnets employ a neodymium, dysprosium, and terbium mixture in a weight percentage ratio of 29:3:1 (1% boron and 66% iron). Dysprosium and terbium help improve a magnet's coercivity and resistance to high-temperature demagnetization (Kara et al. 2010, 24). One downside is that Nd-Fe-B magnets suffer a loss of magnetic output when dysprosium is added; unfortunately, the "substitutability between Dy and Nd and how [this] affects [the magnet] properties [is] not well understood" (Shih et al. 2012, 10).

The addition of dysprosium to a permanent magnet causes reductions in the remanence of a permanent magnet. A permanent magnet's coercivity is inversely related to its remanence; this means that as dysprosium is added and the magnet's remanence decreases, its coercivity increases. The intensity of change in each factor is dependent upon the physical concentration of dysprosium added to the Nd-Fe-B magnets as shown in Figure 2.2. Higher concentrations of dysprosium result in a greater resistance to demagnetization at high temperatures (they have a

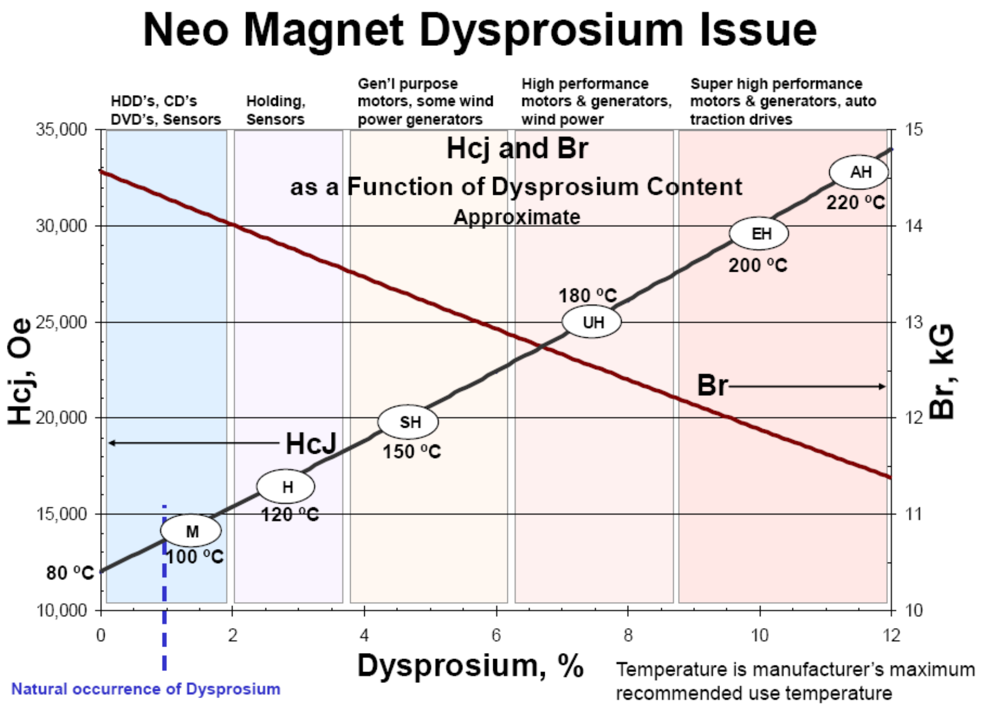

Figure 2.2 Physical magnetic properties of dysprosium at various concentrations (Constantinides, "Status and Outlook of Rare Earth Permanent Magnets" 2011).

linear relationship) but weaker magnetic output (coercivity and remanence are inversely related). As more dysprosium is added to a magnet, the lifespan of magnetization increases and magnetic strength decreases – these are major physical tradeoffs that must be weighed before determining how much dysprosium is appropriate for each type of magnet (shown in Figure 2.2 as bubbles M, H, SH, UH, EH, AH). While the present work does not focus on rare earth supply, it is noteworthy that, as marked in Figure 2.2, the average rate of occurrence for dysprosium in a rare-earth deposit is around one percent. This amount is significantly less than what is required for technologies such as wind turbines and hybrid electric vehicles and could signal a potential future shortage of dysprosium for use in Nd-Fe-B permanent magnets.

Magnet producers use different combinations of rare earths in their magnets depending on the final application of their product. One example is the Nd-Fe-B permanent magnet made from didymium, which is a misch-metal mixture comprised of praseodymium and neodymium There is a weight-percentage ratio of 75:25 Nd:Pr, which accounts for 30% of the total magnet weight. Dysprosium, terbium, boron, and iron are present in the same amounts as a "standard" Nd-Fe-B magnet. Praseodymium is substituted for neodymium as a cost-saving measure (neodymium is fairly rare and tends to be expensive) and to increase the magnet's resistance to corrosion (Kara et al. 2010, 24). This significantly improves the operational longevity of the permanent magnet. Praseodymium is uncommon in Nd-Fe-B magnets however because raw material prices have historically been similar to those of neodymium.

One question remains on the topic of permanent magnets: why are they so important compared to other rare earth applications? The answer is that permanent magnets are currently the largest employer of rare earths and will face the largest growth of all rare-earth applications in coming years (shown in Figures 1.1 and 1.2). Thus it is important to analyze permanent magnet and end-application growth because it is this consumption that will help drive the global supply of rare earths. As concern rises over supply shortages, careful analysis reveals that the permanent magnet market is likely to be affected most.

To this end, it is important to discuss the two main technology markets that utilize rare earth magnets as their primary components: wind turbines and hybrid vehicles.

### 2.3 Historical Background of Wind Turbines and Hybrid Electric Vehicles

Wind turbines and hybrid electric vehicles are the two primary technologies that utilize rare earth permanent magnets. Both are ‘green’ energy technologies and their principal reason for existence is to replace carbon-producing machinery as a means of limiting negative environmental externalities caused by the emission of carbon, sulfur, and other pollutants. Wind turbines generate power by converting pre-existing winds into energy, essentially a zero-carbon process, while hybrid electric vehicles largely run off electricity as opposed to fossil fuels such as gasoline. Hybrid electric vehicles all use rare earth magnets, but many wind turbines do not employ them. For reasons discussed in section 2.3.1, the benefits of wind turbines utilizing rare-earth permanent magnets are immense and they will be crucial for establishing a green energy infrastructure.

#### 2.3.1 Wind Turbines

There are many early historical examples of wind turbines being used to power machines. Primitive versions of the wind turbine, known as windmills, were initially used in Afghanistan “probably early in the seventh century A.D.” to aid with “gristmilling – the grinding of corn and other seeds to produce meal” (Hill 1991, 103). Windmills became prominent in Europe for gristmilling and water pumping between the eleventh and fourteenth centuries (Ackermann and Söder 2002, 71). Eventually, windmills for power generation became popular in places such as Denmark, where approximately 90% of industrial power came from windmills in the 1800s, and the rural United States with 600,000 mills in the early 1900s (Ackermann and Söder 2002, 71).

The invention of steam and fossil-fuel powered engines led to a massive decline in windmill use. It was not until the 1980s that commercially-viable wind turbines began their resurgence (European Wind Energy Association 2002, 3). Between the 1980s and early 2000s, wind turbine power "has increased by a factor of 100 and … costs have declined by some 80 percent" (European Wind Energy Association 2002, 3).

#### 2.3.1.1 Government Legislation

In the United States, there were two major governmental actions that lead to the promulgation of wind power usage by public and private utility companies. The first was the 1992 Energy Policy Act (U.S. Congressional House Committee on Commerce 1992), which laid the groundwork for a sustainable, efficient, and independent U.S. energy infrastructure. Section XII of this act allowed for the provision of fiscal incentives (renewable energy production tax credits, or PTC) to producers of alternative energy such as solar, geothermal, or wind (U.S. Congressional House Committee on Commerce 1992). Producers were to be paid 1.5 cents per kilowatt hour of electricity generated "if the qualifying facility was placed in service after December 31, 1993 and before July 1, 1999" (Dewey 2011, 1125), with the amount being adjusted each year for inflation. The credit currently sits at 2.2 cents per kilowatt hour and will expire on December 31, 2012 (U.S. Department of Energy, "Renewable Electricity" 2011) Despite the seesaw effect on new turbine installations that has been caused by multiple lapses and renewals of the PTC (Dewey 2011, 1127), there has been a positive cumulative increase in the United States' wind power capacity since 1992.

Renewable portfolio standards (RPS) have, to a lesser extent, also aided the spread of wind power in the United States. First developed around 1995, the RPS concept was a method by which state governments could encourage and sometimes force the production of energy using alternative fuels such as wind and solar. It did not catch on until the late 1990s when pioneer states such as Minnesota and Arizona first mandated goals for the amount of electricity that must be generated from alternative sources and set target dates by which producers and suppliers must achieve these goals (Gielecki et al. 2007, 2). Thirty eight states currently have some form of RPS, eight of which are voluntary, with target standards ranging from 4% to 25% and target dates ranging from 2010 to 2025. No two states have the same exact policy and there is no federal RPS. Studies by Lawrence Berkeley National Laboratory regarding the impact of RPS on new wind power have found that "between 2001 and 2006, over 50% of the total wind additions in the U.S. were motivated, at least in part, by these state RPS policies" (Gielecki et al. 2007, 9).

Both renewable energy production tax credits and renewable portfolio standards have played a large role in promoting the installation of wind power in the United States. While other countries have begun using similar tactics to help develop their alternative energy industries, they are slightly different. European countries such as Germany have what is known as a renewable energy payment system, or feed-in tariff. This is similar to the PTC. Governments provide moderate-term contracts to alternative energy producers that guarantee competitive prices for their power (Kaplan and Logan 2008, 41).

Many countries also have their own versions of renewable portfolio standards, which they call "quotas, Renewable Obligations, or Tradeable Green Certificate programs" (Gielecki et al.

2007, 3). Their target goals tend to be higher than in the various U.S. states and can be found in European Union (EU) countries such as Germany and Italy, Asian countries such as China and Japan, and Australia. Exact effects of their RPS and PTC programs on new wind power production are unknown at this time, however, because they have only been implemented in the past ten years (Gielecki et al. 2007, 3) (Junfeng and Martinot 2010). The United States is not alone in promoting alternative energy through government action - many countries have already started down the arduous path of replacing traditional fossil fuel power with alternative energy, albeit under the direct guidance and supervision of their national governments.

#### 2.3.1.2 Market Growth and Technological Design

Greenpeace believes that by the year 2020, approximately 10% of the world's required energy can be drawn from wind turbines (Shikha and Kothari 2003, 4). This will be enabled by marked improvements in wind turbine technical designs and associated economies of scale from high rates of global turbine usage. As a result, costs for the energy produced by wind turbines have declined "to the point where some high yield onshore wind farms are approaching price competitiveness with the cheapest alternative – combined cycle gas power plants" (European Wind Energy Association 2002, 3).

Lower costs and better designs caused wind power to be one of the quickest growing power sources during the 1990s and early 2000s. From 2004 to 2007, new installations of wind-power generation caused it to be the second fastest growing energy source behind "new natural gas-fired generating capacity … [but wind-power] still accounted for only about 1% of the total electricity generated in the US" (Kaplan and Logan 2008, 4). Figure 2.4 shows cumulative installed wind capacity in the United States from 1995 to 2007. Wind turbines are quickly becoming a viable substitute for traditional energy production such as coal and gas and a cheaper alternative to photovoltaics and fuel cells.

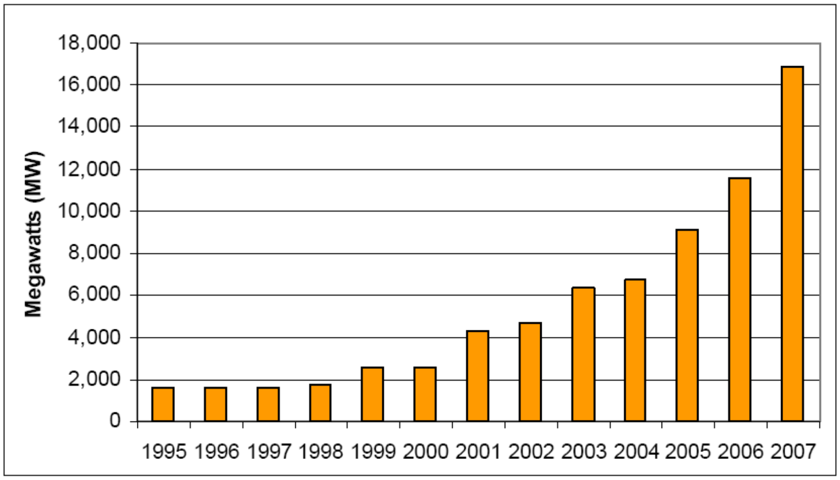

Figure 2.3 Cumulative United States installed wind capacity, 1995 to 2007 (Kaplan and Logan 2008).

There are two primary types of wind-turbine designs: vertical-axis wind turbines (VAWT) and horizontal-axis wind turbines (HAWT). Vertical-axis turbines are colloquially referred to as “eggbeaters” because of the way that their blades are designed to spin; the blades stand vertically in the air and spin around that vertical axis, capturing the wind’s energy and converting it into electricity by way of generator (Kaplan and Logan 2008, 12). VAWT are easy to operate and repair because their equipment and controls are on or near the ground. Wind speeds are faster at higher altitudes, resulting in larger amounts of electricity being generated. Low VAWT heights constrain their ability to generate electricity in commercially-viable amounts (Kaplan and Logan 2008, 12). Thus, HAWT have become the dominant technology for generating wind power.

Horizontal-axis wind turbine blades rotate horizontally around an axis parallel to the ground. These turbines are designed to capture high-altitude, high-speed winds (Kaplan and Logan 2008, 12) by using a yaw control to change the rotor blades’ position relative to wind flow and a variable blade pitch to alter a blade’s angles (Kaplan and Logan 2008, 13). Both elements enable maximum operational efficiency and give HAWT an advantage producing energy. However, there are several mechanical, economic, and social disadvantages of using HAWT. They are often opposed by the general public for being unsightly, initial fixed costs for building them are high, material wear-and-tear is hard to maintain and parts are difficult replace, and finally, there is the interference risk posed to aviation and other radar systems (Kaplan and Logan 2008, 14).

There are three types of mechanical designs for the generation and transmission stages. Gearbox generators are usually high-speed, multi-step energy transmission systems – these are the most common turbines used and have the lowest manufacturing costs of the three systems (Shih et al. 2012, 11). While the evolution of wind turbine technology over time has allowed for lighter, more compact, and longer-lasting mechanical systems, scientists have only recently developed designs requiring simpler gearboxes or eliminating them completely. This second design, a hybrid permanent magnet generator, employs moderate speeds and smaller magnets. Its design helps mitigate issues associated with losses in mechanical efficiency. The third design is a direct-drive permanent-magnet generator that completely removes the gearbox feature; this model is being installed in greater quantities but its use is still limited (Hatch, "How Does" 2009).

Hybrid-drive wind turbines represent a compromise between geared and direct-drive systems. These designs use both a gearbox and permanent magnets in an "attempt to combine the advantages of the geared and [direct-drive] technologies while reducing their downsides" (Shih et al. 2012, 40). Smaller magnets are required due to the presence of the gearbox, which results in lower material costs and reduces exposure to shocks in the neodymium and praseodymium markets. Compared to traditional geared turbines, hybrid-drive systems are gaining a more prominent role in the wind power market because of their improved reliability and decreased costs (Shih et al. 2012, 40).

The direct-drive permanent magnet turbine provides several advantages over the other two designs. However, they have seen limited usage in new wind power installations because they require larger rare earth permanent magnets than the hybrid systems and are more expensive to build and install. Their advantages, as shown in Figure 2.5, include:

- Removing the requirement of electric magnetization to power the turbines
- Reductions in the size of mechanical systems like the drive train and generator
- Elimination of the gear box

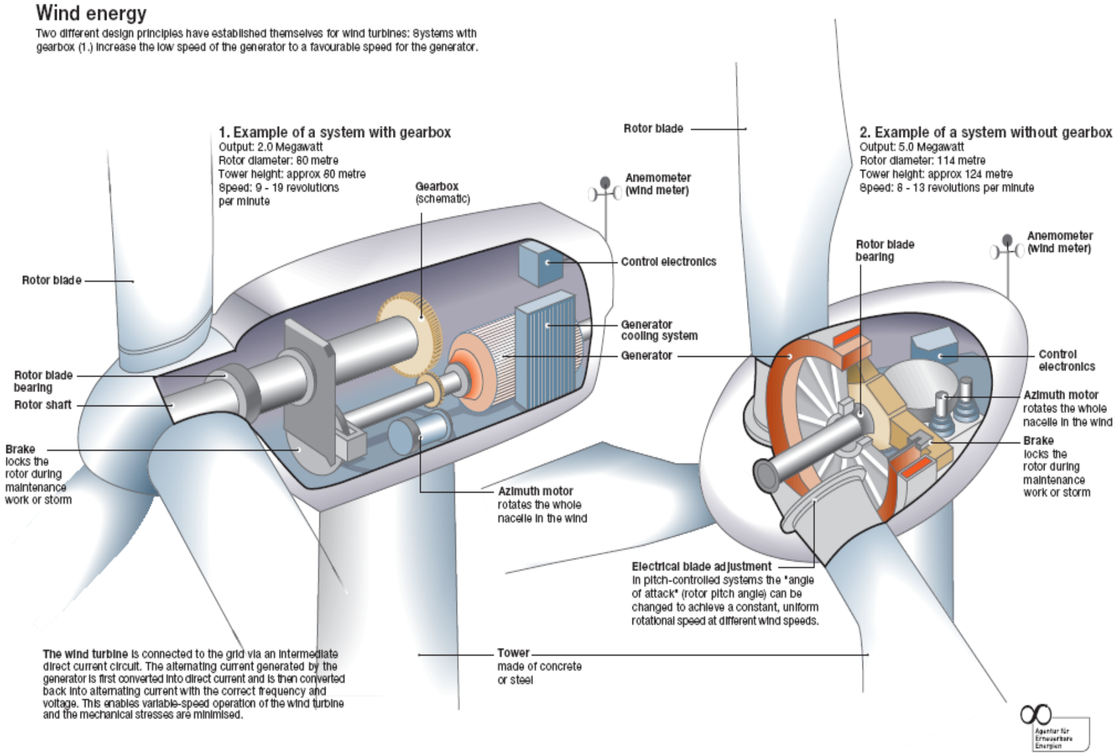

Figure 2.4 Comparison of traditional and direct-drive wind turbine
(German Renewable Energy Agency 2010).

Each of these factors allows for “significantly increased reliability and reduced maintenance costs … [leading to] less non-producing time offline” and “the elimination of associated mechanical losses … [leading to] improved efficiencies in the power conversion process” (Hatch, "How Does" 2009). This limits the need for continual maintenance, increases a turbines' lifespan, and works at a higher rate of power-generating efficiency during non-optimal wind periods.

Countries with coastal access may wish to expand their wind-power capacity using off-shore turbines. They may find it preferential to use hybrid and direct-drive machinery because these technologies require minimal upkeep and provide greater, more consistent power than on-shore turbines. Despite these advantages, off-shore wind power sites have higher installation and maintenance costs because workers must travel relatively long distances over water to reach them (Shih et al. 2012, 40). Wind turbines using hybrid or direct-drive systems are superior in many ways to traditional designs but high initial costs have kept them from gaining an ample share of U.S. and global wind energy markets.

### 2.3.2 Hybrid Electric Vehicles

The first electric vehicle was invented in the 1830s by Scottish inventor Robert Anderson. It was powered by single-use batteries. Subsequent years saw the release of different electric vehicles, each influenced by advances in battery technologies and culminating in 1904 with the first hybrid electric vehicle concept (Hybrid Cars, "History" 2011) (PBS 2009). Full development and deployment of this vehicle was hindered by the 1908 invention of Henry Ford's gasoline-powered Model T, which spread rapidly across the world and is currently the major form of ground, air, and sea transportation (PBS 2009). Victor Wouk, the "godfather of the hybrid electric vehicle", created the initial prototype of the hybrid vehicle drive train. After passing the Environmental Protection Agency's (EPA) initial set of pollution emission tests, Wouk's vehicle lost government support and the project was shelved. Erik Stork, the head of the EPA's Mobile Source Air Pollution Control Program, said that hybrid vehicles received little support because they were "just not a very practical [automotive] technology" (Hybrid Cars, "Hybrids and the EPA" 2006).

### 2.3.2.1 Modern History and Technological Design

It wasn't until the late 1980s and early 1990s that the hybrid electric vehicle began to gain acceptance as a viable mode of automotive transportation. This was made possible under the Clinton administration's Partnership for a New Generation of Vehicles program and the United States Department of Energy's Hybrid Propulsion Program proposed in 1993 (Illumin 2001). Over a billion dollars in research funding provided under these initiatives has lead to improvements in the NiMH battery as it applied to hybrid vehicles, as well as enhancements in "lighter-weight body structures, more efficient engines, better batteries, and more efficient electric motors and generators" (Illumin 2001). Rare earth magnets played a large role in these advances, as they allowed for production of motors and batteries that are smaller, more efficient, and half the weight of iron-based materials. Figure 2.6 shows other uses of rare earths in hybrid vehicles.

Figure 2.5 Rare earth element use in hybrid electric vehicles (Molycorp 2011).

#### 2.3.2.2 Government Legislation

There are two main advantages that exist to using hybrid electric vehicles over traditional fossil-fuel vehicles. First, they offer the benefit of having decreased greenhouse gas emissions, similar to that of the full-electric vehicle, although they still emit approximately thirteen percent of the pollution as compared to a standard gasoline automobile when external energy production is taken into account (Illumin 2001). Second, hybrid vehicles can theoretically provide a much better fuel economy than that of the gasoline auto. First-gen hybrid-electric vehicles were capable of having a fuel economy between forty-five and sixty-eight miles per gallon, depending on a consumer's transportation habits (Lake 2001). Most hybrid vehicles do not have the ability to travel further distances on a single charge than traditional vehicles but research is ongoing to solve this issue, as well as other issues such as those with establishing a sufficient energy distribution infrastructure and higher costs at initial purchase (Illumin 2001).

Several factors have aided the continued development and market penetration of hybrid vehicles. Most Western governments, including those in Europe and the U.S., provide subsidies and incentives for consumer purchases of hybrid vehicles. Although the US government's federal incentives have expired, they were initially set at a value of up to $3,400 which would be credited towards an individual's federal income taxes (U.S. Department of Energy, "Federal Tax Credits" 2012). Many states also offer incentives such as use high-occupancy vehicle lanes, discounts on parking permits, and exemptions from emissions inspections (Hybrid Cars, "Hybrid and Plug-in Incentives" 2010).

Furthermore, several events in the U.S. and across the globe have caused gas prices to increase and shocked the supply-side of the oil market. These include armed conflict in oil-producing regions like the Middle East and Africa, international concern over Iran's nuclear program and ambitions, the Deep Horizon catastrophe, and the burgeoning Idle No More movement over new Canadian legislation regarding environmental protections. Improved hybrid vehicle technology, federal and state incentives, and concerns over the price and supply of conventional fuels has given many entities reason to push for increased deployment of hybrid vehicles.

Multiple types of hybrid and plug-in electric vehicles are sold on the consumer market. Toyota's Prius was the first widely-available hybrid vehicle upon its 1997 release in Japan. Honda's Insight was the second hybrid vehicle to be produced in commercial quantities when it debuted in the United States and Japan in 1999, followed shortly by the global debut of the Toyota Prius in 2000 (Lake 2001). Several generations of these vehicles have been released since 2000 and consumers can now choose from a full line of compacts, sports utility vehicles, and trucks. However, each of these vehicles is either a hybrid or plug-in electric; the first full electric vehicles (Chevy Volt and Nissan Leaf) are just being introduced in 2012-13 to the consumer automobile market (Constantinides, "The Elements of Magnetics" 2012) and it is unclear as to what, if any, impact this will have on the adoption of electric vehicles and permanent magnet consumption.

# CHAPTER THREE

# LITERATURE REVIEW

The following section provides a brief review of literature relevant to this paper. Each of the four documents that are discussed in this section has conducted similar analyses regarding some aspect of the rare earth permanent magnet market. However, while they create scenarios of future magnet and end-use consumption, their primary focus is to determine whether or not there will be shortages of specific rare earths and to detail possible ways of mitigating the risk of shortages. It is the hypothesis of this thesis that growth in consumption of rare earth materials in intermediate and final goods may not be as strong as some publications believe. In that light, it is important to summarize the objectives and conclusions from relevant literature and discuss their shortcomings.

## 3.1 Hykawy, Thomas and Casanovas "Rare Earth Elements – Pick Your Spots, Carefully"

Byron Capital Markets (BCM) is a Canadian-based financial consulting company. Their securities division published an industry report, "Rare Earth Elements – Pick Your Spots, Carefully", on March 25, 2010 (Hykawy, Thomas and Casasnovas 2010), whose primary goal was to analyze potential investment opportunities based on their scenarios of future surpluses and shortages for particular rare earth elements and final-use product markets. This report summarizes what rare earths are and the major various sources of raw mineral deposits. It then compares and contrasts current production from Chinese and Western deposits, notably Bayan Obo in China and Mountain Pass in the United States, and creates a scenario of future supply based on operational startup timelines for major new mine development in the United States, Canada, Australia, South Africa, and Greenland.

In the next section, the Byron report analyzes what they term “New and Growing Demands – Automotive Motor/Generators”, “Less Exciting Growth in Demand – Wind Power”, and “Little to No Growth – High-Efficiency Lighting”. Their automotive demand scenario finds that rare earth element usage will increase tenfold from 2010 to 2015. Also, terbium was not included in Byron’s analysis; praseodymium was included in terbium’s place. Both can be substituted into permanent magnets for neodymium and their usage is constrained largely by their costs.

One item of dispute for Byron researchers here is the commonly-held belief that approximately one kilogram (kg) of neodymium and 121 grams (g) of dysprosium can be found in hybrid vehicles (Hykawy, Thomas and Casasnovas 2010, 12). After interviews with Dr. Peter Campbell, ex-VP at Magnequench and permanent magnet expert, Byron researchers instead concluded that hybrid vehicles only have 193 grams of neodymium and twenty four grams of dysprosium. This is important because it directly contradicts beliefs held by rare-earth industry experts such as Jack Lifton and Gareth Hatch who have decades of experience in the field. Statements such as those made by Byron analysts could lead to vastly different demand scenarios from those estimated by other industry specialists; whether they are more or less accurate, or even correct, remains to be seen.

Byron Markets’ analysis of rare earth usage in wind turbines concludes that, while elemental usage will quadruple from 2010 to 2015, wind turbines will not be a major factor in the demand growth for most magnetic rare earths. They cite a generator expert named Tony Morcos who has stated that “the much higher anticipated efficiency achieved with a rare earth magnet-equipped generator in a wind turbine will not be achieved due to the electrical conductivity of the magnet sections and eddy current losses” (Hykawy, Thomas and Casasnovas 2010, 14). Byron uses this statement to conjecture that rapid growth of permanent magnet wind turbines is unlikely to happen.

The penultimate conclusion of the BCM report is that they “do not believe that REO demand will rise so rapidly and for such an extended period of time” and recommend that investors avoid many of the mining companies that own low-grade deposits (Hykawy, Thomas and Casasnovas 2010, 17). While these conclusions are supported by well-reasoned arguments, there are three potential issues that must be discussed, each of which highlights small but crucial differences between the Byron report and the present work.

First, Byron’s analysis should be tempered by the premise that an investment consulting firm’s goal is to help investors turn profits. Their data and calculations are probably conservative in nature because of their intention to create demand scenarios that are both cautious and reasonable. One example is the assumed value for the amount of neodymium in hybrid vehicles; most industry experts believe that this quantity is five times greater than what Byron estimates (Hatch, “Why I Take Issue” 2010). BCM does not account for permanent magnets found in the non-motor components of hybrid electric vehicles. This smaller amount was likely part of a financially-conservative approach that incorporated a risk factor. Risk-averse investors see Byron’s conservative demand estimates and are likely to invest more money for what appears to be a small but “sure thing” where the potential for huge losses is also limited.

Second, many assumptions that the Byron report makes are drawn from interviews with two or three experts – this is hardly a large enough group of people to create a definite consensus on ideas such as whether the hybrid vehicle uses 650 or 1,000 grams of neodymium. The present work looks at an array of documents produced by entities in the public sector (e.g. non-profit wind energy organizations), private sector (e.g. consulting firms), and government sector (e.g.

national research laboratories). It is believed that using this wide variety of resources and creating several different future growth scenarios will limit the problems associated with this issue and improve the estimates in the present work.

Finally, one of the Byron report's conclusions seems to misunderstand the scientific principles that guide wind turbine and permanent magnet technologies. They state that dysprosium use will stagnate in wind turbines because the mechanical systems in wind turbines would simply be cooled by the wind. However, cooling the mechanical systems of a wind turbine is not dysprosium's only purpose as the Byron report suggests. Gareth Hatch explains in his "Why I Take Issue" blog post that doping permanent magnets with dysprosium helps them to withstand higher operating temperatures and increases their resistance to the demagnetizing effects of other mechanical equipment. Byron has assumed that dysprosium use will not grow even when the possibility of growth, fueled by a growing need for applications requiring permanent magnets that stay magnetized at high temperatures, is quite obvious.

### 3.2 Bauer et al. "Critical Materials Strategy"

The second publication for review was the *Critical Materials Strategy* released in 2010 and 2011 by the United States Department of Energy (Bauer et al. 2010, 2011). This publication provides a government-sponsored analysis of rare earth supply and demand from the perspective that rare earths are "critical minerals at risk of supply disruptions in the short term" (Bauer et al. 2010, 6). It is a more comprehensive analysis than the Byron Capital Markets report because its scenarios are built from a larger group of assumptions and model parameters. Potential demand estimates produced in the CMS are larger than in the Byron report because of two reasons.

First, the DOE's scientific agenda is heavily invested in promoting clean energy technologies, particularly hybrid vehicles. Optimism for a high-risk, high-reward agenda that DOE workers believe is highly beneficial for society is to be expected. This optimism tends to cultivate a strategic bias in the scientists, engineers, and economists, leading to the possibility that future DOE estimates of demand for technologies such as hybrid electric vehicles would tend to be higher than other reports.

Second, the DOE models demonstrate multiple scenarios of future demand for each technology and their rare earths. This whole analysis helps them compare potential future demand and supply scenarios and determine whether or not a material is "critical" (i.e. the possibility of a shortage is impending). The assumption parameters that Bauer et al. used for their analysis covered a large range of values, ensuring that all realistic demand scenarios would be included. An example is the future market share of on-shore, permanent magnet wind turbines as a percent of the total wind turbine market; Bauer et al.'s low penetration rate is 15%, while their high penetration rate is 75%. Obviously, this method of analysis can result in relatively larger estimates of demand than are found in the BCM report.

Rare earths are crucial for many technologies but the primary focus of the CMS involves a generally comprehensive look at "the short (0-5 years) and medium-term (5-15 years) deployment of wind turbines, electric vehicles, solar cells, and energy-efficient lighting" (Bauer et al. 2010, 10). In addition to rare earths, Bauer et al. also examine the criticality of indium, gallium, and tellurium and various government programs that can help coerce the implementation of the clean energy technologies such as the 2005 Loan Guarantee Program and Advanced Technology Vehicles Manufacturing Incentive Program. There is also a discussion regarding the strategic policy-making of foreign governments; specifically, this looks at their implementation of measures like stockpiling and material substitution research as short-term means of relieving supply shortages.

The primary focus of the Critical Materials Strategy is the creation of future demand and supply scenarios for various minerals. Each mineral that is projected to have a supply shortage is then analyzed using a pre-determined set of criteria for identifying criticality and placed on a matrix according to the severity of its shortage. Bauer et al. utilize the International Energy Agency's *World Energy Outlook 2010* forecasts of demand growth for clean energy technologies and adjusts them based on two broad factors:

1. Market penetration, which is split into two separate categories
    a. Deployment of all technologies across world
    b. Specific technology's market share
2. Material intensity within the technology

It is important to note that the authors admit this method simply creates a swathe of "future possibilities and explore[s] the impact of different assumptions … on future requirements of rare earth elements and other key materials" (Bauer et al. 2010, 72). The CMS cannot cover all future possibilities and thus leave out certain assumptions regarding changes in rare earth and technology usage. This reveals key differences between the methodologies of the CMS and this thesis, including items such as technological advancements, price of substitutes, and tax credits. Results from the work of this thesis simply offer an alternate set of future demand scenarios for a limited number of clean energy technologies and their rare earths.

Another difference between (Bauer et al. 2010, 2011) and this thesis is that Bauer et al. do not analyze potential praseodymium or terbium demand (at least in wind turbines and hybrid electric vehicles). This is because they pre-determined that praseodymium was not a critical material and that terbium demand in phosphors was more prevalent. Terbium is usually included in the permanent magnets found in wind turbines, especially the off-shore variety, and most hybrid electric vehicles, while praseodymium usage does occur but in much rarer circumstances. Analyzing future scenarios where there exists significant demand for these two elements may be helpful in determining whether there should be supply concerns for those materials as well.

The CMS scenarios of neodymium and dysprosium demand conclude that, in the high-use scenarios, there could be an approximate tripling of demand for each material (Bauer et al. 2010, 78-79). Each scenario predicts positive demand growth, such as an increase in U.S. demand from 4% to 9% for dysprosium and 1% to 6% for neodymium in clean energy technologies (as percentages of total global demand for each element). This demand would far outpace supply in every year from 2010 to 2025. Bauer et al. posit that this demand growth could be the result of changes in consumer preferences due to better education regarding the environmental consequences of long-term fossil fuel usage and reliance on foreign-born, non-renewable resources.

After the CMS outlines its supply and demand projections, it discusses factors that influence the physical availability and pricing system of rare earths and other materials. These include a lack of adequate price-listing mechanisms, demand-side issues like restricted substitution options, and supply-side issues like intensive capital investments. Data from this exercise is filtered through the minerals criticality matrix developed in the National Academy of Sciences' "Minerals, Critical Minerals, and the U.S. Economy" study in 2008 to determine which minerals are most "critical"; dysprosium, terbium, and europium are the most "critical" followed by yttrium and neodymium. Finally, the CMS goes through potential programs and policies that the

U.S. DOE and federal government could implement to "address risks, constraints, and opportunities across the supply chain" (Bauer et al. 2010, 101).

Some of the issues with the 2010 version of the CMS are addressed through revisions presented in the 2011 publication. Although the new version uses the same methodology for creating future demand scenarios and presents conclusions that vary only slightly from the 2010 version, several minor modifications are made to the parameters and assumptions. In regards to the permanent magnet scenarios, the CMS applies four key alterations which involve changes in the market shares and deployment of the technologies analyzed and their technological specificities.

First, the CMS updates their "market share assumptions for wind turbines … to reflect a more rapid adoption of turbines using rare earth magnets, particularly [in China] … [and] the availability of new medium-speed hybrid-drive turbine designs" (Bauer et al. 2011, 89). In the 2010 version, the DOE's assumptions regarding new adoption rates seemed low given that countries such as China had installed up to 30 gigawatts (GW) of new capacity in 2009 alone. The 2011 CMS also accounts for differences in material intensities of the permanent magnets found in direct-drive and hybrid-drive wind turbines, which altered their "high and low material content range" (Bauer et al. 2011, 89). These changes primarily affect the wind turbine scenarios and the results vary only slightly from estimates made in the 2010 version.

The third assumption change affects the material intensities of the permanent magnets found in wind turbines and hybrid vehicles. Specifically, the CMS accounts for differences in the amount of dysprosium used for each application (hybrid vehicles use more and wind turbines use less). Finally, CMS estimates of vehicle demand provided for the inclusion of electric bicycles, which "reflect [the] electric bicycle's growing role in the global transportation pictures (particularly in China)" (Bauer et al. 2011, 90). Low growth in this sector meant that electric bicycles were not large contributors to the demand for the four magnetic rare earths. Byron Capital Markets included electric bicycles in their analysis but limited the scope to Chinese demand. These updated assumptions improve the overall quality of Bauer et al.'s analysis but do not significantly alter previous demand estimates from the 2010 version.

Other updates focus on the inclusion of updated supply and demand data in order to improve the scenarios previously created in the 2010 CMS. While some of the new data comes directly from companies reporting their production and consumption of rare earths, other data is more speculative in nature. The DOE updates their "expectations for a decrease in overall rare earth demand from 2010 to 2011", accounts for "a 7% (approximate) increase in expected overall rare earth production in 2015", and makes "adjustments to non-clean energy demand, to account for decreases in global REO demand during 2011, followed by annual increases starting in 2012" (Bauer et al. 2011, 78). In addition to these changes in demand, supply information was updated to reflect the provision of new data from producers such as Molycorp. Some of this information related to political events that may have affected supply responses in specific countries. These issues are not covered in this thesis.

### 3.3 Roskill "Rare Earths & Yttrium: Market Outlook to 2015, 14th edition 2011"

Roskill Information Services releases a publication every four to five years that analyses the entire rare earth industry. This analysis covers five main topics: historical supply and demand, end-use applications, prices, and future projections. Estimates of future values such as supply or demand are interwoven into discussions about the other topics. In this newest edition, Roskill updates their future estimates of supply and demand and have added recent (2010) data for producers of rare earth materials and final goods bearing rare-earth components. They have also updated their company and region-specific analysis with social, economic, and political events that occurred during 2010.

This review will only cover demand-related topics; all other topics will be mentioned but not reviewed in-depth. The first chapter summarizes the findings from Roskill's analysis in each of the five thematic subjects (as previously mentioned). A brief introduction to the report is given in chapter two. Chapters three, four, five, and six cover several steps of the rare earth supply chain, starting with "occurrences and reserves". This looks at the geology and location of potential rare earth deposits and current estimates of world and country reserves. Next is "mining and processing", which is a discussion of various rare earth mining techniques used for sites with different geological conditions.

Rare earth production is the next topic covered. They examine world production of rare earth minerals and processed materials, as well as estimates of future supplies. Country and company-specific production details are outlined in chapter six; countries include Australia, Canada, China, South Africa, and the USA; companies include Lynas Corporation, Great Western Minerals Group, Baotou Rare Earth, and Molycorp Minerals. Details include annual production, vertical integration, partnerships, and future plans.

The topics most relevant to this thesis are covered in chapters seven, eight, and nine - "World consumption", "Consumption by end-use", and "Permanent magnets", respectively. In chapter seven, Roskill analyzes the consumption of rare earths from a global perspective, comparing China to the rest of the world (RoW), and from a regional perspective, comparing China, Japan & other Asia, the USA, and "Other" across multiple applications.  These applications were magnets, metallurgy, catalysts, polishing, glass, phosphors, ceramics, and "other".

In 2010, the total global consumption of rare earths (measured in REO equivalent) was 125,000 tons per year, which was an increase of 5% per annum over 2000. This market was valued at approximately $2.4-2.7B in 2010. More importantly, the "market shrank in 2009 because of the effects of the global economic downturn, which had a significant negative effect on markets outside China" (Roskill 2011, 204). Although global demand has begun increasing, gross domestic product (GDP) growth has been less than expected. Roskill estimates that the cumulative annual growth rate of global rare-earth demand will be 7% to 8% annually, reaching 180,000 tons in 2015. Demand is forecasted to "recover from the global economic downturn" and there will be "an increasing quantity of rare earths required in new applications" (Roskill 2011, 205).

The chapter continues on to discuss sector-specific consumption of rare earths. Regarding permanent magnets, it is stated that despite the global economic recession strongly depressing the permanent magnet market, demand growth is expected to "continue [but] at a lower rate than seen before the downturn" (Roskill 2011, 207). However, it is believed that "the future is not certain for NdFeB magnets in [green energy technology] industries if raw material prices continue to rise, as other, non-rare earth technologies already exist" (Roskill 2011, 207) – the growth of permanent magnets in these industries relies upon low material costs and strong consumer spending power.

Roskill estimates that neodymium demand in permanent magnets was approximately 30,000 tons in 2010 and could increase to 54,000 tons in 2015. One interesting detail listed here is the amount of praseodymium usage in 2010 (2-2,500 tons); no other documents reviewed for this thesis had estimates of praseodymium usage in permanent magnets. NdFeB permanent magnet substitutes are also discussed, with the conclusion that "NdFeBs will continue to be phased out in non-essential applications .. there is likely to be increased substitution by ferrite magnets in the future, where applications allow" (Roskill 2011, 208). Finally, global demand for rare earths within the permanent magnet industry was approximately 33,250 tons in 2010; this is expected to grow by 11% to 13% annually until 2015, "when demand is forecast to be 55,000 – 60,000 tonnes" (Roskill 2011, 208). Other non-magnetic applications requiring rare earths are then discussed.

The chapter finishes by discussing the most important players in the rare earth market by region. China, whose "rapid industrialization has been the main drive behind global consumption rates during the last decade" (Roskill 2011, 213), comprised 70% of total world demand for rare earths. Three markets - permanent magnets, polishing powders, and autocatalysts – were the top industries in terms of growth in demand for rare earths. This demand growth for rare earths in China is expected to exceed that of the rest of the world by approximately 1 to 2% through 2015.

Japan and other Asian countries represent the second largest market for rare earths, due to the focus on downstream production of goods. Although the U.S. is the third largest rare earth consumer, demand has declined over the past few years from "16,500 tons in 2003 to 11,300 tons in 2006 … further in 2010 to around 7,000 tons" (Roskill 2011, 218). This decline is believed to have been primarily caused by catalyst manufacturers drawing down their stock of raw materials. Consumption of rare earths is expected to increase in all regions, with China leading the way at 8-9% per annum (130,000 tons in 2015) and the RoW growing at 5-6% per annum (50,000 tons in 2015).

It should be noted that this report appears to use a "top-down" approach in its analysis of growth in the supply of and demand for rare earth materials and applications. Each forecast represents a future rate of growth that has been derived from historical trends – Roskill does not account for specific factors affecting demand growth, either positively or negatively. As well, the information used to create forecasts comes from companies that responded to Roskill's request for information (RFI); even Western companies, who must follow strict reporting guidelines, do not wish to reveal proprietary information that gives them a competitive advantage. This limits the accuracy of Roskill's projections to between 10 and 15%, depending on which supply stage or market is being analyzed. The present work cannot improve upon Roskill's accuracy but it is important to note that even the best source of information is limited in many regards.

Chapter eight is short and covers rare earth consumption by end-use. Essentially, this chapter lists each rare earth and gives a brief blurb about the technologies that use them. The only notable bit of information here is that approximately 23% and 69% of total praseodymium and neodymium (respectively) consumption is from permanent magnets. Clearly, technologies that use these magnets are growing in importance and size.

Permanent magnets are examined in-depth in chapter nine; this is the last chapter that is relevant to this thesis. It first discusses a brief history and main applications of neodymium-iron-boron magnets, the manufacturing process for these magnets, alternative types of permanent magnets, intellectual property rights, and current magnet recycling efforts. Roskill then looks at world production of permanent magnets, drawing comparisons between China, Japan, and the rest of the world, and then details company specifics such as production figures, facility locations, and partnerships. Chapter nine continues on by discussing the various technologies that use permanent magnets – hybrid electric vehicles and wind turbines are covered in-depth here.

Chapter nine concludes with a look at potential future rare earth consumption in the permanent magnet industry and potential substitute technologies. Roskill estimates that the "global demand for rare earths in permanent magnets is likely to grow by around 10-15% [per year] between 2010 and 2015 … [and] as much as 58,000t REO in 2015" (Roskill 2011, 84). China will account for approximately 75% of global rare earth demand; they plan to double their current wind power capabilities by 2020 (up to 100 GW). It is concluded that green energy technologies "could have a positive impact on growth rates from 2011", especially when coaxed along by political legislation aimed at reducing greenhouse gases and government subsidies promoting alternative energy technologies. However, high costs for raw materials such as neodymium may result in a permanent switch to substitute technologies that use either a smaller amount of rare earths or none at all. Research and development (R&D) efforts to develop such technologies remain in the early stages.

Finally, chapter 18 ("Forecast supply and demand") provides Roskill's estimates of future supply and demand in China and the RoW. It begins with a short explanation of the methodology for creating forecasts of future supply and demand in both regions. Previous chapters created forecasts using historical average growth rates; this chapter creates demand scenarios that account for the "forecast GDP in China and the rest of the world" and "trends in demand for rare earths across a range of applications". Supply projection assumptions come from "statements by the Chinese government on likely production of REO over the five years from 2010" and "an appraisal of new [rare earth mining] projects described in detail in Section 6" (Roskill 2011, 474). Essentially, Chinese supply and demand will exceed that of the rest of the world; total global supply will exceed total global demand starting in 2012.

Roskill's publication is useful because it provides valuable details about the usage of rare earths in different regions across a variety of applications. It also provides a set of projections for future supply and demand to use a benchmark for comparison when creating independent estimates. They are a well-reputed organization that has access to many companies, so the information that is provided tends to be the most accurate data available. However, this data remains very proprietary and readers must take Roskill's analysis with a grain of salt – there is no way to independently verify the information they have received and no way to conduct a separate analysis of future supply and analysis. Roskill has given stakeholders and interested parties a very comprehensive (but somewhat general) look at various aspects of the rare earth market One drawback of this is that many other reports draw part or all of their analysis from Roskill's report; this leads to a situation where these reports all have similar conclusions because very little unique analysis has been conducted.

### 3.4 Alonso et al. "Evaluating Rare Earth Element Availability"

The final piece of literature for review is the (Alonso et al. 2012) paper that uses a mathematical basis for evaluating potential rare earth demand. Alonso et al.'s focus is on projecting total future demand for rare earth elements and linking this demand to the co-mining of rare earths in an attempt to "evaluate the state of future [rare earth element] supply availability" (Alonso et al. 2012, 1). It is their goal to create scenarios of future demand in all technological sectors that employ rare earths and compare predicted rare earth demand to predicted supply. This is different from the present work, which focuses solely on magnetic rare earths and only two clean-energy technologies. Alonso et al. conclude that new demand for neodymium and dysprosium could grow by over 700% and 2600%, respectively, driven by rapid growth in the electric vehicle market.

Similar to the DOE and BCM reports, Alonso et al. use a top-down approach to their analysis. They employ a technique not dissimilar from the one found in this thesis, where "evolutionary (historical) and revolutionary (new technology) demand are explicitly considered" (Alonso et al.

2012, 2). Evolutionary refers to historical and potential demand where newer, rare earth-based technologies are limited in use, while revolutionary demand sees a much higher adoption rate of rare earth-based technologies.

Several equations representing the supply and demand for each rare earth in their respective technologies are created by the authors. Using ordinary least-square regression, it is found that the compound annual growth for each technology is likely to follow an exponential pattern. The equations that are formulated by the authors are very similar to the ones used in this thesis because they take known material compositions of the rare earths in each technology and multiply them by the amount of hybrid vehicles, wind turbines, etc. that are sold or installed in past years.

Five demand scenarios are created using the following assumptions. Scenario A ("aggregated evolutionary demand") assumes that demand in all relevant technology sectors increases at a singular rate, following the historical growth trend of all the markets combined. Scenario B ("disaggregated evolutionary demand") reflects a growth path similar to this thesis' baseline scenario, where each technology market grows according to its own average historical growth rate, rather than every market growing at the same rate. These scenarios can be considered their base cases.

In scenario C ("implicit revolutionary demand"), growth rates for each individual market sector are externally provided by industry experts. Alonso et al. assume that these experts have taken all potential determinants of demand into account and that their projections are accurate and revolutionary-based. Scenario D ("aggressive revolutionary demand") takes the assumptions from scenario B and imposes growth rates that are based on estimates from the International Energy Association's Blue Map predictions. This Blue Map scenario assumes that hybrid and all-electric vehicle deployment is going to be 80% of total automobile sales and that all new installations of wind turbines would involve rare-earth permanent magnets. Every other technology market using rare-earth permanent magnets would grow at historical rates. The ultimate goal of this scenario's assumptions is "limiting [the] increase in average global temperature to 2°C" (Alonso et al. 2012, 3) through the aggressive implementation of clean-energy technologies.

The final scenario in this paper ("moderate revolutionary demand") is similar to scenario D. Instead of altering electric-vehicle demand based on the IEA's Blue Map scenario, Alonso et al. use assumptions found in Gruber et al.'s paper "Global Lithium Availability: A Constraint for Electric Vehicles?". This assumption is that the number of sales of electric vehicles, as a percentage of total automobile sales, will "increase from 6% … in 2015, to 27-35% in 2035, and 35-48% in 2050" (Alonso et al. 2012, 3). The authors then apply their own assumption that none of the new wind turbine installations will use rare-earth permanent magnets, as a result of the high costs associated with these types of turbines. Of the five scenarios, the authors consider this one to be their moderate case.

The results from this analysis show several things. First, they find in scenarios A and B that demand for rare earth magnet technologies are likely to increase at a rate between 3.7 - 5.3%. Magnet and polishing compound markets will increase their share of total rare earth consumption while other technologies will face decreasing shares of the market. Neodymium, praseodymium, and dysprosium usage would grow slightly while yttrium, samarium, and gadolinium use would decrease. Scenario C's results are questioned by the authors, as expert predictions of rare-earth market growth have historically been higher than actual rates. Increases in the demand for Nd, Pr, and Dy are, however, similar to those found in scenarios A and B.

Scenario D's results show that rare-earth demand growth is most likely going to be driven by rapidly increasing demand for nickel-metal-hydride batteries in electric vehicles. The so-called revolutionary demand for clean energy technologies would account for more than a quarter of total rare earth demand and lead to a 5.9% growth rate per annum, which is "a less than 1% increase in the growth rate from historical levels" (Alonso et al. 2012, 5). Discussion regarding scenario E's results is limited to a statement that revolutionary demand would represent only 13% of overall rare earth demand and decrease to zero as lithium-ion batteries (LIB) become the electric vehicle standard. Ultimately, these results are used to discuss how supply availability will be affected by increasing demand. Alonso et al. find that the supply of magnetic rare earths must grow rapidly in scenarios B, D, and E, and moderately in scenarios A and C.

The work done in Alonso et al.'s paper appears to fairly representative of what rare earth demand and supply might look like in the future. This can be inferred because they compare their work to others and proclaim that it "provides a good order of magnitude estimate and a reasonable comparison among different rare earth demand volumes" (Alonso et al. 2012, 4) – there is no reason to believe otherwise. There is, however, one small issue of concern that must be discussed.

Alonso et al.'s usage of the IEA assumption regarding electric vehicle sales accounting for 80% of total vehicle sales leads to their primary conclusion that growth in this market will be one of the primary drivers for total rare earth demand growth. A corollary of this is that wind turbines will not play a large role in the growing market demand for rare earths. While the other scenarios contribute to this finding in one way or another, it remains to be seen whether this proves to be a foregone conclusion – the United States and most world nations have failed to achieve even the most basic environmental goals as outlined by international agreements such as the Kyoto Protocol.

IEA assumptions depend on countries actually fulfilling their international obligations to reduce certain greenhouse gas emissions levels as proposed by the Kyoto Protocol and other pro-environmental legislation. It is unlikely that 80% of new automobile sales in the U.S., or any other country, will be comprised of electric vehicles anytime soon, as the growth of national and global economies continues to stagnate. A consequence of persistent economic stagnation is that expensive, under-developed renewable energy technologies are dropped for cheaper and more established means of transportation.

# CHAPTER FOUR

# METHODOLOGY AND DATA

In this chapter, the methodology for this paper will be outlined and there will be a discussion regarding the data sources for this work. Several papers have comparable techniques for analyzing rare earth consumption and it is necessary to show how consumption will be estimated for this paper and how it contrasts with other methods. The primary difference between the present work and similar literature is that it will generate “in-house” estimates of future HEV and wind turbine consumption demand. There are also differences in the parameters used for creating alternate demand scenarios. Examples of these are the effects of a tax credit incentive on hybrid vehicle sales and an improvement in the efficiency of wind turbine systems.

The methodology portion of the paper will explain the assumptions made and various equations used to calculate rare earth consumption in hybrid electric vehicles and wind turbines for 2010 and the short to mid-term period (2011 to 2020). During this dialogue, comparisons between the present work and similar literature will be drawn in order to highlight the value of the present analysis and its potentially unique conclusions. This section will end with an examination of the data sources used for this paper and discuss possible limitations due to different reporting styles and a lack of transparent reporting.

## 4.1 Methodology

It is important to begin this section by clarifying which stage of the rare earth supply chain will have its demand measured and discussing the process for translating this demand between stages. As a reminder, demand is usually measured as a function of multiple variables like the good’s own price, the price of substitute or complement goods, and income. Consumption represents the equilibrium intersection of demand and supply at a specific point in time – this term is largely used in place of demand in this paper.

### 4.1.1 Identifying the Scope

Directly estimating consumption for rare earth magnet metals is difficult to accomplish. There are several steps in the rare earth supply chain, as shown in Figure 4.1.

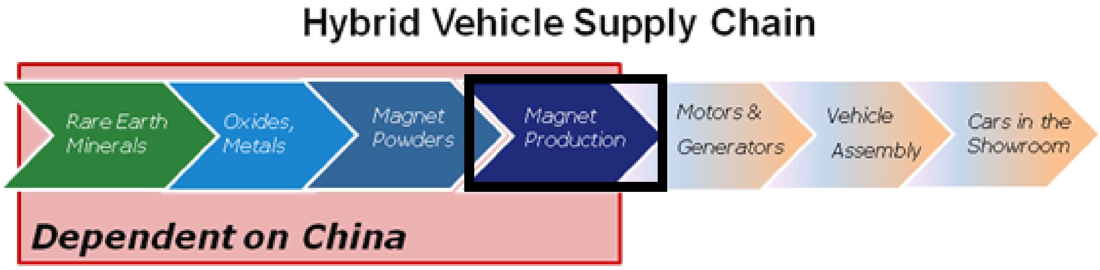

Figure 4.1: Supply chain for rare earth elements, specifically the hybrid vehicle (U.S. Government Accountability Office 2010).

Consumption can be measured at any of the up or downstream processes. This supply chain begins with ore extraction and leads into separation of oxygen-containing compounds called oxides. An example is neodymium oxide, which has the chemical formula $Nd_2O_3$. Rare earth oxides are then converted into metals for use in alloys and powders. These materials are then formed into permanent magnets found in final products such as a Toyota Prius or a Vestas wind turbine (Shih et al. 2012, 6).

Identifying accurate data for certain stages of rare earth production is near impossible. Materials like raw ore or metals are largely found as intermediate components in larger systems and rarely used as end products. Another example is the series of permanent magnets used for the motors found in a hybrid vehicle. Multiple layers of production are involved, causing problems when trying to estimate consumption at specific stages. Instead of directly calculating rare earth consumption, a proxy measure is created by analyzing the consumption of rare-earth end products (wind turbines and hybrid electric vehicles) and working “backwards” to estimate consumption by global magnet producers.

This approach starts by examining the “Cars in the Showroom” stage of Figure 4.1, which is represented by final consumer demand in the U.S. and world for wind turbines and hybrid vehicles. Efficiency factors for each manufacturing process are used to calculate magnet producer consumption in terms of rare-earth-oxide equivalent tonnage. A black box around the “Magnet Production” supply stage in Figure 4.1 shows the level of consumption that will be calculated in this paper.

An important step in this analysis is to convert the quantity of rare earth material found in hybrid vehicles or turbines (the “final good”) into the equivalent amount of rare earth materials required by permanent magnet manufacturers (the “intermediate good”). The next step is further conversion of these units into the equivalent amount of rare-earth oxide material used to make magnetic alloys and powders. This requires knowledge of the “extent of reaction” for each manufacturing process. Extent of reaction is a term describing how far a reaction goes to completion; generally, real-world processes have values less than 100%; essentially, this describes how much starting material, like an alloy or powder, is lost during manufacturing, like the forming of alloys into permanent magnets. Conversion from REO to elemental amounts will not be done in this work because the extent of reaction data was not readily available.

These calculations will estimate the physical quantity of rare earth materials consumed for the production of permanent magnets, which this paper is ultimately trying to determine. Weight units are metric tonnes; tons and tonnes (t) both refer to metric tonnes. Although there are several precursor materials for magnet production, including oxides, alloys, and powders, calculations here use standard assumptions regarding magnet weights, compositions, and extents of reaction for each process. Accounting for these factors leads to standardization of weight units between each stage of production.

### 4.1.2 Estimating Consumption

Given this information, the following steps are used to create baseline and alternate scenarios of future wind turbine and hybrid electric vehicle consumption.

**Step 1 -** Estimate total *short to mid-term* (2011 to 2020) consumption of wind turbines and hybrid electric vehicles in the United States and the rest of the world (base case).

Step one uses historical data for sales of hybrid vehicles and installations of wind turbines in order to create base scenarios of future demand for each technology. These base cases are "naïve" scenarios of future wind turbine and hybrid vehicle consumption. For wind turbines, the historical period used was 1999 to 2009 (U.S.) and 1990 to 2009 (RoW). For hybrid vehicles, the historical period was 1999 to 2009 in the U.S.; data for non-U.S. countries was unavailable so CE Delft's scenario was used as a baseline.

Data for this step was acquired from documents published by non-profit wind power agencies and government entities, as shown in section 4.2. This data is fed into the SAS statistical program, which uses "extrapolative forecasting methods where the forecasts for a series are functions only of time and past values of the series" (SAS Institute Inc. 2013, 579). First, a time-trend regression is conducted under the assumption of a natural growth rate over time. It looks at calculating consumption in year t ($x_t$) as the sum of an initial consumption value ($b_0$), two time-based variables ($b_1 * t$ and $b_2 * t^2$), and a white-noise (or random error) variable. The general equation for this model is shown on the following page.

$$x_t = b_0 + b_1 t + b_2 t^2 + u_t$$

Second, an autoregression is conducted, which assumes that past data values have influence on future values and accounts for unexplained variations from the time-trend regression. It calculates the consumption in year t ($u_t$) as a sum of time variables from previous periods ($u_{t-1}$, $u_{t-2}$, etc.) that are weighted by values representing their statistical significance to the model ($a_1$, $a_2$, etc.). There is also a stochastic error term, $\varepsilon_t$. Weighted values are determined by internal hypothesis testing that is conducted by SAS during the forecast procedure. The equation below shows this the autoregressive relationship.

$$u_t = a_1 u_{t-1} + a_2 u_{t-2} + \ldots + a_p u_{t-p} + \epsilon_t$$

The goal of this exercise is to minimize the difference between actual and predicted historical values to produce the equation for a line of best fit. This equation is then evaluated for the period 2011 to 2020. “Predicted” future values in the base scenarios of this analysis are based solely on time trends found in the set of historical data; there are no exogenous variables here such as those used in a simple linear regression exercise.

SAS-generated estimates represent naïve base scenarios of future hybrid vehicle and wind turbine consumption. Each base scenario is the equivalent of a “business-as-usual” case, where the number of products (wind turbines or hybrid vehicles) sold or installed grows at a pre-determined rate and the technological specifications of each product remain constant as time passes. It is assumed that external factors such as war and technological advancement are negligible and do not positively or negatively affect the demand for wind turbines, hybrid vehicles, or the rare earths that they use.

**Step 2 –** Estimate the quantity of rare earths used per hybrid vehicle and wind turbine from 2011 to 2020 (base case).

Equation 4.1 shows the general model for rare earth demand in end-use technologies. Step one discussed the number of products sold and installed. The quantity of specific rare earths used per product, also known as material composition, is a fixed value assumption used for this analysis and can be found in Table 4.2.

Equation Set 4.1 Naïve base scenario, factors affecting rare earth consumption.

$$Q_x^{C,F} = (\text{\# of products sold or installed}) * \left(\frac{\text{quantity of specific rare earth}}{\text{product}}\right)$$

where:

$Q_x^{C,F}$ = consumption of rare earth metal x in future year F in final goods

$x$ = rare earth metal, x from 1-4

$x = \{\text{Nd}(1), \text{Dy}(2), \text{Pr}(3), \text{Tb}(4)\}$

$F$ = future year, F from 1-10

$F = \{2011(1), 2012(2), \ldots 2019(9), 2020(10)\}$

**Step 3 –** Create naïve, base scenarios of total *short to mid-term* (2011 to 2020) consumption of rare earth magnet metals in the United States and rest of the world.

The naivety of these baseline scenarios arises from two assumptions. First, that the number of products sold or installed between 2011 and 2020 (inclusive) follows a SAS-generated best-fit growth rate and second, that the quantity of rare earths used per unit of product remains fixed over time. Using this method and these assumptions leads to the generation of baseline scenarios for hybrid vehicle and wind turbine consumption in the short to mid-term (2011 to 2020). Alternate scenarios can be compared to this baseline as a means of evaluating how demand may change under different circumstances.

Subsequent calculations must be conducted in order to infer the consumption of rare earth materials in future years. These calculations are static and do not account for changes in a product’s technological specifics or quantity consumed – they are simply used to calculate the derived consumption of magnetic rare earths in hybrid electric vehicles and wind turbines. Equation Set 4.2 determines the total amount of rare earths consumed by permanent magnet manufacturers who provide the magnets for hybrid vehicles and wind turbines in each year.

Equation Set 4.2 Quantity consumed of rare earth magnet metals in 2010.

**For hybrid vehicles :**

$$Q^{C,F}_{x,HEV} = [(\frac{\text{total magnet weight}}{\text{hybrid electric vehicle}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}}) *$$
$$(\text{\# total hybrid electric vehicles sold in year F})$$

**For wind turbines :**

$$Q^{C,F}_{x,turbine} = [(\frac{\text{total magnet weight}}{\text{MW of turbine power}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}})$$
$$* (\text{MW of new capacity in year F}) * (\text{\% market penetration of PM turbines})$$

such that:

$Q^{D,F}_{x,i}$ = quantity consumed of rare earth metal x for end product i in future year F (kg)

x = rare earth metal, x from 1-4

x = {Nd(1), Dy(2), Pr(3), Tb(4)}

Nd = neodymium, Dy = dysprosium, Pr = praseodymium Tb = terbium

i = {Hybrid Electric Vehicles(1),Wind Turbines(2)}

F = future year, F from 1-10

F = {2011(1), 2012(2), ... 2019(9), 2020(10)}

Calculating the amount of rare earth materials needed by manufacturers requires the inclusion of waste that is generated as a result of inefficiencies in these processes. According to (Bauer et al. 2011), magnet producers lose roughly 30% of their starting material during production. Some disagreement exists over what the actual manufacturing loss is for neodymium-iron-boron permanent magnets. Steve Constantinides of Arnold Magnetics gives 60% (Constantinides, “The Elements of Magnetics” 2012) and Peter Dent of Electron Energy Corporation gave 50% at a Boeing meeting in August 2011 (Boeing Company 2011). This paper’s use of Bauer et al.’s value is based on the fact that it was derived from input provided by different magnet producers. Values provided by Mr. Constantinides and Mr. Dent are likely based on personal experience with the technologies and practices of the permanent magnet industry. It is unclear as to which values are more correct, leading to potential uncertainty in this paper's analysis.

The extent of reaction for the conversion of rare-earth oxides into alloys, powders, and metals is assumed to be 80% (Constantinides, "Status and Outlook of Rare Earth Permanent Magnets" 2011). Although the present work does not convert the quantity of REOs into elemental amounts, the extent of reaction for this process is probably less than 100%. It can be assumed that the quantity of raw ore required for REO production is greater than the actual REO amount. Each of these losses is reflected in Equation Set 4.2 as "% manufacturing loss".

Note that Equation Set 4.2 is generalized for each technology. There are numerous manufacturers of wind turbines and hybrid vehicles whose products may use differing amounts of permanent magnets in varying material compositions. Data for each individual vehicle or turbine is proprietary knowledge, so modeling the specifics of each one is difficult. Additionally, the market share of permanent magnet wind turbines is currently unknown, as discussed in (Shih et al. 2012).

It can be difficult to decide what values should be assumed for each of these items. For example, the market share of permanent magnet wind turbines cannot be determined based solely on the amount of new wind power capacity in each country. Shih et al. ran into this same problem, stating that "[they] were unable to find reliable and detailed information for the market share of global PMG [permanent magnet generator] wind turbine installations … no information about the share [of PMG turbines] actually used by the U.S. wind turbine industry is available". For their scenarios, Shih et al. use a 5% value for the market share of permanent magnet wind turbines. Other publications use different values; a summary of some assumptions for permanent magnet specifications and technological market penetrations from external sources are given in Table 4.1.

The assumptions used for this paper are summarized in Table 4.2. Permanent magnet material compositions are based upon values commonly found in scientific publications like (Bauer et al. 2010, 2011); market share of permanent magnet wind turbines is based on the research conducted in Shih et al.; the quantity, or weight, of permanent magnets found in each technology is based on information from industry experts Gareth Hatch and Jack Lifton. Each of these values was chosen based on the experience and reputation of the organizations that provided the information and tend to represent the lower bound of the spectrum, providing an analysis is properly representative of reality.

Table 4.1 External assumptions for permanent magnet specifics and technologies.

| | **Bauer et al. 2011** | **Shih et al. 2012** | **Hykawy, et al. 2010** | **Hatch, "CRE" 2011** |
|---|---|---|---|---|
| **PM Wind Turbine Market Share (% of total)** | | | | |
| *Current (2010)* | 5 - 15% (non-China)<br>25% (China) | 5% | Unknown | "Very low" (unknown) |
| *Future (2011 to 2020)* | 15% (low)<br>75% (high) | 20% | 20% | 25% |
| **Total Magnet Weight (kg)** | | | | |
| *Hybrid Electric Vehicles* | 1 (low), 2 (high) | N/A | 0.65 | 1.2 |
| *Wind Turbines* | 200 (low), 600 (high) | Unknown | Unknown | 235 |
| **Composition of PM (weight %)** | | | | |
| *Neodymium* | 31% | 28% | 31% | 30-35% |
| *Dysprosium* | 4.5 - 6% (HEV)<br>2 - 4% (wind turbine) | 6% | 4% | 3% |

Table 4.2 Assumptions used for the present analysis.

| | Composition of Perm. Magnet (weight %) | Market Share (% of total) | Total Magnet Weight |
|---|---|---|---|
| **HEV** | Nd-Dy-Tb (30%, 4%, 1.5%) | N/A | 1.175 kg per vehicle |
| **Wind Turbines** | Nd-Dy-Tb (30%, 4%, 1.5%) | 5% | 1,000 kg per 1.5 megawatts (MW) |

**Step 4** – Generate alternate scenarios of *short to mid-term* (2011 to 2020) wind turbine and hybrid electric vehicle consumption in the United States and the rest of the world.

Step four takes the two "naïve" assumptions (page 55) about wind turbines and hybrid vehicles and alters them to create different scenarios of future consumption. This is an attempt to explore the effects of changes in the model's assumptions. The first assumption stated that future sales or installations of each technology follow a SAS-generated pattern of growth based solely on historical data. Examples of factors that can affect the total quantity of turbines installed or hybrid vehicles sold are national economic growth, gasoline prices, and government tax incentives. Each one alters rare earth consumption indirectly through changes in technological demand and will be used for the analysis in chapters five and six.

The second assumption was that the quantity of rare earths required per unit of each technology would remain fixed over time. Altering this assumption leads to direct changes in rare earth demand because they affect the amount of rare earths per vehicle or turbine rather than the overall level of demand for each technology. Factors that can affect this assumption primarily affect the technological specificities of hybrid vehicles and wind turbines. In the present work, the primary focus will be changes to the material composition of permanent magnets and improvements in mechanical efficiencies.

Four scenarios will be created for wind turbines. Two involve changes to the overall level of new installations, while the other two examine changes to the rare earth content of each technology. Table 4.3 summarizes the four scenarios and their assumptions.

Table 4.3 Wind turbine scenarios and assumptions.

| Scenario | Assumption |
|---|---|
| 1A (High economic growth) | EIA "high economic growth", GWEC "advanced" |
| 1B (Market penetration increase) | 1.5% increase per year (20% in 2020) |
| 1C (Material composition change) | Didymium use (Nd 22.5%, Pr 7.5%, Dy 4%, Tb 1.5%) |
| 1D (Technological efficiency improvement) | 1 ton of rare earths per 3.5MW |

The first scenario, 1A ("High economic growth"), assumes that national (U.S.) and global economic growth, or GDP, will be positive and moderately strong. A strong level of economic growth means that a country's government can spend more of its budget on programs that are beneficial for the long-term sustainability of the country but might otherwise be cut during an economic recession. Examples of these programs include funding for research and deployment of renewable energy technologies such as wind turbines and photovoltaic panels and federal tax incentives for clean transportation methods such as hybrid and full-electric cars.

This thesis will not develop GDP forecasts. External projections of economic growth and the resulting new wind turbine installations must be used. Forecasts of economic growth and new installations in the United States will come from the U.S. Energy Information Administration's (EIA) *Annual Energy Outlook 2011* (AEO11). The AEO11's "high growth scenario" will be employed for this analysis because it assumes that the U.S. economy will eventually recover from the current recession as opposed to completely collapsing. In this scenario, the EIA assumes that the U.S.'s real GDP will grow at an average rate of 3.2% per year from 2009-35.

Analogous projections of future economic growth in non-U.S. countries are found in the Global Wind Energy Council's (GWEC) *Global Wind Energy Outlook 2010* (GWEO10). The GWEC's "advanced scenario" will be used in an analogous fashion to the EIA's "high growth scenario"; in addition to strong economic growth in non-U.S. countries, the GWEC's presumption is that the set-up, framework, and execution of European and Asian renewable energy production is stronger than in the United States.

Scenario 1B (“market penetration increase) assumes that there will be a switch from traditional gearbox wind turbines to hybrid and direct-drive permanent magnet systems. According to Shih et al., the installation of permanent-magnet turbines in the U.S. and other countries will increase because of their “simpler design and reduced maintenance costs” (relative to gearbox-only turbines). Hybrid systems are facing increased usage because they have smaller magnets than direct-drive turbines and yet provide more reliable power than gearbox turbines. These advantages were discussed in section 2.3.1.2 and they are the primary reason that any country would switch from traditional, low-cost wind turbines to more radical designs involving rare earth permanent magnets.

Current market penetration of permanent magnet turbines is low in the United States (approximately 5%) while other countries generally have a higher rate of penetration. This value may be as high as 25% in countries such as China (Bauer et al. 2011, 20), where wind turbine markets are relatively new and energy producers have taken advantage of domestic permanent magnet and wind turbine production. Increasing market penetration from 5 to 20% between 2011 and 2020 (1.5% per year) aligns with predictions from (Bauer et al. 2011) and (Shih et al. 2011).

Scenario 1C (“material composition change”) looks at changes in the material composition of permanent magnets. This change results in a different mixture of rare earths being employed than what is traditionally found. A “traditional” permanent magnet uses neodymium, dysprosium, terbium, iron, boron, and several trace elements; in terms of weight, the three rare earths comprise approximately 35.5% of the total magnet weight (30% Nd, 4% Dy, and 1.5% Tb).

One possible change to the material composition of permanent magnets is the usage of didymium. Didymium is a mischmetal mixture of neodymium, praseodymium, dysprosium, and terbium (Nd-Pr-Dy-Tb). Praseodymium is substituted for neodymium so that 22.5% of the magnet's weight is neodymium and 7.5% is praseodymium – the amounts of terbium and dysprosium remain unchanged. This may occur as a result of rising neodymium prices due to more restrictive export quotas on neodymium materials in China. If praseodymium is cheaper than neodymium, then it makes sense to substitute the maximum amount possible without significantly perturbing the magnet's properties.

The fourth and final scenario (1D, "technological efficiency improvement") examines what happens to wind turbine consumption when there is an improvement in technological efficiency due to scientific research and development. One type of improvement that can be made is an increase in the efficiency of a turbine's mechanical systems. Newly installed wind turbines would have the ability to generate more power than traditional ones without significantly altering the quantity or composition of rare earth magnets.

An example is General Electric (GE) Wind Energy's ScanWind wind turbine. It comes in two different models (both direct-drive), one of which produces 3 MW of power and the other 3.5 MW. Each model uses a slightly larger quantity of rare earths than current-generation 1.5 MW generators. Other models like the Vestas V112 (3 MW, hybrid drive) use fewer rare earths than current models (about 90kg) (Hatch, "Why I Take Issue" 2010). For the purpose of this analysis, it will be assumed that doubling the current average power production from 1.5 MW to 3 MW requires no change in the amount of rare earths used.

Similar to the analysis of wind turbine demand, there will be four scenarios that examine how changes in the base scenario assumptions affect hybrid vehicle and rare earth consumption.

Assumptions used for the hybrid vehicle scenarios differ from those used in the wind turbine analysis. Three scenarios examine changes in the overall level of hybrids sold and only one that looks at different quantities of rare earths used per vehicle. Table 4.4 gives a summary of the four alternate scenarios that will be examined for hybrid electric vehicles and the primary assumptions used to create future scenarios.

One concern with these scenarios is that they do not necessarily harmonize between the United States and other countries. For example, gasoline prices in Germany were $9.07 U.S. dollars (USD) per gallon in May 2011, while the average price in Kuwait was $0.81 USD per gallon. In the U.S., gasoline prices were $3.96 per gallon at the time. There are major variations in gas prices between countries. Studying the effects of a tax incentive leads to similar issues – European governments tend to provide consumers with more lucrative incentives than their American counterparts. Modeling the effect of gasoline prices on hybrid vehicle sales in every single non-U.S. country would be incredibly time consuming and difficult. This is beyond the scope of this thesis.

Table 4.4 Hybrid electric vehicle scenarios and assumptions.

| Scenario | Assumption |
|---|---|
| 2A (Gas price increase, high economic growth) | EIA "high economic growth" gasoline prices |
| 2B (Gas price increase, extreme) | $6 per gallon price of gasoline |
| 2C (Material composition change) | Didymium use (Nd 22.5%, Pr 7.5%, Dy 4%, Tb 1.5%) |
| 2D (Tax incentive present) | $3,400 tax incentive for new HEV |

Instead of modeling each country individually, these assumptions will be applied across the board. Both the sign and magnitude of any effect from gasoline prices on hybrid vehicle sales in the United States will be applied to non-U.S. countries such as Canada, Germany, and Japan. The same can be said for tax incentives in the U.S. and non-U.S. countries; e.g. if a $3,400 tax credit in the U.S. caused an additional 50 hybrid vehicles to be sold, the same would be true of tax credits and hybrid sales in places like France and China. Unfortunately, the use of blanket assumptions like these is likely to introduce further uncertainty into an already uncertain, forward-thinking analysis.

Scenario 2A ("gas price increase, high economic growth") explores changes in the price of a substitute good. Gasoline prices, a proxy measure of the primary alternative to hybrid vehicles, can reveal how a substitute good's price can affect hybrid demand. Projections of gasoline prices are taken from the U.S. EIA's "high economic growth" scenario[2]. The EIA's projections from 2011 to 2020 find that gas prices in the U.S. will increase from current prices but won't reach $4 per gallon. This seems very optimistic, as average U.S. prices are above $3.50 and in some cases over $4 (as of September 2012)[3]; creating new price projections is beyond this paper's scope however. It is possible in extreme cases that gasoline could reach a price of $6 per gallon. Many events could turn this into a real possibility including an Iranian blockade of the Strait of Hormuz, terrorist attacks on Middle Eastern production sites, and increasingly restrictive environmental laws in producing countries. Scenario 2B ("gas price increase, extreme") will test the effect of an extreme increase in the price of a substitute good on hybrid vehicle sales.

The third scenario, 2C ("material composition change"), is similar to scenario 1C because it examines how changes in the material composition of permanent magnets could affect the level of rare earths found in each vehicle. This concept was explained previously for wind turbines; basically, the substitution of praseodymium for neodymium occurs due to increasing prices for neodymium, perhaps as a result of higher neodymium prices caused by increases in Chinese export quotas on neodymium materials

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[2] The EIA's assumptions neglect possible effects of a conflict with Iran, cuts to OPEC's production, and other external factors that would substantially increase the price of gasoline.

[3] According to GasBuddy.com, South Carolina has the lowest gas price ($3.586/gal) and Connecticut has the highest gas price ($4.150/gal), excluding non-contiguous states.

The fourth and final scenario, 2D ("tax incentive present") looks at how an extension in the federal tax credit for new hybrid vehicle purchases might affect HEV demand. When President George W. Bush signed the Energy Policy Act in 2005, one provision was a credit up to $3,400 for new hybrid vehicle owners on their personal income taxes (Hybrid Cars, "Hybrid Car Tax" 2011). This credit expired at the end of 2010 and is no longer in effect; however, legislation is ongoing to provide a tax credit for new purchases of modern plug-in hybrids and full-electric vehicles with an upper limit of $7,500. Imagining a scenario where the $3,400 tax credit gets re-instated is something that (Bauer et al. 2010, 2011) and (Hatch, "Critical Rare Earths" 2011) did not do.

In order to test how changes in gasoline prices and the presence of a tax credit will affect the consumption of hybrid vehicles, a multi-variate regression was devised. Gasoline prices and a tax credit are the explanatory variables in the model while the quantity of hybrid vehicles consumed is the response variable. The regression model is shown in Equation Set 4.3. Historical data for non-U.S. hybrid vehicle sales was unavailable so it is impossible to run this regression for non-U.S. countries; therefore, it will be assumed that these results hold true for the U.S. and non-U.S. countries (as previously discussed). Although this regression is simplistic and not representative of all possible determinants of hybrid vehicle demand, it provides a simplistic method for looking at the effect of a substitute good's price and a tax credit on this demand.

Upon running this basic regression using the ordinary least-squares method in SAS, interpretation of the results is easy. Coefficient $\beta_{gas}$ represents the number of additional hybrid vehicles ($Q_{C,HEV}$) that will be bought should gasoline prices (explanatory variable $x_1$ or $P_{gas}$) change. A positive sign on this coefficient means that as gas prices go up, more hybrid vehicles will be purchased. Coefficient $\beta_{TaxCred}$ represents the number of extra hybrids ($Q_{C,HEV}$) that will

Equation Set 4.3 Multi-variable regression for quantity consumed of HEV.

$$Q_{C,HEV} = \alpha + \beta_1 x_1 + \beta_2 x_2$$

$$Q_{C,HEV} = \alpha + \beta_{gas} P_{gas} + \beta_{TaxCred} TaxCred$$

where:

$Q_{C,HEV}$ = quantity of hybrid vehicles consumed (sold)

$\alpha$ = intercept

$x_1$ = price of substitute good (gasoline) = $P_{gas}$

$\beta_1$ = price of substitute good (gasoline) coefficient = $\beta_{gas}$

$$x_2 = \text{tax credit dummy} = \text{TaxCred}, \begin{Bmatrix} x = 0, \text{no tax credit} \\ x = 1, \text{tax credit present} \end{Bmatrix}$$

$\beta_2$ = tax credit coefficient = $\beta_{TaxCred}$

be purchased if the federal government re-instates the consumer tax credit (explanatory dummy variable $x_2$ or TaxCred). Tax credit availability is represented by a dummy variable (1 = tax credit in effect, 0 = no tax credit). The coefficient on this variable should also have a positive sign, indicating that more hybrids will be bought if a tax credit is available.

A supplemental part of this paper, found in chapter seven, links these scenarios to potential government policy options. This is an extension of step four and focuses on the application of these scenarios to policy decisions made by government bodies. Both hybrid vehicles and wind turbines have three basic possibilities from which to choose; no specific recommendation will be made however as that is not the focus of this paper.

**Step 5** – Calculate the total inferred quantity of rare earths consumed in the *short* to *mid-term* (2011 to 2020) period for the U.S. and the rest of the world in the alternate scenarios.

The next step is to calculate the quantity of rare earths consumed in each scenario for both end-uses. Equations representing this calculation for the wind turbine scenarios are shown in Equation Set 4.4. Each modification is texted bold, providing a qualitative look at the analytical calculations of rare earth consumption in each scenario. Rare earth demand in each of the hybrid vehicle scenarios must also be calculated.

Equation Set 4.4 Quantity consumed of magnetic rare earths (wind turbines, 2011-2020).

**Wind Turbines**

*Scenario 1A - High economic growth*

$$Q_{x,i}^{C,F} = [(\frac{\text{total magnet weight}}{\text{MW}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}})$$
$$* \ \mathbf{(MW\ of\ new\ capacity\ in\ year\ F,\ \Delta GDP)} * (\text{\% market penetration of PM turbines})$$

*Scenario 1B - Market penetration increase*

$$Q_{x,i}^{C,F} = [(\frac{\text{total magnet weight}}{\text{MW}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}})$$
$$* (\text{MW of new capacity in year F}) * \mathbf{(\%\ market\ penetration\ of\ PM\ turbines + \%\ increase\ per\ year)}$$

*Scenario 1C - Material composition change*

$$Q_{x,i}^{C,F} = [(\frac{\mathbf{total\ weight\ of\ didymium\ magnet}}{\text{MW}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}})$$
$$* (\text{MW of new capacity in year F}) * (\text{\% market penetration of PM turbines})$$

*Scenario 1D - Technological efficiency improvement*

$$Q_{x,i}^{C,F} = [(\frac{\text{total magnet weight}}{\mathbf{MW_o}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}})$$
$$* (\text{MW of new capacity in year F}) * (\text{\% market penetration of PM turbines})$$

such that:

$Q_{x,i}^{C,F}$ = quantity consumed of rare earth metal x, for end product i, in future year F

x, i, F same as previous equations

$\Delta GDP$ = Growth in GDP where $\Delta GDP \geq 0$

% increase per year = 1.5% growth per year

$MW_o$ = output capacity of new hybrid and direct-drive turbines

% manufacturing loss = loss during magnet manufacturing, i.e. (30% = 0.3)

Equation Set 4.5 Quantity consumed of magnetic rare earths (HEV, 2011-2020).

**Hybrid Vehicles**

*Scenario 2A - Gas price increase, high economic growth*

$$Q_{x,HEV}^{C,F} = [(\frac{\text{total magnet weight}}{\text{HEV}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}}) *$$

$$(\text{\# HEV purchased in year F} \;\mathbf{+ \# \textbf{ new HEV sold in year F due to } \Delta P_{gas,\,EIA}})$$

*Scenario 2B - Gas price increase, extreme*

$$Q_{x,HEV}^{C,F} = [(\frac{\text{total magnet weight}}{\text{HEV}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}}) *$$

$$(\text{\# HEV purchased in year F} \;\mathbf{+ \# \textbf{ new HEV sold in year F due to } \Delta P_{gas,\$6}})$$

*Scenario 2C - Material composition change*

$$Q_{x,HEV}^{C,F} = [(\frac{\textbf{total weight of didymium magnet}}{\text{HEV}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}}) *$$

$$(\text{\# HEV purchased in year F})$$

*Scenario 2D - Tax incentive present*

$$Q_{x,HEV}^{C,F} = [(\frac{\text{total magnet weight}}{\text{HEV}})] * (\text{\% weight rare earth used}) * (\frac{1}{\text{\% manufacturing loss}}) *$$

$$(\text{\# HEV purchased in year F} * \;\mathbf{+ \# \textbf{ new HEV sold in year F due to presence of TaxCred}})$$

such that:

$Q_{x,i}^{C,F}$ = quantity consumed of rare earth metal x, for end product i, in future year F

x, i, F same as equation 4.4

$\Delta$Due to $P_{gas}$ = Change factor, $\beta_1$, found from regression in eq. set 4.3

$P_{gas,EIA}$ = EIA projections of gas prices

$P_{gas,\$6}$ = Extreme case, \$6 gas price

TaxCred = Change factor, $\beta_2$, found from regression in eq. set 4.3

## 4.2 Data Sources and Limitations

Table 4.5 provides a summary of the data sources used in this paper and the type of data each one provided. Primary sources of historical data for wind turbine installations were government reports and publications by non-partisan wind power associations. They are comprehensive documents that provide a full view of yearly demand for wind turbines in the United States, Europe, and the rest of the world, usually split into regions and individual countries. Historical data for hybrid vehicle sales was limited, especially for non-U.S. countries. Future scenarios of

HEV demand in non-U.S. countries were found in the 2011 CE Delft publication, *Impacts of Electric Vehicles* (Duleep et al. 2011).

Creating a base scenario of hybrid vehicle consumption in non-U.S. countries was difficult because there was almost no historical data. SAS generates models from data that has been previously collected – if there is very little (or even no) data available, then future demand scenarios cannot be created. Since a base scenario could not be created, external projections of hybrid vehicle sales were used. These projections came from (Duleep et al. 2011). Duleep et al.'s publication was used because it examined "pessimistic' forecasts that show PHEV and EV models each taking less than 1% of global [vehicle] sales in 2020" and "optimistic forecasts … [claiming] that EV models could account for 10% of global sales in 2020" and then "constructed a scenario that lies between the extremes" (Duleep et al. 2011, 53). A moderate substitute is appropriate in the absence of in-house demand estimates; however, even Duleep et al. believe that their projections are "optimistic".

Their results were, however, found to be consistent with those in the SB Limotive "fuel economy" scenario (Duleep et al. 2011, 54-55). SB Limotive (a subsidiary of Bosch and Samsung) created several scenarios analyzing electric vehicle penetration in the automobile market. These projections, as well as Duleep et al.'s, were largely based on "sales target announcements and goals set by Governments around the world" (Duleep et al. 2011, 55) and industry input regarding vehicle and battery technologies. It seems unlikely that many of these goals will be reached on time, largely due to the ongoing global economic crises, especially in the U.S. and Europe, and a slowdown in Chinese growth (Duleep et al. 2011). However, the reputation of Bosch, Samsung, and CE Delft lend credibility to their projections of future hybrid vehicle sales, making them into a (hopefully) good source of data for the baseline scenario of non-U.S. hybrid vehicle sales.

Other data was required for the model assumptions. These include the material composition of permanent magnets in turbines or hybrid vehicles, the quantity of permanent magnets per unit of each technology, and the amount of waste produced during manufacturing. Additional data was needed for historical and predicted gasoline prices as well as government incentives for clean energy technologies.

Table 4.5 Data sources and information provided.

| | **Installations, sales** | | **Model Assumptions** | **Gas Prices** | **Govt. Incentives** |
|---|---|---|---|---|---|
| | **Turbines** | **HEV** | | | |
| **Bauer et al. 2010, 2011** | | | X | | |
| **Duleep et al. 2011** | | X | | | |
| **Hatch ("CRE", "Why I Take")** | | | X | | |
| **European Wind Energy Association (*Wind Energy,* Wilkes)** | X | | | | |
| **Global Wind Energy Council (*Global Wind Report*)** | X | | | | X |
| **Hybrid Cars ("Hybrid Car Tax")** | | X | | | X |
| **Hybrid Cars ("Hybrid & Plug-In")** | | X | | | X |
| **Lifton ("China Circles", "A Report")** | | | X | | |
| **J.D. Power & Associates** | | X | | | |
| **Lynas Corporation (Lynas Corp.)** | | | X | | |
| **Molycorp (Smith, Molycorp)** | | | X | | |
| **Shih et al. 2012** | | | X | | |
| **U.S. DOE DSIRE** | | | | | X |
| **U.S. DOE, "HEV Sales"** | | X | | | |
| **U.S. DOE, "U.S. Installed"** | X | | | | |
| **U.S. EIA, AEO11** | X | | | X | |
| **U.S. EIA, "Gasoline and Diesel"** | | | | X | |

Each data source has limitations though. This is a problem because limitations could alter the results from each demand scenario in a positive or negative manner. A big limiting factor for sources of wind turbine data was the difference in reporting styles between various organizations. For example, the Global Wind Energy Council and European Wind Energy Association report slightly different values for the wattage of turbine power previously and currently installed in European countries. Demand in each scenario would only slightly increase or decrease, depending on which publication you lean upon. Problems associated with this difference in methodologies are alleviated by using average values when necessary.

Issues arising from differences in reporting methodologies also contribute to limitations in sources for non-U.S. hybrid electric vehicle sales data. In some years, new vehicle sales are recorded as such – the number of Priuses sold in 2010 in Europe is the number of new sales. Other years are reported using new hybrid vehicle registrations as a proxy measure for new HEV sales. What makes this problem even worse is the lack of extensive data for hybrid vehicle sales in non-U.S. countries. This issue was overcome by using the future scenarios found in CE Delft's "Impacts of Electric Vehicles" publication.

There are also the statistical limitations associated with the regression analysis. Wind turbines and hybrid vehicles are both relatively new technologies in their current format and any historical data is going to be limited. An example is the data for new wind turbine installations in the United States – the sample size is only 11 years from December 31, 1999 to December 31, 2010. A generally accepted principle in statistics is that a bigger sample size always improves the results from statistical analysis; having a small sample size means that the statistical model likely suffers from a lack of robustness. Each of the SAS-generated base scenarios, as well as the regression coefficients in scenarios 2A, 2B, and 2D, are potentially affected by this issue. Additionally, historical data for non-U.S. hybrid vehicle sales was limited, forcing the use of external projections in lieu of a SAS-generated baseline. These issues mainly lead to less accurate results when creating scenarios of short to mid-term hybrid vehicle sales in non-U.S. countries.

### 4.3 The "Ideal" Study

The analysis presented here is deficient in many ways and does not represent the most "ideal" method of study. It suffers from a major lack of data in regards to hybrid vehicles sales and wind turbine installations, as well as problems associated with the fact that there is no strong consensus regarding permanent magnet compositions, market penetration rates of each technology, and the total magnet weight per vehicle or turbine. Transparency issues arise when measuring the demand for and consumption of rare earth materials at various stages of the supply chain due to the proprietary nature of processes and technologies used to create rare earth materials and final goods. Despite these issues, a crude methodology was developed to measure the basic consumption of rare earth magnet metals using assumptions that fell within the ranges given by industry experts and data provided by unbiased sources.

If there was a substantially larger amount of information available, the approach to modeling the rare earth magnet metal market would have been much different. A more voluminous amount of data (in terms of number of data points, specific demand from each magnet producer, etc.) would allow for the creation of an econometric model involving several multi-variate equations. This would include demand and supply equations for world consumers and producers of the four rare earth magnet metals, in which factors such as own and substitute good prices, material costs, and facility locations are taken into account. Market-clearing equations (equilibrium points found at the intersection of supply and demand in each time period) can then be determined.

Two examples of this include the seminal study on the copper market by (Fisher, Cootner and Baily 1972) and similar work being conducted on biofuels at the National Renewable Energy Laboratory. The (Fisher, Cootner and Baily 1972) paper used econometric analysis to determine a model that best described the copper market. Supply equations for the major producers of copper look at the relation between specific mine production and the world price of the extracted material in previous time periods. This is also done for secondary supplies of the metals such as scrap materials. Demand equations were created for the major consumers of copper; these looked at the effect of previous year own prices and manufacturing indices on total copper demand. To finish the model, the authors created equations to represent the effect of inventory changes and different prices on the supply and demand of copper. Fisher, Cootner and Baily then use this model to create forecasts of future copper demand and supply.

The aforementioned paper set the benchmark for economic analysis of the copper market. A wealth of freely available information from both producers and consumers of copper, dosed with a large hit of market transparency, clearly leads to improved results and can help set the stage for a useful analysis of a given market. Furthermore, many non-apparent trends in a market can be elucidated in this manner; for example, Fisher, Cootner and Baily calculate the short and long-run elasticities of copper market participants. Measuring these elasticities allows them to show how the supply or demand of copper changes in response to price changes. Ideally, analysis of the rare earth magnet metal market would follow a similar route as the Fisher, Cootner and Baily study and incorporate vast amounts of data provided (transparently) by companies. This would help determine the equations that best model supply, demand, and the equilibrium market-clearing quantities in each time period.

Another extension to this work would be the inclusion of a dynamic component. This would account for changes that occur to factors like GDP growth over time; GDP growth is affected by a multitude of items such as political attitudes towards taxes. Naturally, the political ideologies of a country such as the United States can change over time as a result of national elections for new leadership. Dynamic analysis requires a more transparent reporting of demand and supply data and is only possible when historical market-clearing equations have been calculated. By including changes in factors over time, this analysis could be more predictive of how the rare earth permanent magnet and technology markets could evolve and specifically respond to the aforementioned changes.

# CHAPTER FIVE

# SCENARIOS: U.S. AND WORLD CONSUMPTION OF WIND TURBINES

Chapter five supplies part one of this thesis' core contributions. It provides an analysis of historical and potential short to mid-term future (2011-2020) consumption of wind turbines in the world using alternative scenarios as previously discussed. Implied demand for the rare earth magnet metals (neodymium, dysprosium, terbium, and praseodymium) is estimated under each scenario. The methodology was explained in chapter four; chapter five is an analysis of the results from each scenario.

## 5.1 Base Scenario

This section begins by showing historical installations of wind turbines in the United States and the rest of the world. A SAS-generated growth rate is used to create a base scenario of future wind turbine and rare earth consumption. Both assumptions previously made about this naïve base scenario hold true; i.e. there are no changes in the factors affecting total wind turbine demand or the quantity of rare earths used per turbine.

### 5.1.1 Historical and Base Scenario Consumption in the U.S.

The first step was to analyze historical data and create an equation of best-fit that represents one possible model of future growth. Figure 5.1 shows annual new and cumulative U.S. installations of wind turbines from 1999 to 2010. Data for new U.S. installations was modeled in SAS, where a quadratic function was the best fit[4].

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[4] See appendix A for SAS output of historical and predicted U.S. and RoW wind turbine installations.

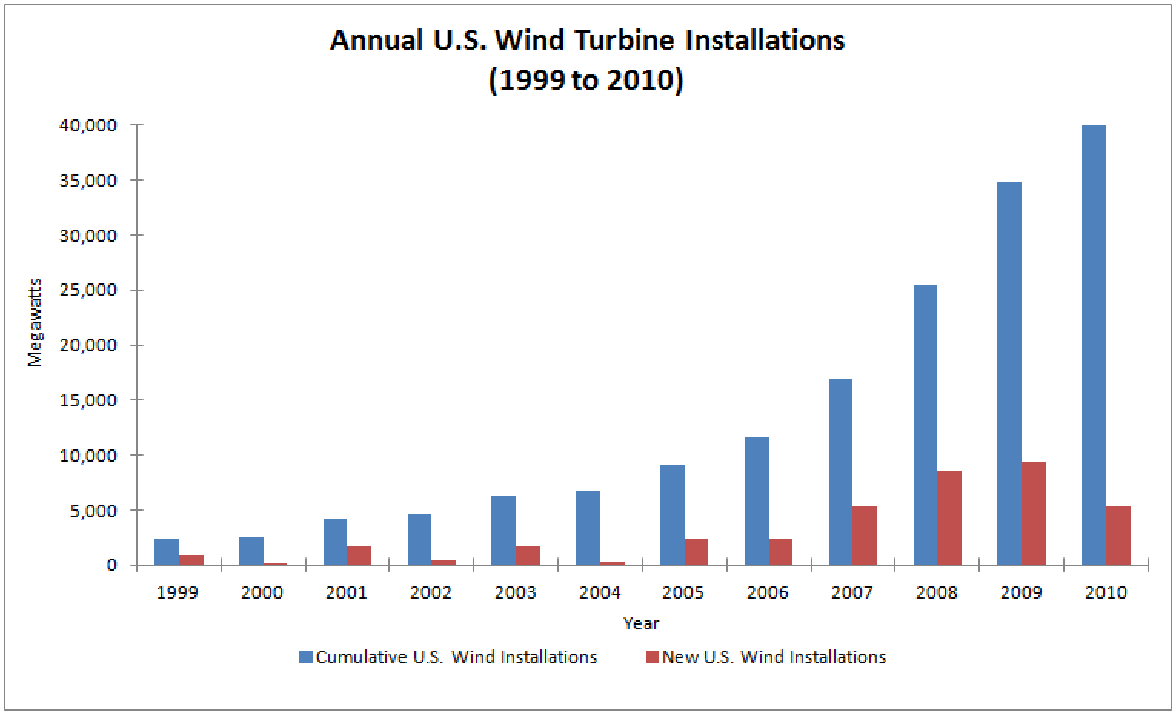

Figure 5.1 Annual wind turbine installations in the United States (1999 to 2010).

Quadratic equations follow the general form $y = ax^2 + bx + c$; the actual equation was found to be $y = 67.606x^2 - 270298x + (3*10^8)$. The choice to use this function was based on the $R^2$ statistic, which measures how close the yearly predicted values are to the actual values. In this case, the quadratic equation given by SAS had an $R^2$ value of 0.738 (on a scale of 0 to 1, with 1 being a perfect fit), while the highest $R^2$ calculated for other equation forms was approximately 0.684. Note that a value of 0.738 means that natural growth over time is not the only variable explaining new turbine installations.

The base scenario shows increasing new turbine installations over time. Cumulative installations of wind power capacity also increased at an exponential rate under this scenario. Historically, large dips in new installations occurred from 2001 to 2002 and 2003 to 2004, coinciding with the expiration of renewable energy PTC. Massive increases in new installations occurred from 2006 to 2009, coinciding with renewal of the PTC and fulfillment of state renewable portfolio requirements. New installations fell in 2010, likely due to high rare earth prices and low natural gas prices (P. Brown 2012).

Figure 5.2 shows historical (1999 to 2010) values for new U.S. wind turbine installations along with the predicted historical values given by the quadratic equation modeled in SAS. This quadratic equation helped create a base scenario of future growth in consumption (Figure 5.3). It gives one possible scenario of future consumption growth for wind turbines that might occur, given two key assumptions. First, this growth happens in the absence of influence from external factors; second, the rate of this growth is assumed to be constant. Results from this exercise show that between 2011 and 2020, the amount of new wind turbine capacity would grow quadratically.

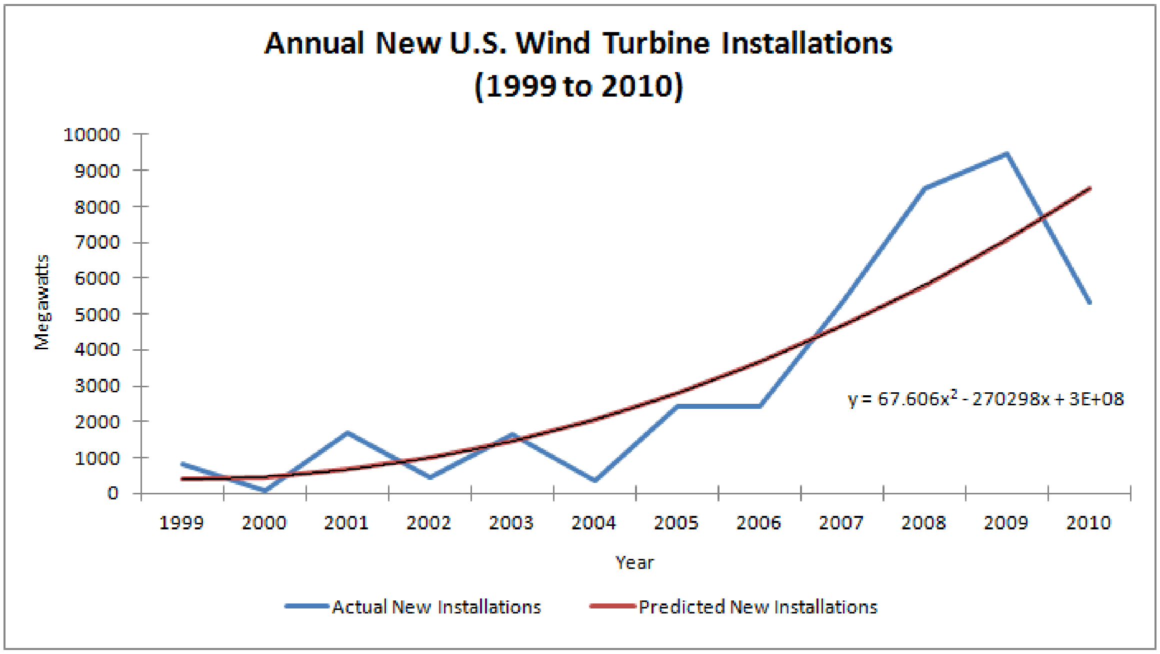

Figure 5.2 Annual predicted new wind turbine installations (United States, 1999 to 2010).

New installed capacity in this scenario is approximately 30GW in 2020. This is triple the 2009 capacity (9.5GW) and six times higher than in 2010 (5.3GW). Table 5.1 compares this base scenario to those found in reports from the GWEC, (Bauer et al. 2010, 2011), and (Shih et al. 2012). Predicted growth of new wind turbine installations is higher in this thesis than in other documents; it is double the estimates in (Global Wind Energy Council 2010) and (Bauer et al. 2011) and five times higher than (Shih et al. 2012).

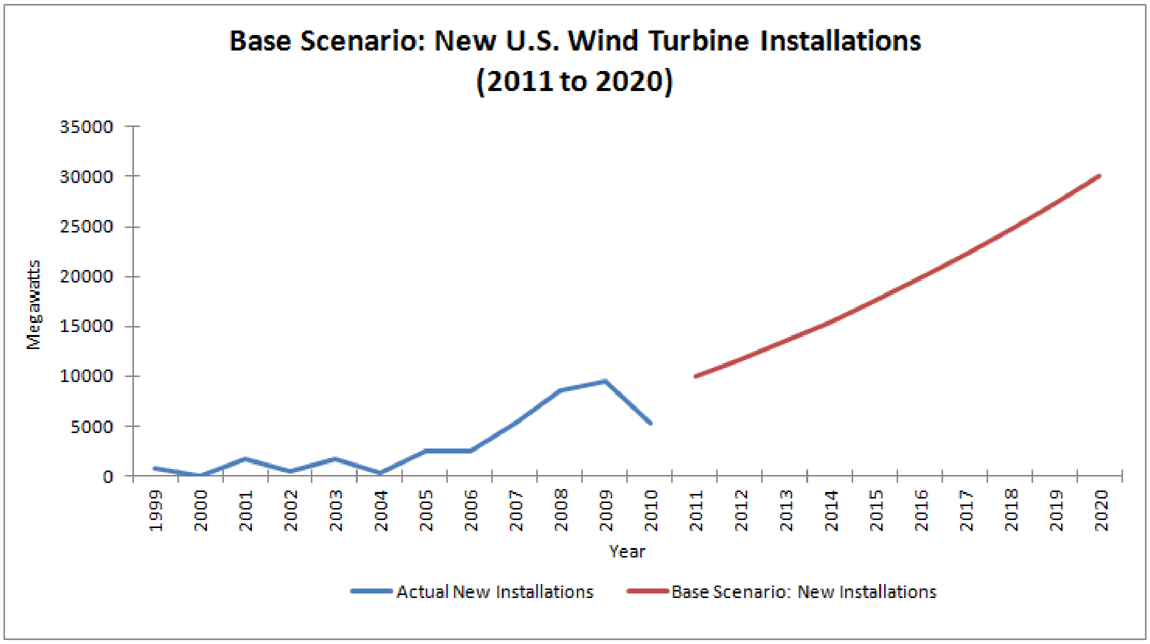

Figure 5.3 Base scenario, annual new U.S. installations of wind turbines (2011 to 2020).

Table 5.1 Comparison of scenarios for wind turbine installation in the U.S. (2015-2035).

| | **GWEC (2010)** | **Hart (Base Case, 2012)** | **Bauer et al. (2011, 20% Scenario)** | **Shih et al. (2012)** |
|---|---|---|---|---|
| **End Year** | 2015 | 2020 | 2030 | 2035 |
| **Annual Change (GW)** | 12 | 30 | 16 | 0.68 (low)<br>6.61 (high) |

Despite a downturn in the U.S. economy between 2008 and 2010, the base scenario shows an increase in new installations from 2011 to 2020. Wind turbine power has grown steadily in the United States as a result of several factors. First, the federal government extended the renewable PTC and an Investment Tax Credit (ITC) to wind power producers for one year in the new "fiscal cliff" deal (Lee 2013). This is part of the national strategy to reduce dependence on foreign oil and curb greenhouse gas emissions. Federal funding is also being provided for scientific research and development that helps reduce material and operating costs and improve technological efficiencies (Kaplan and Logan 2008, 15). Lower fixed (startup) and variable (operating) costs for wind turbines leads to a higher adoption rate as more companies begin to "go green".

Second, state-wide renewable portfolio standards for power generation and consumption are often part of binding legislation that leads to new installations of wind turbines. Other forms of renewable energy such as fuel cells and photovoltaics are generally less developed, have lower mechanical or chemical efficiencies, and thus are more expensive alternatives to wind turbines (Kaplan and Logan 2008). As a good, wind power often displays the qualities of being an impure public good. This is the result of wind power being a non-rival good (one person's use does not limit another person's use), but not a non-excludable one. Certain users can be excluded from receiving electricity produced by wind, either because they do not live in an area with wind turbines or because they cannot afford it. It has become a key part of the mandated changes in the way that the United States generates power.

### 5.1.2 Historical and Base Scenario Consumption of Nd, Dy, Tb in the U.S.

Rare earth magnet metal consumption directly corresponds with the demand for new wind turbines. Figure 5.4 shows that historical consumption of neodymium, dysprosium, and terbium in U.S. turbines has increased from 1999 to 2010. Historical growth in the rare earth market may not actually have followed the same path as that of wind turbine installations. Experts such as Shih et al. and Gareth Hatch have said that the current (2008 to 2010) market penetration of permanent magnet wind turbines is low (assumed to be 5% of total wind turbine installations). There is a high probability that permanent magnet wind turbines were not used in 1999 or even 2005 – it is unknown as to when these turbines began entering the market. Figure 5.4 is a simple approximation of past growth in the demand for rare earths used in wind turbines; this assumes that market penetration of permanent magnet turbines was 5% from 1999 to 2010.

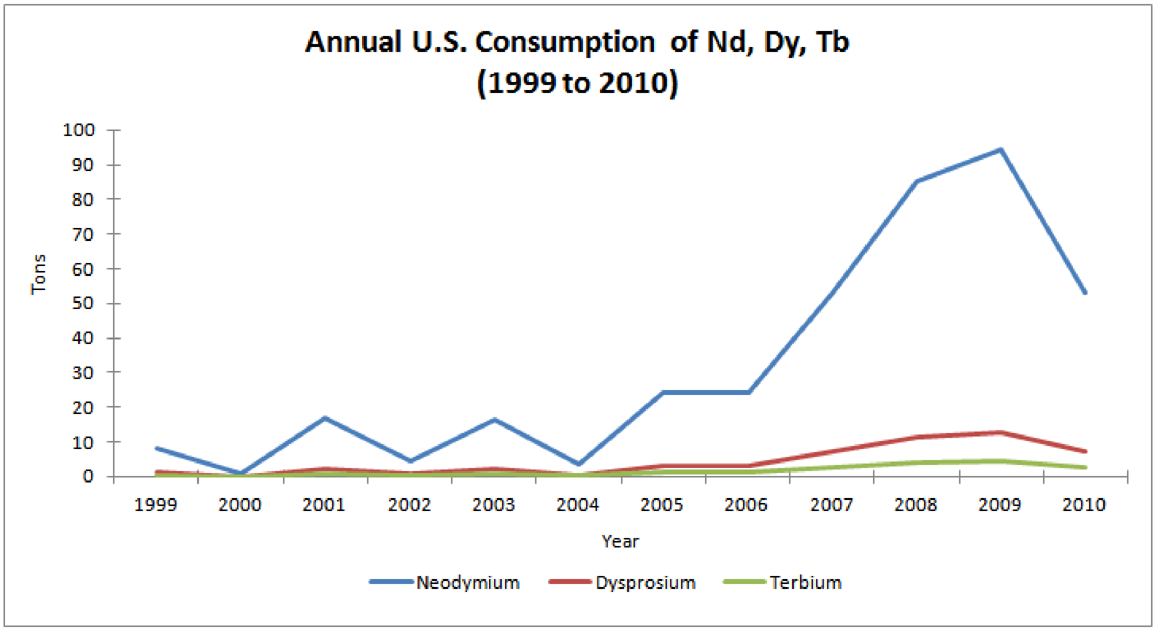

Figure 5.4 Annual consumption of neodymium, dysprosium, and terbium (United States, 1999 to 2010).

Short to mid-term consumption of these metals follows demand for wind turbines. Each one grows quadratically according to function modeled in SAS. Rare-earth turbines are steadily penetrating the wind turbine market and will continue to be employed due to the benefits discussed in chapter two. Figure 5.5 shows the base scenario for neodymium, dysprosium, and terbium consumption from 2011 to 2020.

Growth of new turbines in the base scenario is positive and thus the consumption of magnetic rare earths will also grow in a positive fashion. Neodymium would have the largest growth (total quantity-wise), with 300 tons consumed in 2020. It increases approximately threefold from 2009 quantities (95 tons) and is six times greater than 2010 quantities (53 tons). This occurs because neodymium is the main rare earth used in permanent magnets, a fact that remains true in every scenario.

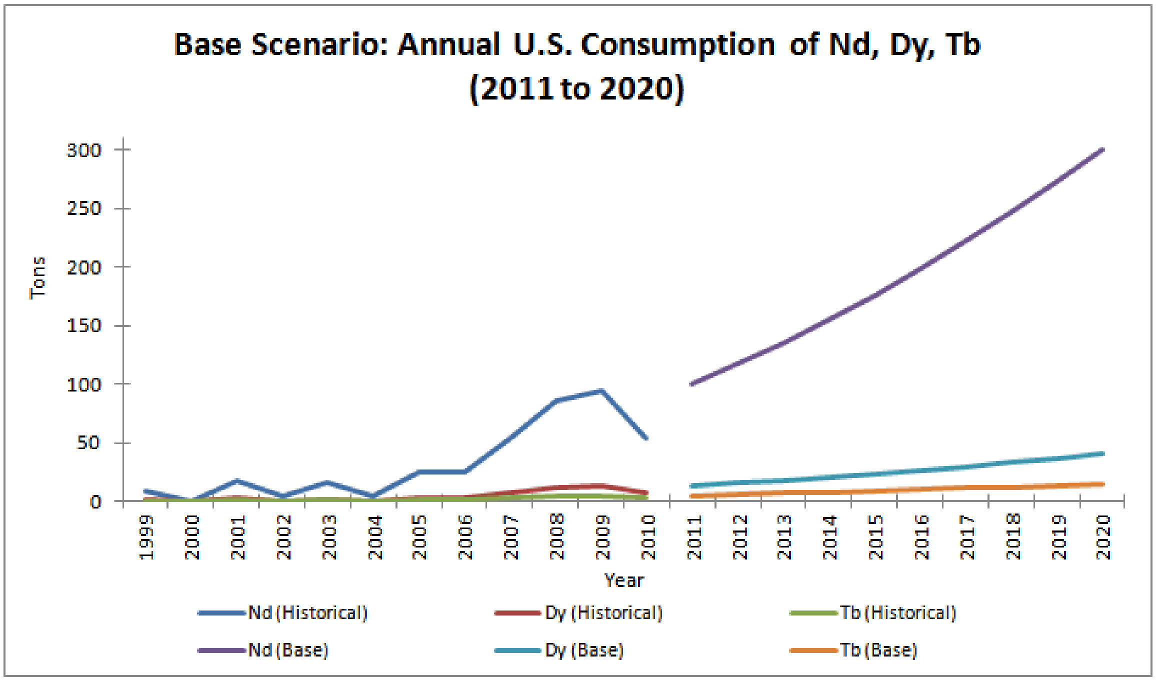

Figure 5.5 Base scenario, annual consumption of neodymium, dysprosium, and terbium (United States, 2011 to 2020).

Both dysprosium (40 tons in 2020) and terbium (15 tons in 2020) grow the same rate as neodymium and would see approximately three and six-fold growth compared to 2009 (13 tons of Dy and 5 tons of Tb) and 2010 (7 tons of Dy and 3 tons of Tb) (respectively) values. Table 5.2 provides a summary of consumption for each metal in 2009, 2010, 2015, and 2020. Note that values in parentheses are pre-manufacturing quantities demanded by permanent magnet producers, assuming a production efficiency rate of 70%, while the other values are the physical quantities of rare earths found in wind turbines.

Once again, this base scenario assumes that the growth of rare earth consumption follows SAS-generated rates based on historical values and that there will be no change to the number of turbines sold or quantity of rare earths used per turbine. These include alterations to the material composition of permanent magnets, improvements in technological efficiencies, and positive U.S. economic growth. Additionally, new demand for magnetic rare earths will only come from additional turbine installations. Wind turbines generally have a lifespan of twenty to thirty years

(Bauer et al. 2011, 42), so magnet recycling efforts are limited and the need for replacement turbines has yet to arise. These issues are assumed to be irrelevant in the base scenario.

Table 5.2 Base scenario consumption of Nd, Dy, Tb in the U.S. (2009, 2010, 2015, 2020).

| Year | Neodymium (met. ton.) | Dysprosium (met. ton.) | Terbium (met. ton.) |
|---|---|---|---|
| **2009** | 95 (135) | 13 (18) | 5 (7) |
| **2010** | 53 (76) | 7 (10) | 3 (4) |
| **2015** | 176 (251) | 23 (33) | 9 (13) |
| **2020** | 300 (429) | 40 (57) | 15 (21) |

### 5.1.3 Historical and Base Scenario Consumption in the RoW

Annual historical consumption of wind turbines in non-U.S. countries was modeled in SAS. The resultant equation of best fit was found to be exponential. Figure 5.6 provides historical new and cumulative installations of non-U.S. wind turbines from 1999 to 2010. SAS estimated the model to be a damped trend with exponential smoothing – this model analyzes time trends in the data and predicts future values based on these trends (no exogenous variables were used). A damped trend model is useful because it corrects for errors associated with the assumption of a linear time trend (McKenzie and Gardner Jr. 2010) (e.g. forecasts being too optimistic or too pessimistic due to the assumption of a straight-line trend) through the use of an exponential component. The $R^2$ statistic for this model was found to be 0.952, which was much higher than similar values for other models, thus the reason it was chosen. Figure 5.7 shows historical new installations of wind turbines in the rest of the world and the demand values in each past year as predicted by the damped trend exponential smoothing model.

Unlike the U.S., the rest of the world saw no dips in new installations, signaling much stronger markets for wind power in regions such as Europe and Asia. China added 13.6 GW and 19 GW of wind power capacity in 2009 and 2010 alone; experts believe that approximately 25%

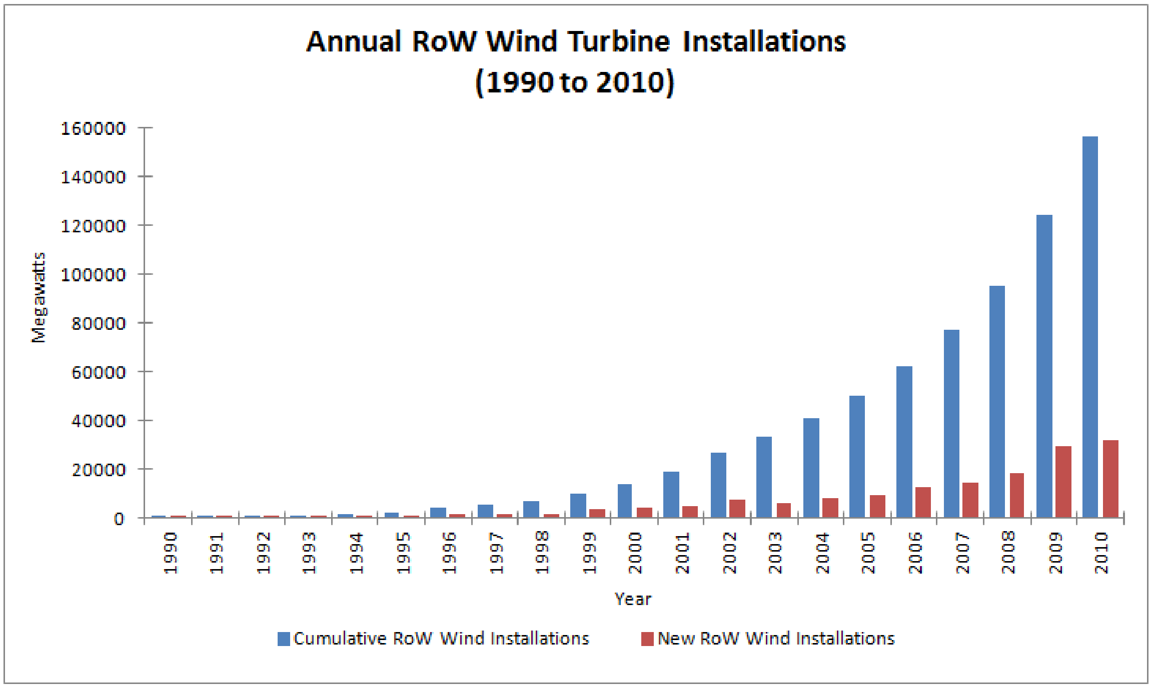

Figure 5.6 Annual wind turbine installations in the rest of world (1990 to 2010).

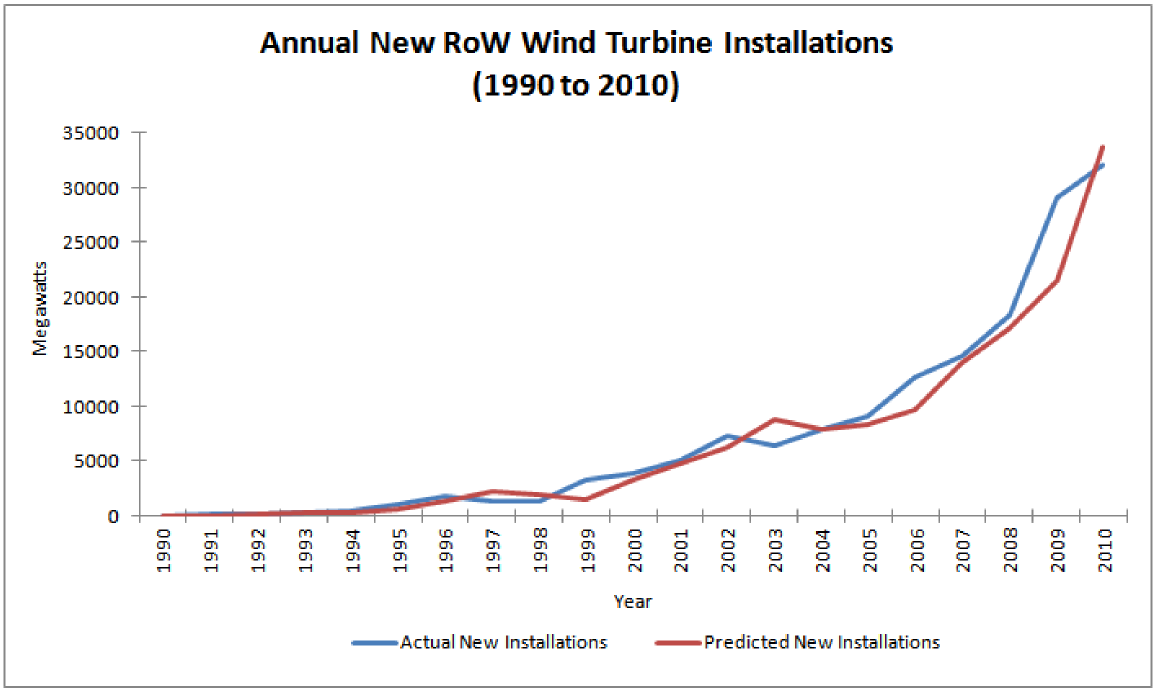

Figure 5.7 Annual predicted new wind turbine installations (RoW, 1990 to 2010).

of this was from permanent magnet turbines (Bauer et al. 2011). This was likely influenced by the strong, pro-environmental policies of governments in these regions. Many have potent, well-developed national energy policies that include renewable energy portfolio standards and lucrative market incentives such as feed-in tariffs. Governments in these nations simply provide more vehement support for renewable energy technologies than in the United States, resulting in particularly strong growth of wind power capacity throughout these regions.

China's growth was particularly notable because "it has been the largest annual market since 2009 [and] in 2010, China overtook the United States as the country with the most installed wind energy capacity" (Global Wind Energy Council 2010, 30). There has been a massive level of wind power investment in China, with approximately twenty billion U.S. dollars spent in 2009 and 2010 accounting for half of the world's total wind power spending. The Chinese government expects to add another 160 GW of capacity by 2020 (Global Wind Energy Council 2010, 30).

Similar to their European counterparts, the Chinese government has pushed wind power and other renewable energy development through the usage of feed-in tariffs (20 year contracts that promise 5.7 – 6.8 Euro cents per kilowatt-hour) and laws promoting a national renewable energy portfolio. This legislation requires energy producers to generate a specific amount of renewable power; suppliers are then obligated to purchase a certain quantity of this renewable energy. Strong financial support from local and national governments in China and extensive vertical integration of their domestic rare earth, permanent magnet, and wind turbine industries, make it apparent that the growth of Chinese wind power will drive non-U.S. turbine demand in the short to medium-term.

Figure 5.8 shows the base scenario for future consumption of new wind turbines in non-U.S. countries. Non-U.S. countries would see approximately 350% more new installations in 2020 (102GW) than 2009 (29GW) and 320% more new growth than 2010 (32GW). Wind power could continue growing at an exponential rate as it has in the past due to constraints on the positioning of turbines and the total number of optimal locations for wind farms. Positive linear growth of turbine consumption could occur from 2011 and 2020, spurred on by continual investment in a booming Chinese energy market and strong governmental policies in Asia, Europe, and developing nations such as India.

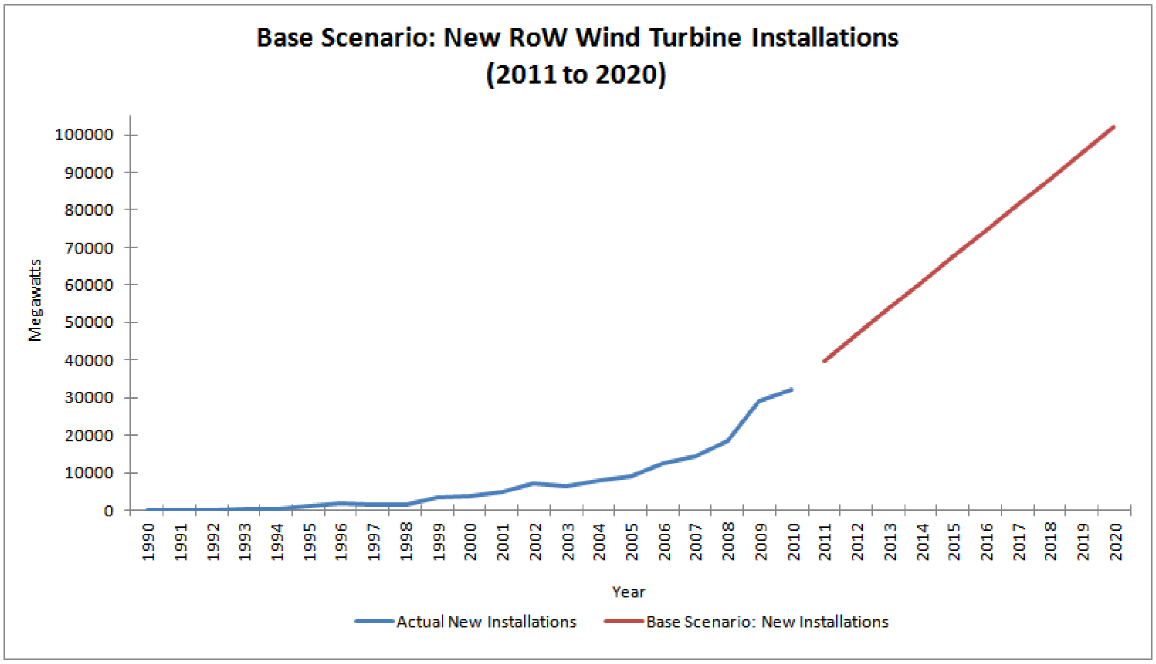

Figure 5.8 Base scenario, annual new RoW installations of wind turbines (2011 to 2020).

### 5.1.4 Historical and Base Scenario Consumption of Nd, Dy, Tb in the RoW

Historical demand for the magnetic rare earths in non-U.S. countries grew in a largely exponential fashion, corresponding to new turbine installations (Figure 5.9). While the U.S. had a dip in new wind turbine installations from 2009 to 2010, the rest of the world continued to grow between those two years. This was the result of unrelenting government and public support for renewable energy technology programs by socially and environmentally-oriented national governments as previously discussed.

The short to mid-term consumption of these three metals is shown to follow a linear growth pattern in the base case (Figure 5.10). This scenario assumes that permanent magnet wind turbines hold a 5% share of the wind turbine market; however, this is a simplification that makes it easy to standardize and compare U.S. and non-U.S. demand. Many European countries have penetration rates between 5% and 15% while some Asian countries like China have up to 25% penetration. Also, it was assumed that every 1.5MW of power generated requires approximately 1000kg of rare earths (total) in the form of permanent magnets. Each turbine manufacturer uses different specifications for their product and each one contains a slightly different amount of rare earths; the 1000kg value creates homogeneity between turbine models.

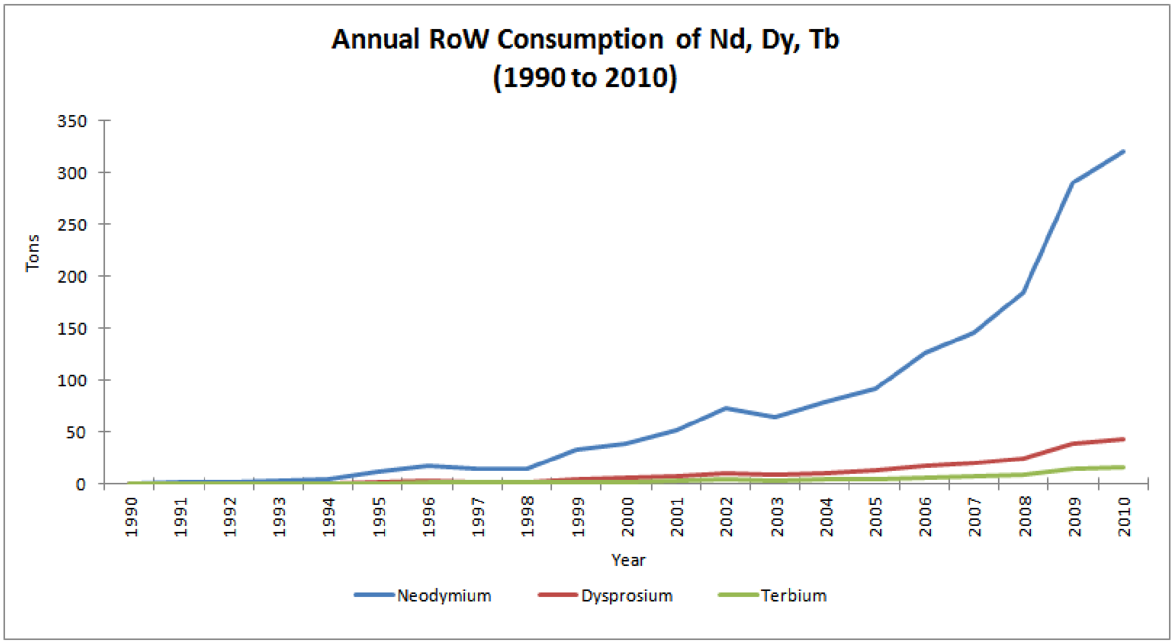

Figure 5.9 Annual consumption of neodymium, dysprosium, and terbium (Rest of world, 1990 to 2010).

New consumption of neodymium in 2020 would be 350% greater than in 2009 (1,021 tons vs. 290 tons) and 318% greater than in 2010 (1,021 tons vs. 321 tons). Dysprosium consumption would be approximately 348% and 316% larger than in 2009 and 2010 (136 tons in 2020 as compared to 39 and 43 tons in 2009 and 2010). Terbium demand is 319% and 316% greater than in 2009 and 2010 (15 and 16 tons, respectively). Table 5.3 gives a summary of base scenario consumption of rare earths in 2009, 2010, 2015, and 2020.

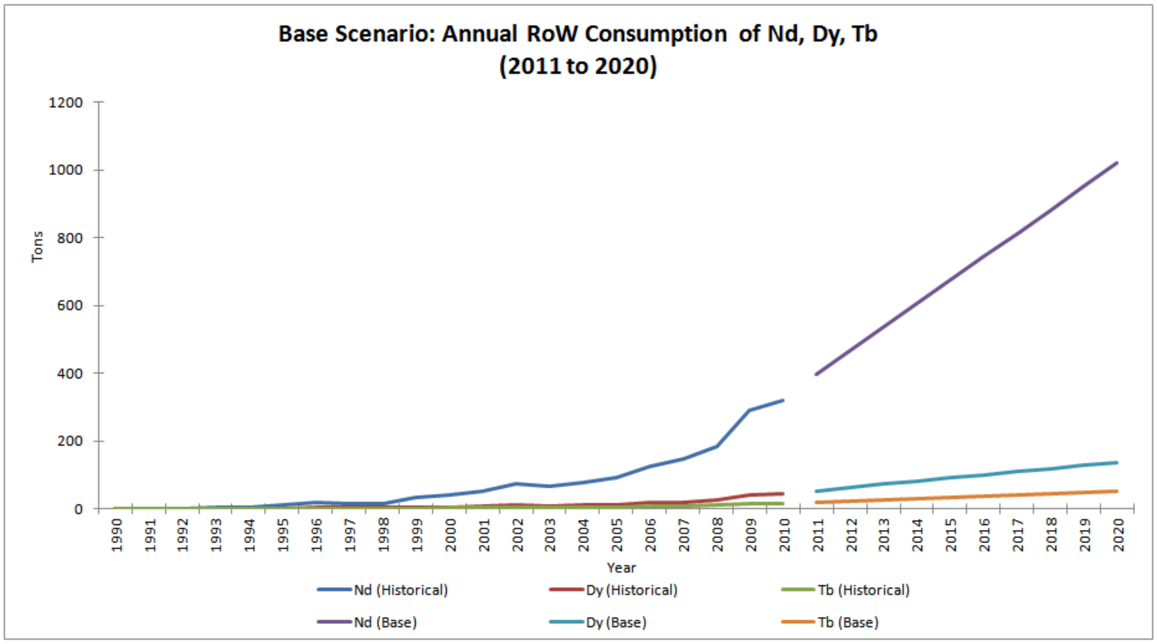

Figure 5.10 Base scenario, annual consumption of neodymium, dysprosium, and terbium (Rest of world, 2011 to 2020).

Table 5.3 Base scenario consumption for Nd, Dy, Tb in the RoW (2009, 2010, 2015, 2020).

| Year | Neodymium (met. ton.) | Dysprosium (met. ton.) | Terbium (met. ton.) |
|---|---|---|---|
| **2009** | 290 (414) | 39 (56) | 15 (21) |
| **2010** | 321 (459) | 43 (61) | 16 (23) |
| **2015** | 675 (964) | 90 (129) | 34 (49) |
| **2020** | 1,021 (1,459) | 136 (194) | 51 (73) |

## 5.2 Alternative Scenarios

This section accomplishes two tasks. First, it shows the implied new consumption of neodymium, dysprosium, praseodymium, and terbium in the short to mid-term period (2011 to 2020) based on the scenarios described in chapter four. Second, it provides a techno-economic discussion about each scenario, primarily focusing on why each of the scenarios seems reasonable or unreasonable. This is based on current market and economic situations in the United States and the rest of the world. Both sets of scenarios will be shown in order to compare and contrast differences in wind power and rare earth demand between the two regions.

### 5.2.1 United States

United States demand during the ten-year period starting 2011 and ending in 2020 would grow at nominally different rates in each scenario. Figure 5.11 shows the consumption of neodymium in scenarios 1A, 1B, 1C, and 1D, along with five previous years and the base case. Inclusion of data from 2005 to 2010 shows how growth in each scenario differs from recent growth. Table 5.4 gives a summary of the neodymium consumed in 2010, 2015, and 2020 for all scenarios.

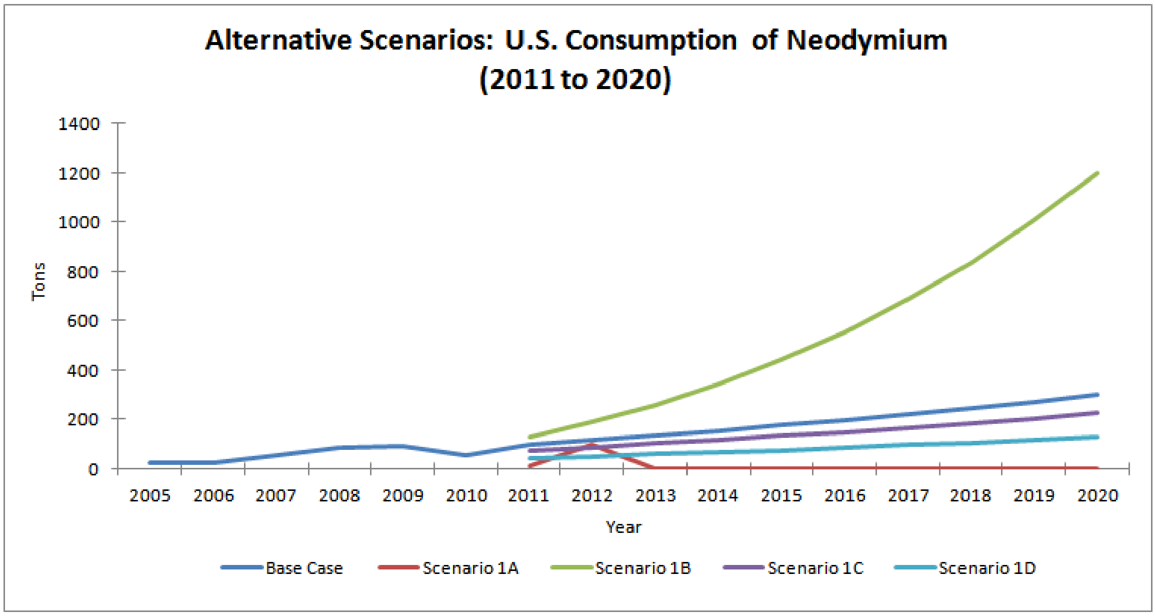

Figure 5.11 Alternative U.S. consumption of neodymium in wind turbines (2011 to 2020).

Table 5.4 Alternative consumption of neodymium in U.S. wind turbines (2010, 2015, 2020).

| **Wind Turbines** | **U.S. Neodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 53 (76) | 176 (251) | 300 (429) |
| **Scen. 1A** | - | 0 | 0 |
| **Scen. 1B** | - | 440 (629) | 1,202 (1,717) |
| **Scen. 1C** | - | 132 (189) | 225 (321) |
| **Scen. 1D** | - | 75 (107) | 129 (184) |

In scenario 1A ("high economic growth"), external predictions from the U.S. Energy Information Administration (EIA) were used to model wind turbine and rare earth growth. The

EIA's growth projections assumed that there would be a high level of economic growth in the U.S., reflected by the assumption of a 3.2% annual increase in the gross domestic product. Technology would not change and sunset clauses for legislation like renewable production tax credits would kick in and the credits would expire. Based on the EIA's projections, there will only be new turbine growth in 2011, 2012, 2018, and 2020. Neodymium consumption in this scenario would be approximately 114 tons in 2011 and 2012 and 2.5 tons between 2018 and 2020. This is significantly lower than what is estimated in this paper's base scenario.

The potential quantity of neodymium consumption demanded between 2011 and 2020 is much lower than in all the other scenarios. This is a result of the EIA's belief that approximately 73% (18 GW) of new wind capacity will be installed between 2009 and 2012 – the other 27% (7 GW) will get installed between 2012 and 2035. From 2012 to 2017, there will be no new wind power installations (U.S. Energy Information Administration, "Annual Energy Outlook 2011" 2011, 77). Even the "No Sunset" and "Extended Policies" scenarios predict that wind power will go unchanged from 2012 to 2018 and that cumulative capacity over this period is lower for both cases as compared to the "High Economic Growth" scenario (U.S. Energy Information Administration, "Annual Energy Outlook 2011" 2011, 77).

A lack of growth in wind power capacity between 2012 and 2020 is believed to be the result of slowing growth in public and private energy consumption during that period. The collapse of the U.S. financial sector and resulting slowdown in public and private sector spending means that less energy-generating capacity will be required in order to power these institutions. Furthermore, a lack of optimal on-shore sites will limit opportunities for new wind turbine installations (U.S. Energy Information Administration, "Annual Energy Outlook 2011" 2011, 21). Switching to off-shore facilities that use hybrid or even direct-drive systems would allow for the expansion of wind power capacity and enable future growth of the energy-generation sector to fulfill capacity requirements after 2020. That is, of course, if the U.S. economy recovers and does not suffer the consequences of unforeseen circumstances such as war with Iran or full economic collapse.

Before continuing, it is important to note that the amount of dysprosium and terbium required for wind turbines is also very low in scenario 1A. New demand for dysprosium is approximately 15 tons in 2011 and 2012 and 0.33 tons from 2018 to 2020, while demand for terbium is only 6 tons and 0.013 tons in the same two periods, respectively. These are shown in Figures 5.12 and 5.13 and Tables 5.5 and 5.6. Small values of new demand for these two rare earths are consistent with previous discussions regarding non-existent growth between 2012 and 2017 and then a resurgence in growth starting in 2018.

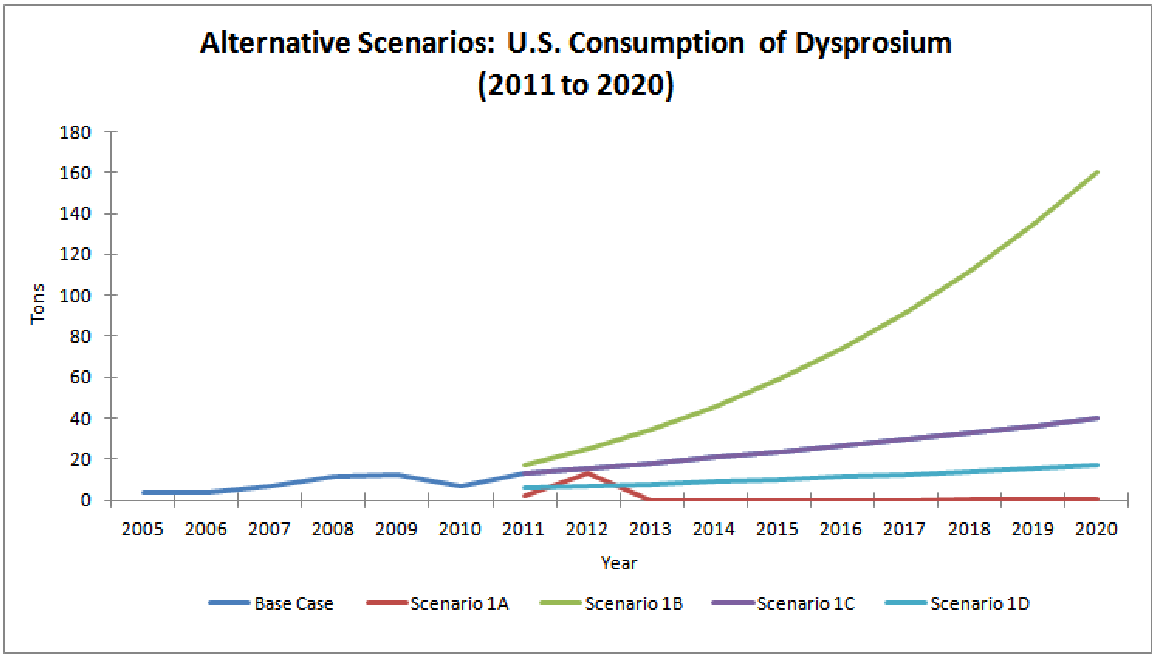

Figure 5.12 Alternative U.S. consumption of dysprosium in wind turbines (2011 to 2020).

In the second scenario (Scenario 1B, "market penetration increase"), it is assumed that the market penetration of hybrid and direct-drive permanent magnet turbines for on and off-shore sites will increase. For the purposes of this paper, the current rate of market penetration in all countries is 5% and will increase by 1.5% per year until reaching 20% in 2020.

Table 5.5 Alternative consumption of dysprosium in U.S. wind turbines (2010, 2015, 2020).

| Wind Turbines | U.S. Dysprosium (met. ton.) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| **Base Case** | 7 (10) | 23 (33) | 40 (57) |
| **Scen. 1A** | - | 0 | 0 |
| **Scen. 1B** | - | 59 (84) | 160 (229) |
| **Scen. 1C** | - | 23 (33) | 40 (57) |
| **Scen. 1D** | - | 10 (14) | 17 (24) |

Scenario 1B is estimated to have the highest quantity of new demand for neodymium, dysprosium, and terbium between 2011 and 2020 (in comparison to the base case and three other scenarios). An increase in the market penetration of permanent magnet turbines will increase neodymium demand to 440 tons in 2015 (two and a half times bigger than the same year of the base case), and 1,202 tons in 2020 (four times greater than the base scenario). Dysprosium demand would also be higher than the base case in 2015 (59 tons vs. 23 tons) and in 2020 (160 tons vs. 40 tons). It follows that new terbium demand will face similar increases in 2015 and 2020, with 22 tons and 60 tons (respectively) as compared to 9 tons and 15 tons.

Scenario 1C ("material composition change") is an important scenario in terms of techno-economic analysis of the demand for wind turbines and their rare earths. In this scenario, it is hypothesized that praseodymium will be substituted for neodymium in permanent magnets. Praseodymium is added to permanent magnets for two reasons: first, it can reduce manufacturing costs when its prices are lower than those of neodymium, which they historically have been, and second, it increases a magnet's resistance to corrosion and lengthens the lifespan of the technology employing permanent magnets (Shih et al. 2012, 140). Called didymium, this mixture serves as a substitute in standard neodymium-iron-boron permanent magnets and only affects the quantity of neodymium and praseodymium used. The quantity of dysprosium and terbium remains untouched.

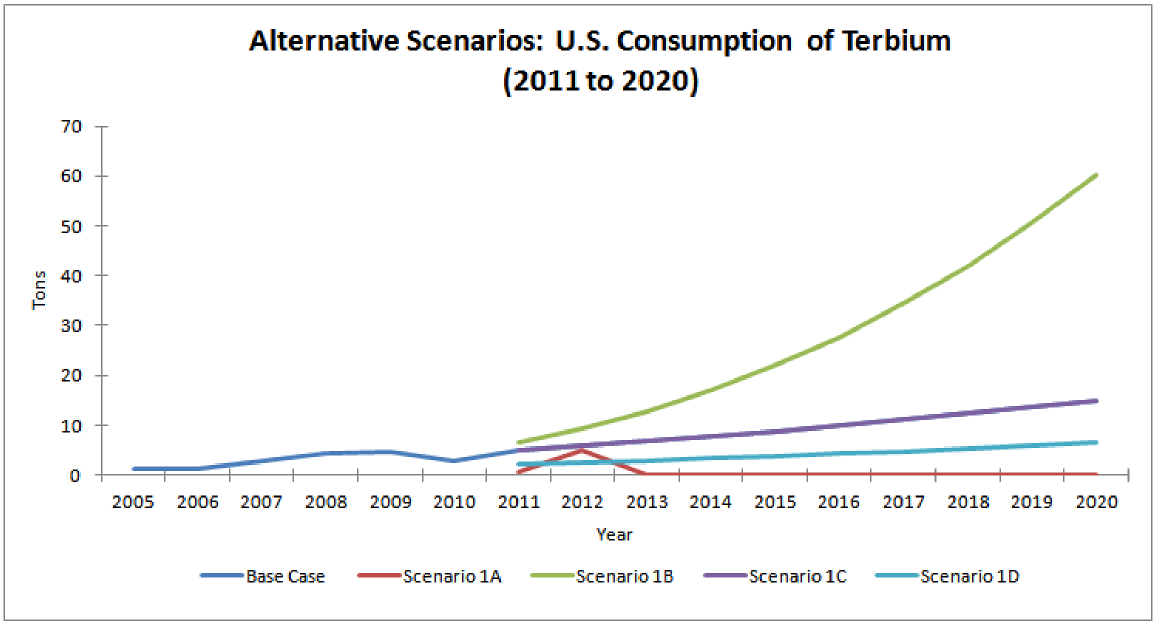

Figure 5.13 Alternative U.S. consumption of terbium in wind turbines (2011 to 2020).

Table 5.6 Alternative consumption of terbium in U.S. wind turbines (2010, 2015, 2020).

| **Wind Turbines** | **U.S. Terbium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 3 (4) | 9 (13) | 15 (21) |
| **Scen. 1A** | - | 0 | 0 |
| **Scen. 1B** | - | 22 (31) | 60 (86) |
| **Scen. 1C** | - | 9 (13) | 15 (21) |
| **Scen. 1D** | - | 4 (6) | 6 (9) |

The weight mixture of a didymium-iron-boron magnet is 22.5% Nd, 7.5% Pr, 4% Dy, and 1.5% Tb. Neodymium usage is reduced by 7.5%, resulting in unspecified cost savings and an increase in the lifespan of both the magnet and turbine; the magnetic components are less likely to rust and corrode due to environmental weathering. While the total amount of cost savings is currently unknown, due to differences in manufacturing processes and the fact that praseodymium usage is not widespread (Shih et al. 2012, 140), it is assumed to be significant when neodymium prices are high.

Scenario 1C showed that neodymium demand would be significantly reduced in the short (2015) and medium (2020) terms. In 2015, the quantity of neodymium demanded for the base case was 176 tons – scenario 1C estimates that approximately 132 tons of neodymium will be demanded (a 25% reduction). This reduction continues to 2020, where 225 tons of neodymium would be demanded; compared to the 300 tons in the base case, this is also a 25% reduction. Eliminating 25% of the neodymium demand in this period would result in relatively high cost savings for manufacturers through reductions in upfront material costs and future maintenance and replacement costs. Dysprosium and terbium demand in scenario 1C will be unchanged from the base case, as their usage is unaffected by the addition of praseodymium.

Praseodymium is not believed to be widely used in the manufacturing of permanent magnets. This means that there is no historical reference for praseodymium demand. Scenario 1C assumes that magnet producers will start using praseodymium in their component mixture and that these magnets will be used in all permanent magnet wind turbines. Figure 5.14 shows the growth of the four rare earth magnet metals under these conditions and Table 5.6 summarizes the demand for praseodymium in this scenario.

The quantity of praseodymium demanded in scenario 1C is expected to increase from 0 tons (2010) to 44 tons (2015). This figure would then double and reach 75 tons in 2020. Neodymium demand would decrease by 25% compared to what it would otherwise have been as it is replaced in part by praseodymium. A lack of historical and current demand for praseodymium shows that it will probably not be an important factor in future discussions about the rare earth market. Praseodymium use could become more prevalent if new sources of raw materials became available and neodymium prices began to rise.

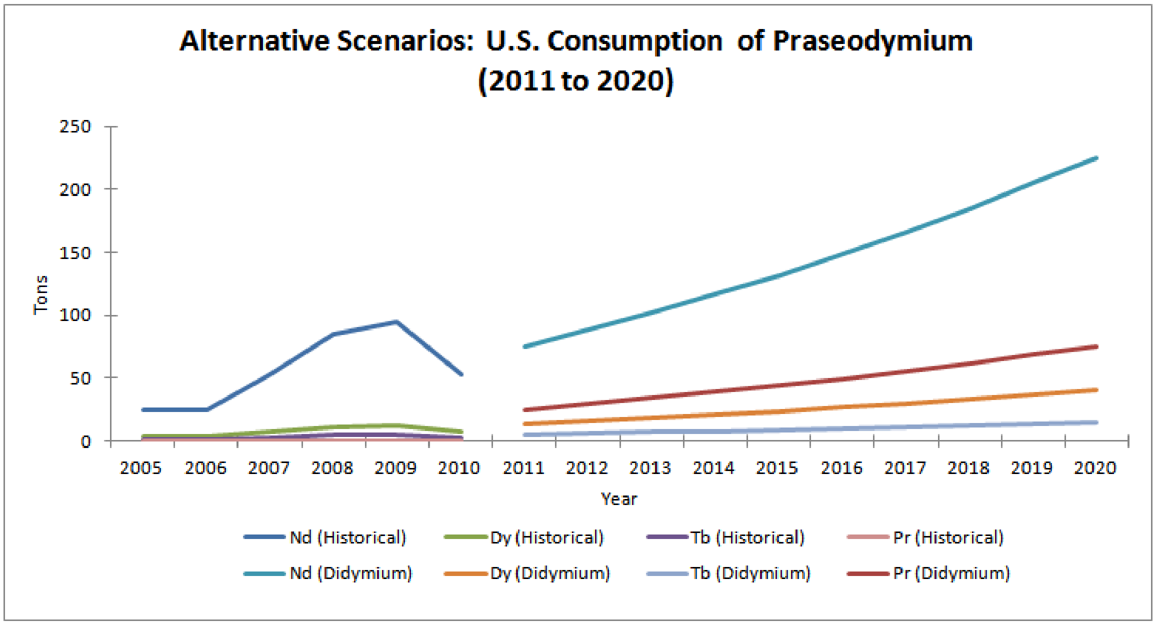

Figure 5.14 Alternative U.S. consumption of praseodymium in wind turbines (2011 to 2020).

Table 5.7 Alternative consumption of praseodymium in U.S. wind turbines (2010, 2015, 2020).

| **Wind Turbines** | **U.S. Praseodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 1A** | - | - | - |
| **Scen. 1B** | - | - | - |
| **Scen. 1C** | - | 44 (63) | 75 (107) |
| **Scen. 1D** | - | - | - |

Scenario 1D ("technological efficiency improvement") assumed that research and development efforts would lead to permanent magnet wind turbines with higher mechanical efficiency ratings. New turbines would produce 3.5 MW of power instead of the 1.5 MW found in the base case while still using one ton of rare earths. The basis for this was the GE ScanWind and other new direct-drive and hybrid turbines mentioned previously and by Gareth Hatch (Hatch, "Why I Take Issue" 2010). Currently, larger magnets are required in order to produce more power, but R&D efforts could advance the energy collection, storage, and delivery aspects of wind turbine systems; their power output would increase without a simultaneous increase in the level of rare earths required.

Demand for neodymium in Scenario 1D would be smaller than in the base case. It follows the same growth rate but would be 129 tons (2020) rather than 300 tons in the base case, roughly half the amount. A technological improvement alone could greatly decrease the usage of neodymium in U.S. wind turbines; however, these improvements in technological efficiencies are usually more revolutionary and require significant time and cost investments in R&D. They may not be available during the short to mid-term period and are likely to play a role in reducing long-term neodymium demand.

Dysprosium and terbium demand in scenario 1D will also be less than in the base case. Tables 5.5 and 5.6 showed that dysprosium demand will be 10 tons and 17 tons in 2015 and 2020 (respectively), while terbium demand in 2015 and 2020 will be 4 tons and 6 tons (respectively). Each of these values is roughly 2.3 times less than the base case and shows that a change in technology such as this will essentially cut the new demand for neodymium, dysprosium, and terbium in half over the short to mid-term period.

Scenario 1B leads to the highest level of demand for the three magnetic rare earths. Demand will be significantly greater each year between 2011 and 2020. This scenario has the most potential to be affected by the lack of supplies portended by other publications. Scenarios 1A and 1C are the most likely to occur in the short to mid-term; changes in material composition and increasing market penetration rates are easy to facilitate, especially because the technology is already available and costs remain the only major barrier to widespread implementation. This does not speak to the potential simultaneity of these scenarios. It is possible that as market penetration of permanent magnet turbines increases, material substitution may become more prevalent or positive developments in technological and manufacturing efficiencies might transpire.

### 5.2.2 Rest of World

Demand for rare earths in wind turbines in non-U.S. countries could grow in a similar fashion to United States growth. Figure 5.15 shows that scenarios 1A, 1C, and 1D ("high economic growth", "market penetration increase", and "technological efficiency improvement") each have a demand for neodymium that is less than or equal to the base case - only scenario 1B has greater demand. These results hold true for the other rare earths analyzed. Specific estimates for each scenario are given in Table 5.8.

Scenario 1A is based off the "advanced" growth scenario projected by the Global Wind Energy Council. The GWEC scenario assumes that the growth of cumulative wind power capacity is 27% in 2010 and will decrease to 9% in 2020; this represents an average decline in new growth of 1.8% per year. Demand growth in this scenario follows the base case until 2014 when it declines significantly until 2020 as a result of decreasing growth. Neodymium, dysprosium, and terbium demand would be approximately 1% lower in 2011 than in the base case (395 tons, 53 tons, and 20 tons in scenario 1A vs. 398 tons, 53 tons, and 20 tons in the base case, respectively). This difference grows to about 40% in 2020 as the amount of new wind power capacity growth declines to 9% per year, with 621 tons of Nd, 83 tons of Dy, and 31 tons of Tb demanded in the year 2020.

This scenario is likely to occur as a result of several factors. First, many countries are dealing with ripple effects from the United States' economic downturn and have had issues with the failure of their own financial institutions. Second, despite strong government policies that incentivize the building of new wind power facilities, natural limitations on new growth are beginning to be met. Years of building wind turbines have lead to the installation of wind turbines in all optimal locations and has left many nations in Europe and other regions with little room to grow (Bauer et al. 2010, 2011) (Global Wind Energy Council 2011).

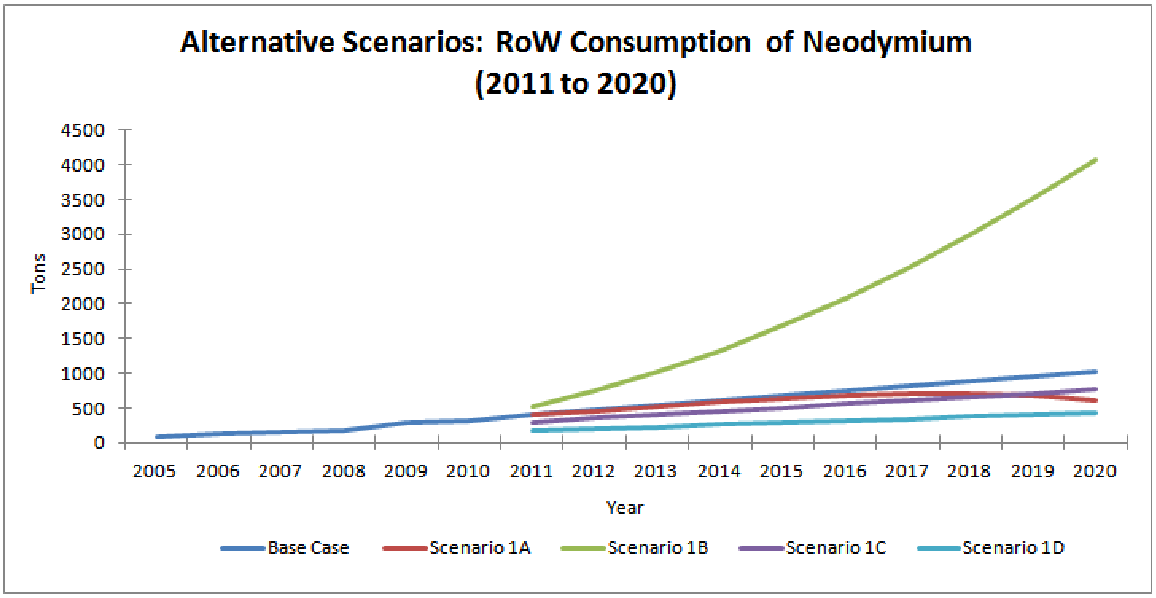

Figure 5.15 Alternative RoW consumption of neodymium in wind turbines (2011 to 2020).

Table 5.8 Alternative consumption of neodymium in RoW wind turbines (2010, 2015, 2020).

| **Wind Turbines** | **RoW Neodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 321 (459) | 675 (964) | 1,021 (1,459) |
| **Scen. 1A** | - | 634 (906) | 621 (887) |
| **Scen. 1B** | - | 1,688 (2,411) | 4,082 (5,831) |
| **Scen. 1C** | - | 506 (723) | 765 (1,093) |
| **Scen. 1D** | - | 289 (413) | 437 (624) |

The crux of scenario 1B was that there would be changes in the penetration rate of permanent magnet wind turbines within the wind turbine market. Demand in this scenario would increase 1.5% per year, with neodymium, dysprosium, and terbium facing 2015 demand of 1,688 tons, 225 tons, and 84 tons (respectively). In 2020, demand for neodymium, dysprosium, and terbium was 4,082 tons, 544 tons, and 204 tons.

Although the U.S. has low rates of market penetration for permanent magnet wind turbines, countries like China have up to 25% of their wind turbine market comprised of hybrid and direct-drive systems. This is due to their relatively recent adoption of wind turbine technology and the ability to install low-cost wind turbines produced by vertically-integrated domestic firms. Permanent magnet turbines in Europe also have higher levels of market penetration than the U.S.; specific numbers vary between countries (Shih et al. 2012). These rates are due to strong government support for renewable energy technologies. A single, 5% value for scenarios of global permanent-magnet wind turbine demand may produce estimates that are either too low or high for some countries.

In scenario 1C ("material composition change"), estimates of terbium and dysprosium demand were exactly the same as the base case. This is expected because the substitution of praseodymium for neodymium does not affect the usage of these two rare earths. Neodymium demand would be reduced by 25% to 506 tons (2015) and 765 tons (2020) in this scenario relative to the base case, corresponding to a potential reduction of 25% in the quantity of neodymium used for permanent magnets. Praseodymium demand would increase fairly linearly from zero to 169 tons in 2015 and 255 tons in 2020. The growth of praseodymium is shown in Figure 5.18 and Table 5.10.

Estimates in scenario 1D find that neodymium demand will be 289 tons in 2015 and 437 tons in 2020, compared to 675 tons (2015) and 1,021 tons (2020) in the base case (Table 5.7). This means that an improvement in technological efficiency without increasing rare earth use could result in a 57% reduction in neodymium demand from the base case over the ten-year period.

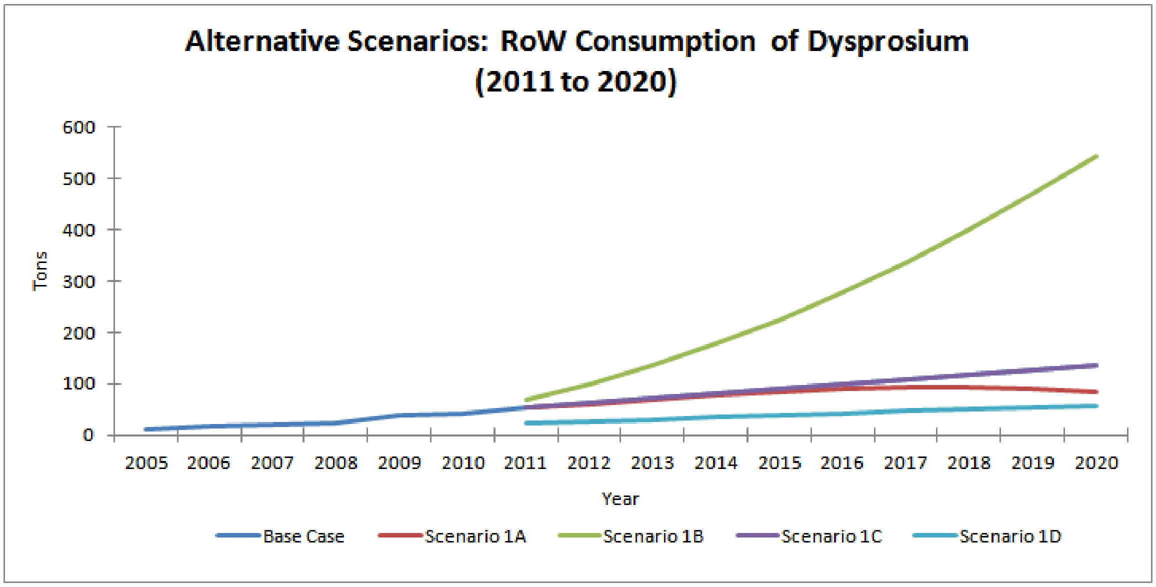

Figure 5.16 Alternative RoW consumption of dysprosium in wind turbines (2011 to 2020).

Table 5.9 Alternative consumption of dysprosium in RoW wind turbines (2010, 2015, 2020).

| **Wind Turbines** | **RoW Dysprosium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 43 (61) | 90 (129) | 136 (194) |
| **Scen. 1A** | - | 85 (121) | 83 (119) |
| **Scen. 1B** | - | 225 (321) | 544 (777) |
| **Scen. 1C** | - | 90 (129) | 136 (194) |
| **Scen. 1D** | - | 39 (56) | 58 (83) |

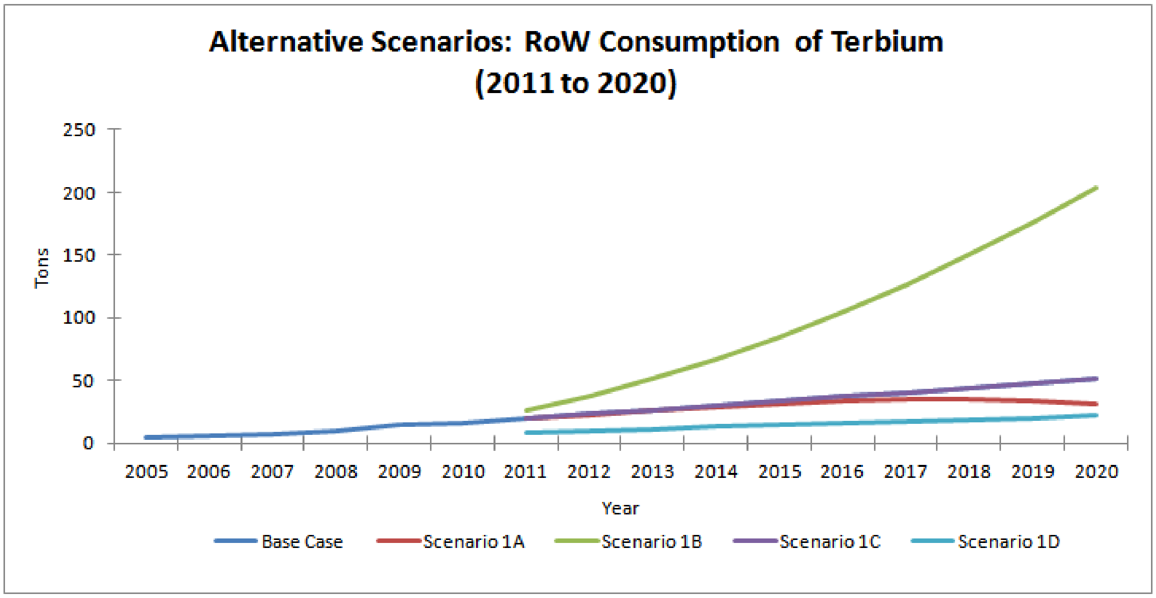

Figure 5.17 Alternative RoW consumption of terbium in wind turbines (2011 to 2020).

Table 5.10 Alternative consumption of terbium in RoW wind turbines (2010, 2015, 2020).

| Wind Turbines | RoW Terbium (met. ton.) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| **Base Case** | 16 (23) | 34 (49) | 51 (73) |
| **Scen. 1A** | - | 32 (46) | 31 (44) |
| **Scen. 1B** | - | 84 (120) | 204 (291) |
| **Scen. 1C** | - | 34 (49) | 51 (73) |
| **Scen. 1D** | - | 14 (20) | 22 (31) |

Dysprosium demand in scenario 1D would be 39 tons (2015) and 58 tons (2020), down from 90 and 136 tons in the base case. Terbium demand would be reduced to 14 tons (2015) and 2 tons (2020) (34 and 51 tons in 2015 and 2020 of the base case). Growth in scenario 1D is shown in Figure 5.18 and Table 5.11.

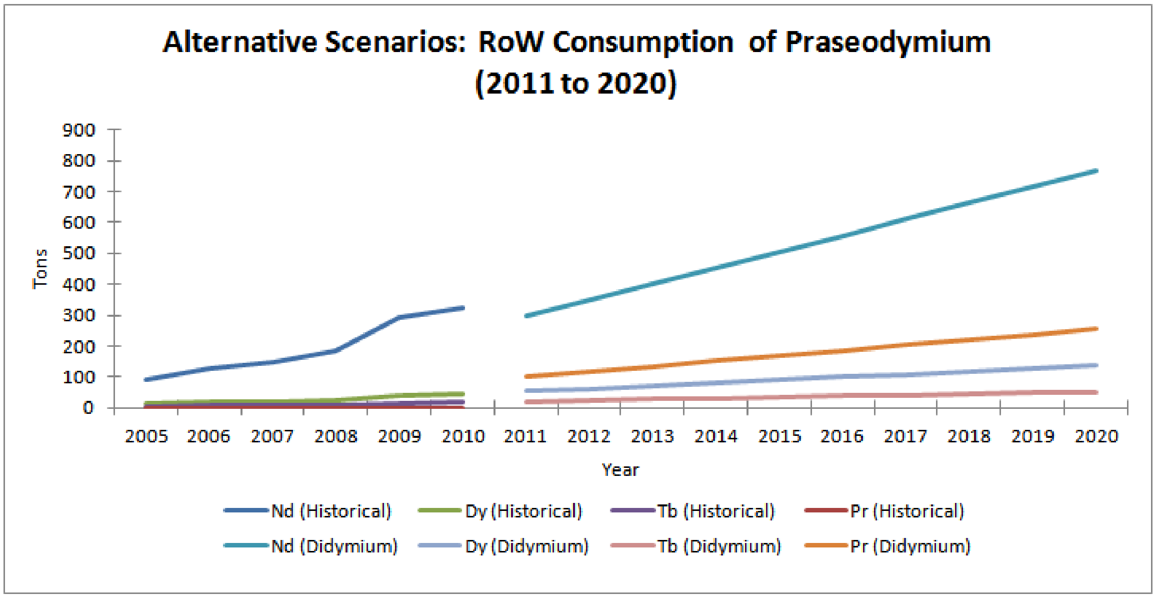

Figure 5.18 Alternative RoW consumption of praseodymium in wind turbines (2011 to 2020).

Table 5.11 Alternative consumption of praseodymium in RoW wind turbines (2010, 2015, 2020).

| Wind Turbines | RoW Praseodymium (met. ton.) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 1A** | - | - | - |
| **Scen. 1B** | - | - | - |
| **Scen. 1C** | - | 169 (241) | 255 (364) |
| **Scen. 1D** | - | - | - |

### 5.3 Further Discussion: Wind Turbines

At this point, it is important to discuss a couple methods that might reduce demand for magnetic rare earths in wind turbines. One involves improving manufacturing efficiencies in a way that significantly reduces the amount of starting material lost during manufacturing. This could lead to significant reductions in the demand for each rare earth used. Baur et al. state that some magnet manufacturers only lose 30% of their starting materials during the manufacturing process (others give higher numbers, as discussed previously); one could imagine a situation where permanent magnet manufacturers could improve their production process and reduce efficiency losses by 25%.

Table 5.12 shows how U.S. demand for neodymium would change in each scenario if this improvement in manufacturing efficiency occurred. Non-parenthetical values represent the total physical quantity of neodymium found in all U.S. wind turbines. Each of the values in parentheses shows the neodymium demanded by magnet manufacturers, given different efficiency losses. The first value represents a 30% loss of starting material (which was the original assumption used in this analysis) and the second value represents a loss of less than 30% - specifically, a quarter reduction in the loss of starting material, resulting in 22.5% of the starting material being lost instead of 30%. Neodymium demand would decrease b 10 tons (2015, scenario 1D) up to 166 tons (2020, scenario 1B). Each of these reductions in demand would become important should rare earth availability decrease, prices increase, and the usage of rare earths become dependent on technological innovation as opposed to large quantities of supplies.

Material substitution is another way to reduce the demand for certain magnetic rare earths. Several publications and experts report that a magnet can be doped with up to 6% dysprosium or terbium (as a function of total magnet weight), which is an increase of 2% total over this paper's

Table 5.12 Alternative U.S. neodymium consumption with 15% manufacturing loss (2010, 2015, 2020).

| **Wind Turbines** | **U.S. Neodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 53 (76, 68) | 176 (251, 227) | 300 (429, 387) |
| **Scenario 1A** | - | 0 | 0 |
| **Scenario 1B** | - | 440 (629, 568) | 1,202 (1,717 / 1,551) |
| **Scenario 1C** | - | 132 (189, 170) | 225 (321, 290) |
| **Scenario 1D** | - | 75 (107, 97) | 129 (184, 166) |

assumptions and what is commonly used in for manufacturing. The addition of dysprosium or terbium is done to boost performance of permanent magnets under high operating temperatures.

However, it is unlikely that either of these metals will be substituted for neodymium in significant amounts within the foreseeable future. Both are very scarce and incredibly expensive (Bauer et al. 2011, 150). Free-on-board prices for Chinese dysprosium were approximately \$3,000 US per kg in September 2011; the price for dysprosium is eight to nine times larger than that of neodymium (\$350 US per kg) (Shih et al. 2012, 28). Terbium’s price is similar to that of dysprosium. This is largely a result of the inherent geological characteristics of heavy rare earths (such as Tb and Dy) and the overwhelming lack of heavy rare earth production. Intensive substitution of dysprosium and terbium for neodymium is not economical and a balance of cost and performance seems to have already been struck (as evidenced by items like Figure 2.2).

Recycling is another way that new demand for rare earth magnet metals could be reduced. Extraction of rare earths from spent wind turbine units (and other technologies as well) would allow manufacturers to re-use old materials. Additionally, recycling of new and old scrap stocks that accumulate during the manufacturing process would also help reduce the demand for newly mined and processed materials, which could instead be diverted to other applications. Rare earth recycling is, however, almost non-existent in Western countries and is primarily limited to Japanese firms. Magnets in wind turbines and other technologies can be extracted from each unit but are difficult to recycle because of their nickel plating and possible corrosion. Japanese companies also hold many international patents that protect their intellectual property, including processes that deal with new and old scrap stocks and spent magnets and magnetic materials (Shih et al. 2012, 27). Research and development for new techniques is ongoing in many countries but any recycling effort of note would likely be unable to reduce rare earth demand by any significant quantity during the short to mid-term period studied in this paper.

# CHAPTER SIX

# SCENARIOS: UNITED STATES AND WORLD CONSUMPTION OF HYBRID VEHICLES

This next chapter discusses historical and future demand scenarios for hybrid electric vehicles in the world. Modeling U.S. hybrid vehicle sales was completed using the SAS program, following the process described in chapter four. External forecasts of non-U.S. HEV sales were found in CE Delft's "Impact of Electric Vehicles" publication (Duleep et al. 2011). Regression analysis was used in order to estimate the effects that the price of gasoline and presence of a tax credit have on hybrid vehicle sales. These change factors were used as part of the assumptions in the scenarios involving changes in the price of a substitute good and the presence of a government tax credit for new hybrids.

## 6.1 Base Scenario

Section 6.1 examines historical sales of hybrid electric vehicles in the United States and the rest of the world. It also looks at the use of SAS-generated growth rates to create a base scenario of new sales from 2011 to 2020 and discusses the (Duleep et al. 2011) projections of future hybrid sales in non-U.S. countries. These scenarios represent one possible path of future demand for hybrid electric vehicles and their rare earths. Once again, the assumptions regarding total sales growth and the per unit quantity of rare earths in the naïve base-case scenarios remain true.

### 6.1.1 Historical and Base Scenario Consumption in the U.S.

Cumulative sales of hybrid electric vehicles in the United States increased at an exponential rate. New sales of hybrid vehicles increased between 1999 and 2007 but then decreased from

2008 to 2010. Figure 6.1 shows growth in new and cumulative hybrid vehicle sales between 1999 and 2010. The decline in new sales from 2008 to 2010 coincides with the recent economic recession that has beset the United States. Hybrid vehicles have historically been thought of as a luxury good with demand largely driven by personal and social aesthetics (Duleep et al. 2011, 53) rather than scientific reasoning. Traditionally, HEV demand will falter if the economy falters (Duleep et al. 2011). People will continue to buy hybrid vehicles despite the cost barriers, but not as voraciously because the purchasing power of many consumers has decreased.

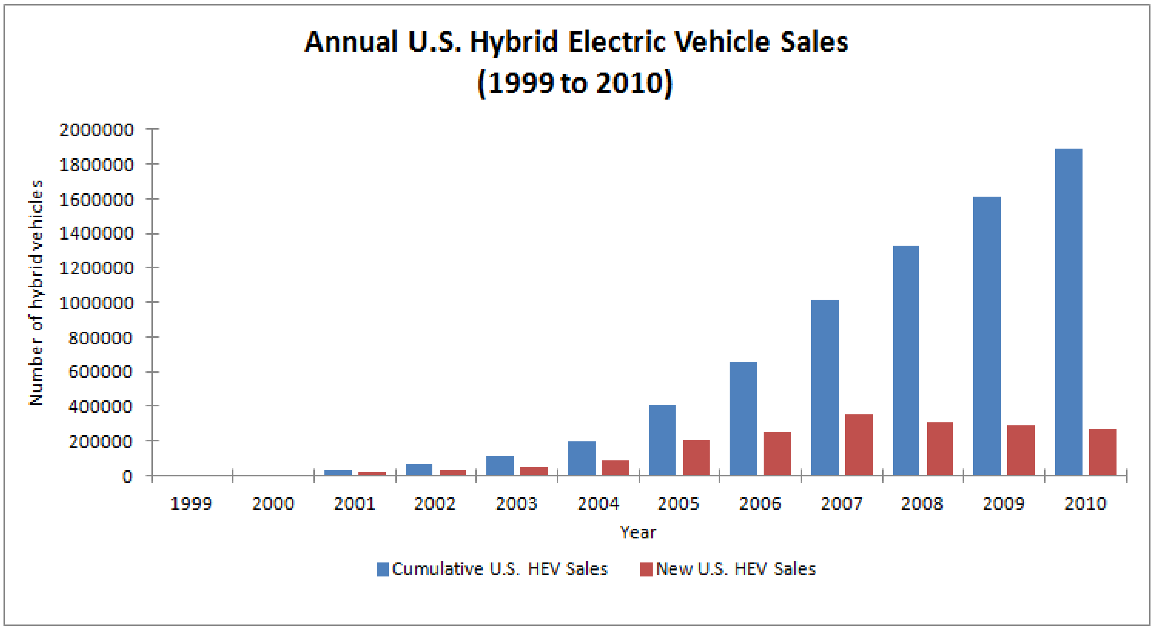

Figure 6.1 Annual hybrid vehicle sales in the United States (1999 to 2010).

Actual and predicted new hybrid vehicle sales from the model created in SAS are shown in Figure 6.2. It was determined that the damped trend exponential smoothing model best described U.S. demand for hybrid vehicles from 1999 to 2010. The $R^2$ statistic for this model was found to be 0.878, which was the highest value compared to other models. This means that inherent upward trending over time does not fully explain new sales; instead, it provides a starting point for creating a base scenario of future sales.

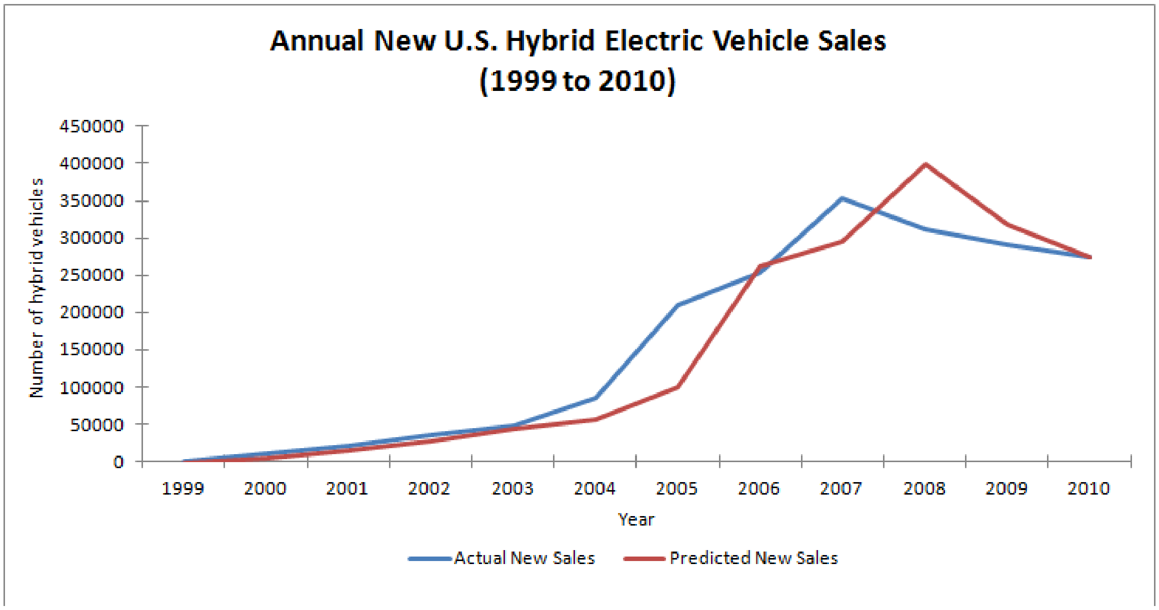

Figure 6.2 Annual predicted new hybrid vehicle sales (United States, 1999 to 2010).

The base scenario of future hybrid vehicle consumption is shown in Figure 6.3. Between 2011 and 2020, new sales of hybrid vehicles would decline. Eventually, this decline would cease, reaching equilibrium at approximately 236,000 new sales per year. As the U.S. stays mired in recession, the demand for hybrid vehicles will continue but at a decreasing rate. This scenario ignores events such as recovery of the U.S. economy or beneficial breakthroughs in technology.

One possible reason for the decline of hybrid sales in the U.S. is the emergence of plug-in and full-electric vehicles. Although hybrid vehicles represent about 90% of current electric vehicle sales (Constantinides, "The Elements of Magnetics" 2012), their market share would decrease as technologically-advanced plug-in and full-electric vehicles become available. Both types of vehicle boast greater mileage, improved reliability, and reduced emissions over hybrids. Naturally, hybrid vehicle sales would decrease as the number of alternative options increases.

The major difference between wind turbine and hybrid vehicle demand is that when the economy sags, demand for hybrid vehicles follows closer suit because of their status as a luxury good (Thatchenkery 2008). Hybrid vehicles and wind turbines are inherently different technologies, despite commonalities in their design goals and component parts. The gasoline infrastructure is deeply entrenched in modern society and fossil fuels will remain important sources of energy for public, private, and commercial transportation while renewable methods become more economically viable for the average consumer.

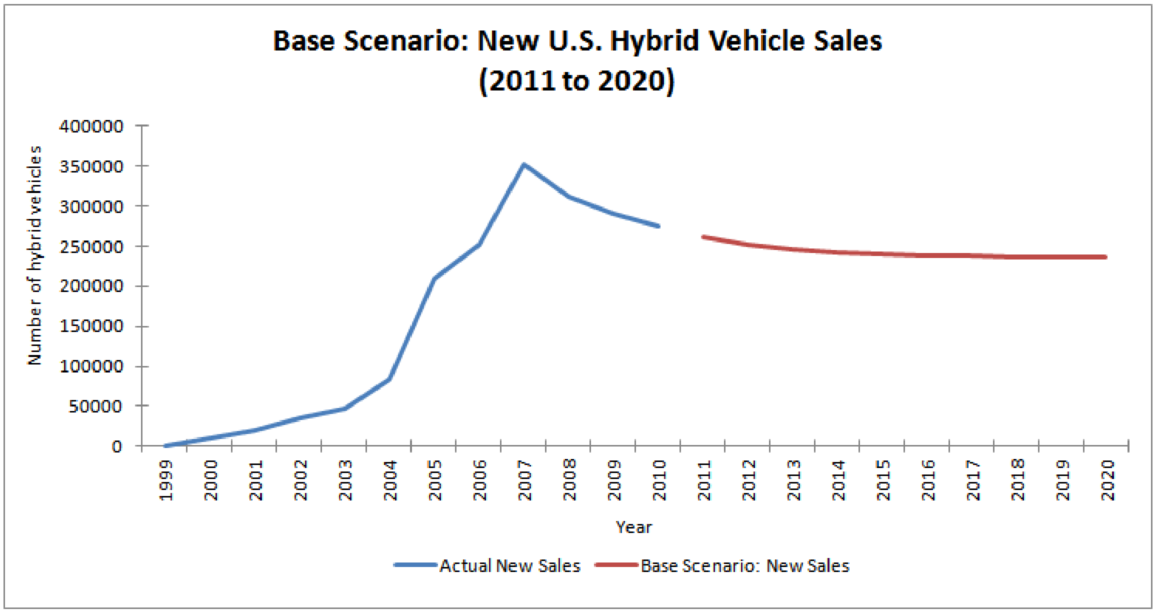

Figure 6.3 Base scenario, annual new U.S. hybrid vehicle sales (2011 to 2020).

Unlike wind turbines, there is no government requirement that individuals or companies purchase hybrid vehicles. The U.S. government has soft targets for the total number of electric vehicles that they would like on the road by a given year but there is no legislation that specifically mandates the implementation of these goals. Existing fiscal incentives improve the economics of hybrid vehicles but consumers must still decide whether this type of vehicle fits into their price range and desired fuel economy (Thatchenkery 2008). Therefore, hybrid vehicles are considered to be luxury goods, especially with no specific government-mandated obligation to increase their usage.

A flagging U.S. economy directly affects the decision making of consumers because they no longer have the disposable income necessary to purchase expensive luxury items such as hybrid vehicles. Every good that they normally purchase has now increased in price. Consumer preference theory says that when consumers are faced with a lack of disposable income and decreased spending power, they will choose to spend less of their money on expensive luxury products. Instead, they opt for cheaper alternatives such as gasoline automobiles and public transportation.

This theory is reinforced in a recent L.A. Times article called “Few hybrid vehicle owners are repeat buyers” (Hirsch, “Few Hybrid Vehicle Owners” 2012). A study by R.L. Polk & Co. found that “35% of current hybrid vehicle owners chose to purchase a hybrid vehicle again when they returned to the market in 2011 ... if you factor out the super-loyal Toyota Prius buyers, the repurchase rate drops to 25%” (Hirsch, “Few Hybrid Vehicle Owners” 2012). The author postulates that this is partially caused by the emergence of plug-in and full-electric vehicles and lawsuits against Honda over the failure of their vehicles to live up to stated fuel-economy specifications. Researchers also found that consumers will compare hybrid vehicles to their gasoline brethren and as Hirsch’s article states, “alternate-drive vehicles and their premium price points just aren’t appealing enough to consumers … especially given the growing strength of fuel economy among compact and mid-size competitors”.

Poor economic conditions weigh heavily on consumers when deciding to purchase a new vehicle. Even a third of current hybrid owners are switching to conventional gasoline automobiles (Hirsch, “Few Hybrid Vehicle Owners” 2012), which have a well-established service infrastructure and are facing improved mileage costs. This is a direct result of President Obama’s push for higher fuel economy standards to help reduce gasoline and oil consumption. Additionally, traditional gas-powered cars are cheaper alternatives to hybrid vehicles, despite the federal tax rebate that has previously been available for new hybrids. Hybrid vehicle sales are unlikely to cease entirely yet a decline is possible over the short to medium term.

### 6.1.2 Historical and Base Scenario Consumption of Nd, Dy, Tb in the U.S.

Historical consumption of rare earth magnet metals follows that of hybrid vehicles because the two are inherently linked through technological design. Consumption grew steadily from 1999 to 2003 and then grew exponentially until 2007. The U.S. economy sagged from 2007 to 2010, resulting in lower demand for hybrid vehicles and their rare earths. Past U.S. consumption of neodymium, dysprosium, and terbium is shown in Figure 6.4 and the future base scenario is shown in Figure 6.5.

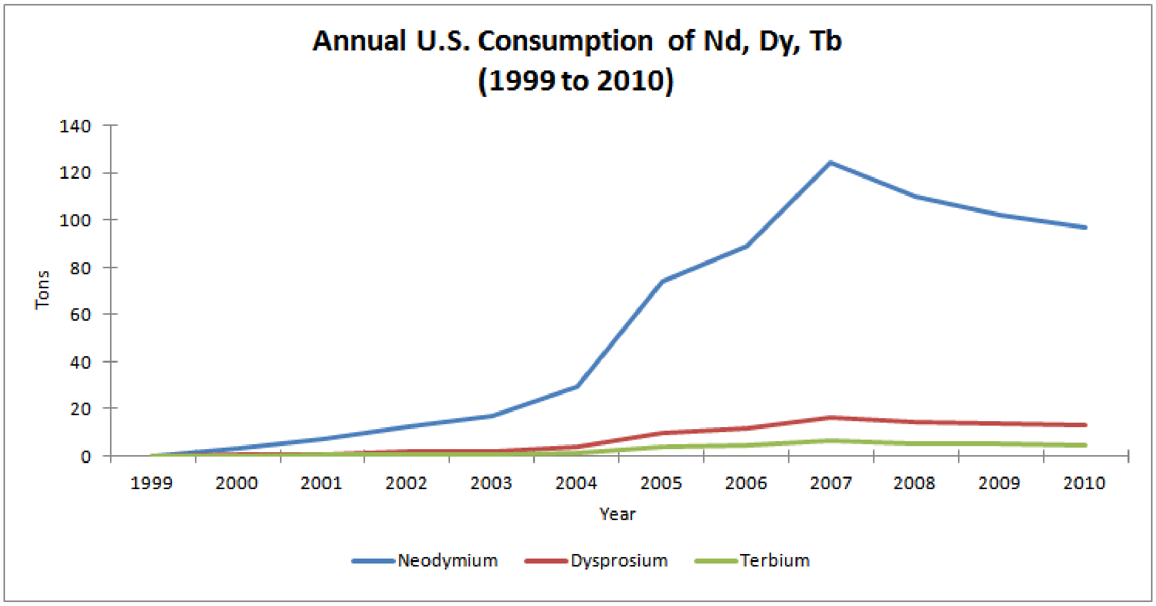

Figure 6.4 Annual consumption of neodymium, dysprosium, and terbium (United States, 1999 to 2010).

New U.S. neodymium consumption in hybrid vehicles is expected to drop from 97 tons in 2010 to 85 tons (2015) and then 83 tons (2020). The new demand in 2020 is approximately 14% lower than in 2010. Dysprosium consumption drops 14% from 13 tons to 11 tons in 2015 and

2020 and terbium consumption decreases from five (2010) to four tons (2015 and 2020). Table 6.1 summarizes the base scenario of U.S. rare-earth magnet metal consumption in HEV.

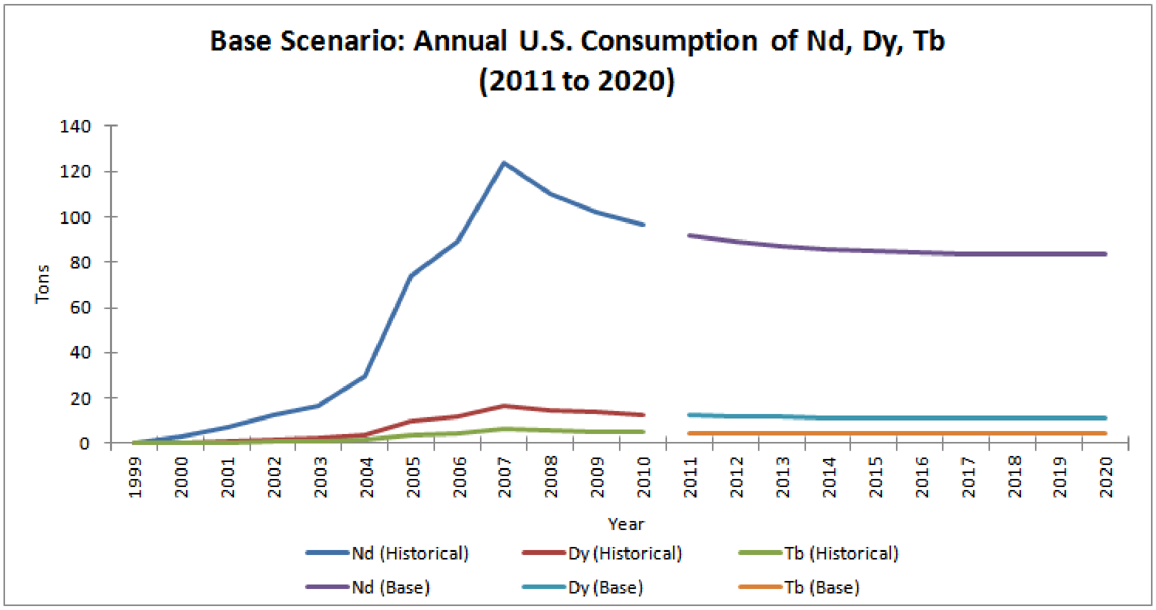

Figure 6.5 Base scenario, annual consumption of neodymium, dysprosium, and terbium (United States, 2011 to 2020).

Table 6.1 Base scenario consumption of Nd, Dy, Tb in U.S. hybrid vehicles (2009, 2010, 2015, 2020).

| Year | Neodymium (met. ton.) | Dysprosium (met. ton.) | Terbium (met. ton.) |
|---|---|---|---|
| **2009** | 102 (146) | 14 (19) | 5 (7) |
| **2010** | 97 (138) | 13 (18) | 5 (7) |
| **2015** | 85 (121) | 11 (16) | 4 (6) |
| **2020** | 83 (119) | 11 (16) | 4 (6) |

### 6.1.3 Historical and Base Scenario Consumption in the RoW

Figure 6.6 shows the estimates from (Duleep et al. 2011) of non-U.S. hybrid sales in the future and predicts they will grow linearly. Their projections for new “North American” (U.S., Canada, Mexico) sales are also shown, in addition to the estimates from the scenarios in this paper. Comparing these two estimates, it can be seen that this paper’s base scenario for hybrid sales in the U.S. is approximately ten times lower than the one created by (Duleep et al. 2011). A one order magnitude of difference can be important when comparing final results so it must be noted. Note that in (Duleep et al. 2011) do not make a distinction between Canada, the U.S., and Mexico, instead grouping them together - their U.S. sales are approximately half of the total shown in Figure 6.6.

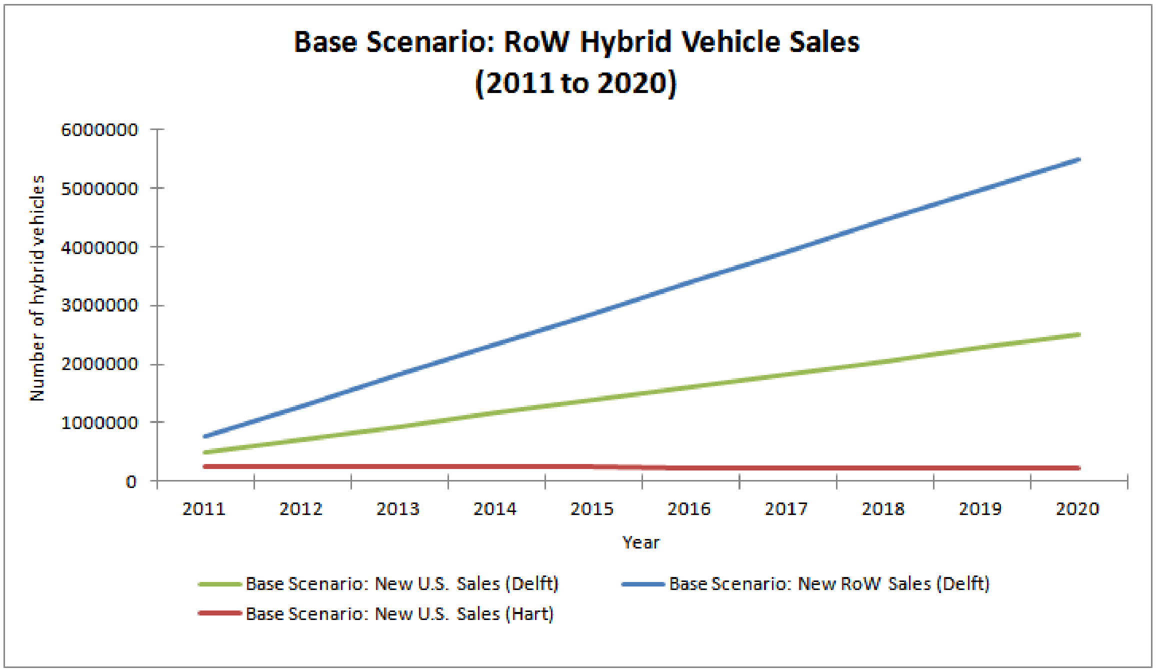

Figure 6.6 Base scenario, annual new RoW hybrid vehicle sales (2011 to 2020).

### 6.1.4 Historical and Base Scenario Consumption of Nd, Dy, Tb in the RoW

Figure 6.7 shows the base scenario for consumption of each rare earth from 2011 to 2020. There would be linear growth in this consumption over time. Neodymium consumption in the RoW from hybrid vehicles will increase from 86 tons (2010) to 1,012 tons (2015) and eventually to 1,939 tons in 2020. Dysprosium demand follows a similar pattern, increasing from 11 tons (2010) to 135 tons (2015) and then 259 tons (2020). Terbium's demand also increases over the ten-year period (4 tons in 2010 to 97 tons in 2020). Table 6.2 summarizes the base scenario values of non-U.S. demand for neodymium, dysprosium, and terbium in HEV.

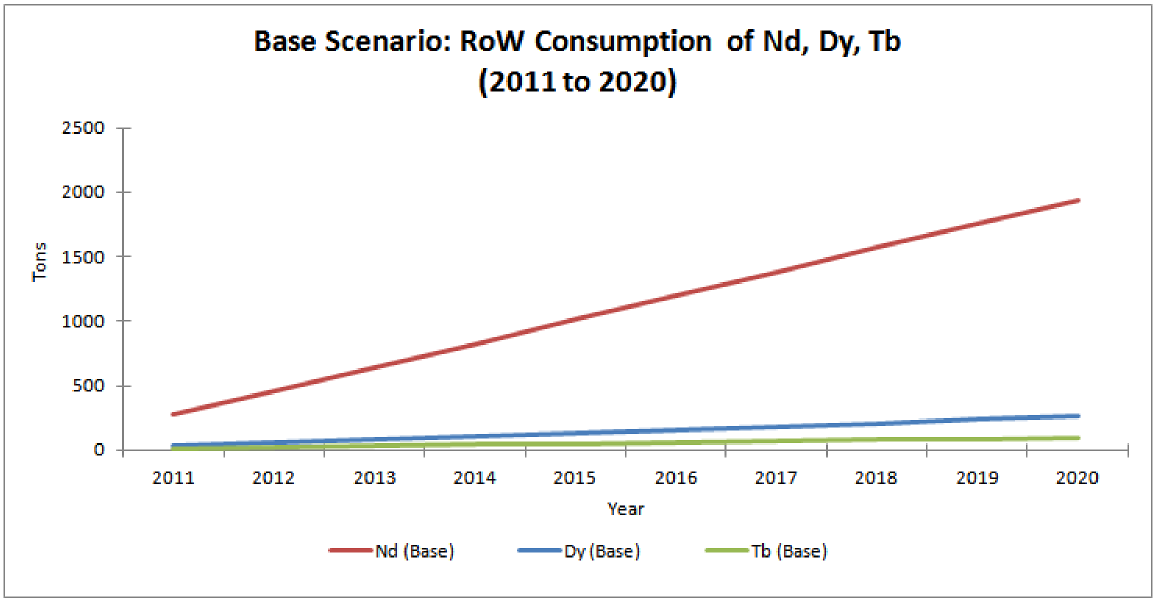

Figure 6.7 Base scenario, annual consumption of neodymium, dysprosium, and terbium (RoW, 2011 to 2020).

Table 6.2 Base scenario consumption of Nd, Dy, Tb in RoW hybrid vehicles (2009, 2010, 2015, 2020).

| Year | Neodymium (met. ton.) | Dysprosium (met. ton.) | Terbium (met. ton.) |
|---|---|---|---|
| **2009** | - | - | - |
| **2010** | 86 (123) | 11 (16) | 4 (6) |
| **2015** | 1,012 (1,446) | 135 (193) | 51 (73) |
| **2020** | 1,939 (2,770) | 259 (370) | 97 (139) |

### 6.2 Alternative Scenarios

This section covers the alternate scenarios of future demand for hybrid vehicles in the world, using the assumptions discussed in chapter four. It evaluates inferred demand for neodymium, dysprosium, terbium, and praseodymium used in permanent magnets. Future demand scenarios for the United States are examined first in section 6.2.1, followed by the scenarios for non-U.S. countries in section 6.2.2.

#### 6.2.1 United States

Three of the four scenarios for short to mid-term hybrid vehicle demand in the U.S. required regression analysis as prescribed in chapter four. Recall that each of these scenarios involves a factor that may directly affect hybrid vehicle demand. Scenario 2A examined the effect of a change in the price of a substitute good (gasoline) on the quantity of hybrid vehicles demanded. Scenario 2B built upon 2A and used a \$6 USD per gallon gas price in an extreme case of product substitution. Scenario 2D assumed that the federal government still offers an income tax credit for purchasing a new hybrid vehicle.

The regression equation (Equation Set 4.3) from chapter four is as follows:

$$Q_{D,HEV} = \alpha + \beta_{gas} P_{gas} + \beta_{TaxCred} TaxCred$$

Equation Set 6.1 shows the linear regression results:

Equation Set 6.1 Results from linear regression.

$$Q_{C,HEV} = -103266 + 94962 P_{gas} + 134964 TaxCred$$

SE (48,386) (32,573) (42,997) $R^2 = 0.9576$

(t = -2.13) (t = 2.92) (t = 3.14)

The implication of a negative intercept value is that below a certain price and in the absence of a tax credit, no hybrid vehicles will be purchased. By setting TaxCred and $Q_{C,HEV}$ equal to zero and solving for $P_{gas}$, it is found that this price is \$1.09 per gallon. However, this does not mean that these are the only two determinants of hybrid vehicle demand, as discussed further in the (Thatchenkery 2008) study. Positive signs on the price of gas and tax credit coefficients were expected and indicate that a tax credit and rising gas prices would increase hybrid vehicle consumption. These estimates are used as a simple way to determine the effects of a tax credit or an increase in a substitute's price on new demand. Estimated coefficients on these variables support this effect: a \$1 increase in gas prices leads to 94,962 new hybrid sales and a tax credit leads to 134,964 new sales[5].

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[5] Full SAS output of regression results found in appendix B.

It is important to check these results against those provided by other studies in order to determine if they are realistic. According to the results in (Gallagher and Muehlegger 2010), the cross-price elasticity of hybrid vehicle demand in terms of gasoline price is 0.86. This means that a 10% increase in price leads to an 8.6% increase in the quantity of hybrid vehicles consumed (Gallagher and Muehlegger 2010, 7). In contrast, the cross-price elasticity of hybrid vehicle demand with respect to gas price in this analysis was 1.37; increasing the price of gas by 10% leads to a 13.7% increase in the number of hybrid vehicles purchased. A 5% margin of difference is small enough to assume that the value calculated in the present work is comparatively realistic.

Gallagher and Muehlegger also analyzed the effect of different tax incentives on hybrid vehicle consumption. When a flat-rate incentive of $1,000 was available, hybrid sales increased by 5%; the presence of a “mean value” incentive (representing any tax incentive other than the flat $1,000 rate or one proportional to the vehicle’s sale price) increased hybrid vehicle sales 22% (Gallagher and Muehlegger 2010, 7-9). This thesis calculated that the presence of such a credit lead to a 31% increase in hybrid sales. While this value is 9% higher than Gallagher and Muehlegger’s estimate, it is close in magnitude and one might consider the difference to be within a reasonable margin of error. A $3,400 tax incentive (approximately 10-12% of current sale prices for hybrids like the 2013 Toyota Prius) (Toyota Motor Sales 2013) could, realistically, increase hybrid sales up to 30%.

Results in scenario 2A showed that neodymium demand would initially decrease from 2012 to 2013 and then grow to 190 tons in 2015. The quantity consumed was approximately 2.2 larger than the base case and would grow at an increasing rate, reaching 199 tons in 2020 (Figure 6.8 and Table 6.3). Dysprosium consumption in scenario 2A was larger than in the base case (11 tons in 2015 and 2020), with 25 tons in 2015 and 27 tons in 2020 (Figure 6.9 and Table 6.4).

Finally, terbium demand decreased from 2012 to 2013 and then increased to 10 tons in 2015 and 2020 (Figure 6.10 and Table 6.5).

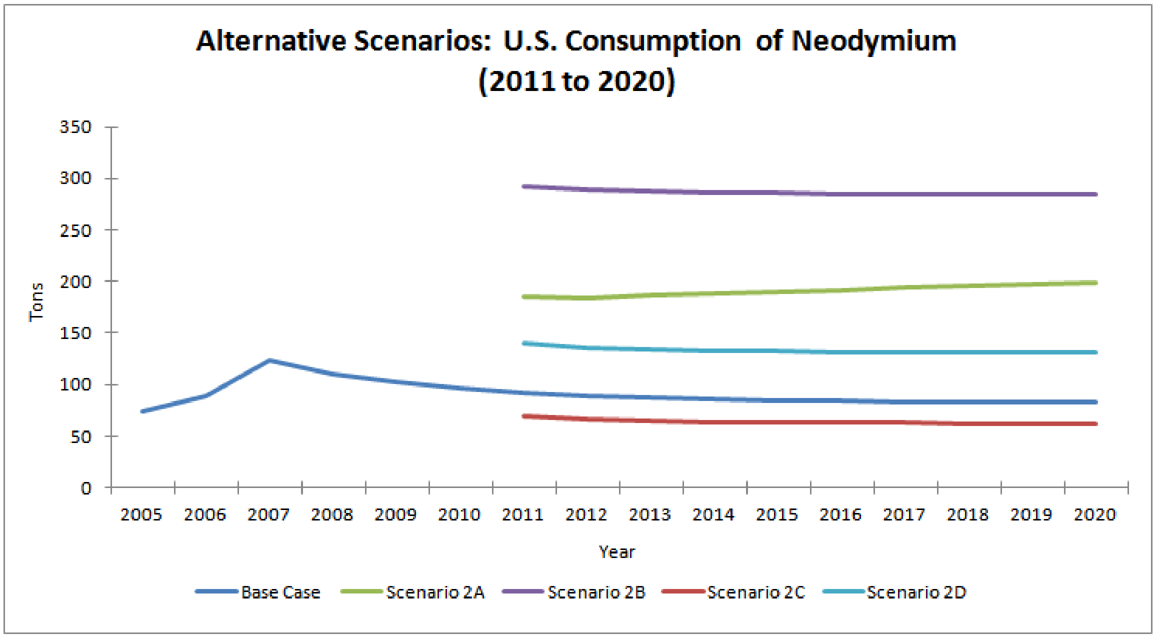

Figure 6.8 Alternative U.S. consumption of neodymium in hybrid vehicles (2011 to 2020).

Table 6.3 Alternative consumption of neodymium in U.S. hybrid vehicles (2010, 2015, 2020).

| **Hybrid Vehicles** | **U.S. Neodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 97 (139) | 85 (121) | 83 (119) |
| **Scen. 2A** | - | 190 (271) | 199 (284) |
| **Scen. 2B** | - | 285 (407) | 284 (406) |
| **Scen. 2C** | - | 63 (90) | 62 (89) |
| **Scen. 2D** | - | 132 (189) | 131 (187) |

Gas prices in the EIA's projections reach a maximum value of $3.46 USD per gallon. Currently, the price of gas is $3.85 USD per gallon, at least in Colorado; the projections from the EIA appear to be outdated despite their recent publication. This is the reasoning behind the creation of a more extreme case where gasoline costs $6 USD per gallon. Scenario 2B ("gas price increase, extreme") had the largest consumption of all four scenarios. Demand for neodymium, dysprosium, and terbium declined at a decreasing rate until reaching equilibrium at

284 tons, 38 tons, and 14 tons in 2020. It is expected that consumption would be high in this scenario; if weekly gasoline costs double or even triple, the consumers have a greater incentive to switch to hybrid vehicles.

In the third scenario, Scenario 2C, it was assumed that overall growth of the hybrid vehicle market would follow a SAS-generated growth rate and there would be changes in the material composition of the permanent magnets. It is assumed that praseodymium will be substituted for neodymium as described in chapter four and sections 5.1 to 5.3.

Neodymium consumption (Figure 6.8) in scenario 2C showed a 26% reduction from the base scenario in each future year. Approximately 62 tons of neodymium would be required in 2020 under scenario 2C, compared to 83 tons in 2020 (base case). Table 6.3 shows neodymium consumption in 2010, 2015, and 2020 for each scenario. Dysprosium and terbium consumption in 2C is the same as the base scenario. Praseodymium substitution does not affect their usage.

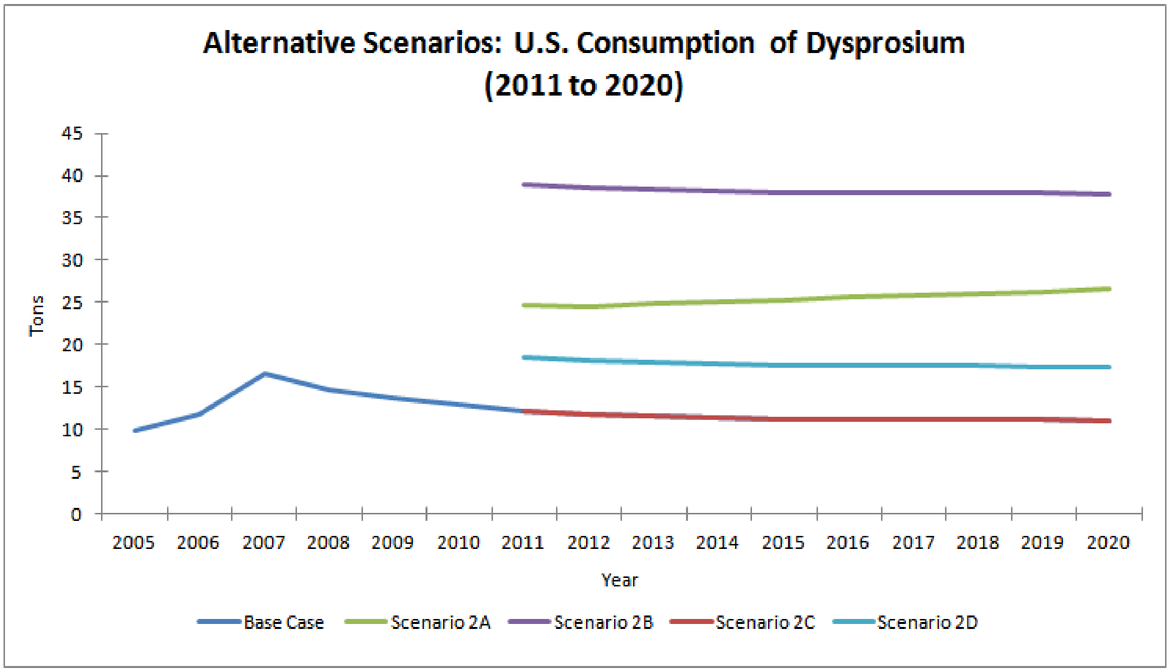

Figure 6.9 Alternative U.S. consumption of dysprosium in hybrid vehicles (2011 to 2020).

Table 6.4 Alternative consumption of dysprosium in U.S. hybrid vehicles (2010, 2015, 2020).

| Hybrid Vehicles | U.S. Dysprosium (met. ton.) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| **Base Case** | 13 (19) | 11 (16) | 11 (16) |
| **Scen. 2A** | - | 25 (36) | 27 (39) |
| **Scen. 2B** | - | 38 (54) | 38 (54) |
| **Scen. 2C** | - | 11 (16) | 11 (16) |
| **Scen. 2D** | - | 18 (26) | 17 (24) |

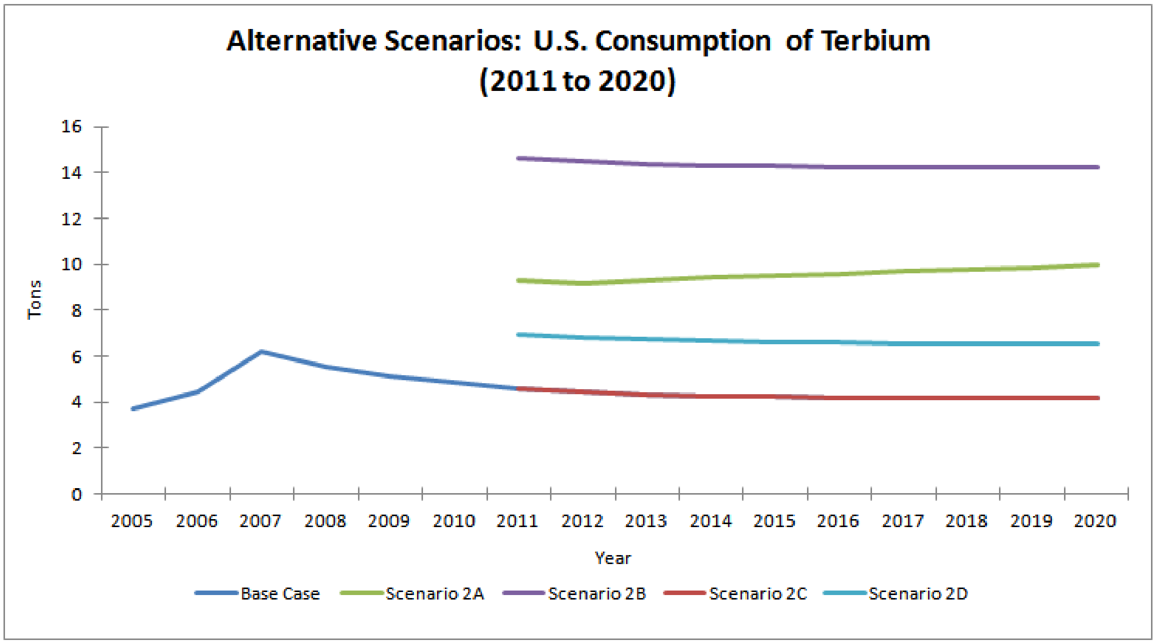

Figure 6.10 Alternative U.S. consumption of terbium in hybrid vehicles (2011 to 2020).

Table 6.5 Alternative consumption of terbium in U.S. hybrid vehicles (2010, 2015, 2020).

| Hybrid Vehicles | U.S. Terbium (met. ton.) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| **Base Case** | 5 (7) | 4 (6) | 4 (6) |
| **Scen. 2A** | - | 10 (14) | 10 (14) |
| **Scen. 2B** | - | 14 (20) | 14 (20) |
| **Scen. 2C** | - | 4 (6) | 4 (6) |
| **Scen. 2D** | - | 7 (10) | 7 (10) |

Praseodymium consumption is zero in all of the scenarios except for 2C. This is because praseodymium usage is limited (and possibly non-existent) in permanent magnets for wind turbines and hybrid vehicles (Shih et al. 2012, 140). In 2011, consumption of praseodymium was

23 tons and decreased to approximately 21 tons in 2015 and 2020. Figure 6.11 shows praseodymium growth in scenario 2C and Table 6.6 summarizes praseodymium usage in all scenarios.

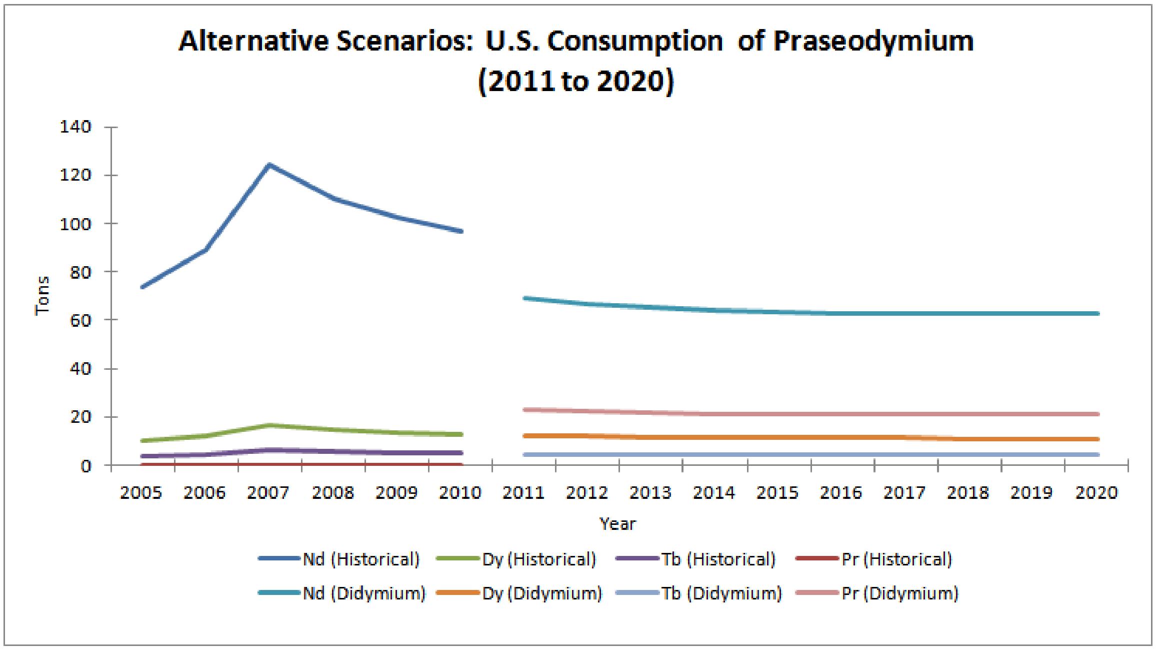

Figure 6.11 Alternative U.S. consumption of praseodymium in hybrid vehicles (2011 to 2020).

Table 6.6 Alternative consumption of praseodymium in U.S. hybrid vehicles (2010, 2015, 2020).

| **Hybrid Vehicles** | **U.S. Praseodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 2A** | - | - | - |
| **Scen. 2B** | - | - | - |
| **Scen. 2C** | - | 21 (30) | 21 (30) |
| **Scen. 2D** | - | - | - |

The final scenario (2D, "tax incentive present") assumed that the $3,400 tax credit for new hybrid vehicles would continue through 2020. Tax credits for new plug-in and full-electric vehicles (and some hybrids) are expected to reach $7,500 per vehicle in the near future (U.S. Department of Energy, "Federal Tax Credits" 2012). This scenario can be updated for future studies by running the calculations with a value of $7,500 for a tax credit. Regression analysis calculated a positive coefficient for the tax credit variable, meaning that rare earth demand will be greater than the base case.

Neodymium consumption decreased from 132 to 131 tons (2015 and 2020) but remained larger than the base case. Consumption of dysprosium was 1.5 times bigger than the base case and decreased from 18 to 17 tons (2011 and 2020). Terbium usage was 7 tons per year during this period. Analysis of this scenario highlights the positive effect of a hybrid vehicle tax credit on neodymium, dysprosium, and terbium demand.

### 6.2.2 Rest of World

Only four points of historical data for hybrid vehicle sales (2007, 2008, 2009, and 2010) were available for non-U.S. countries. Due to this lack of data, no historical graphs were created and this work was unable to develop its own statistically robust set of future demand scenarios. Any results produced here rely upon the accuracy of the projections from (Duleep et al. 2011) – once again, non-negligible estimation error has been introduced to the model. Since these projections claim to represent a compromise between a multitude of both optimistic and pessimistic forecasts, the hope is that they actually create an adequate middle-of-the-road projection of future hybrid vehicle sales in the non-U.S. world.

Additionally, the regression analysis developed for U.S. hybrid vehicle sales is specific to the United States and most likely does not apply to European, Asian, or South American countries. The results from this analysis are applied to non-U.S. countries because it is impossible to determine the effects of gasoline prices or government tax incentives on hybrid vehicle sales in every single non-U.S. country. That task is well beyond the scope of this paper. Future studies may choose to utilize a full host of externally forecasted growth values for every single electric vehicle market in the rest of the world but an undertaking such as this would be long and arduous.

Figure 6.12 shows that neodymium consumption increased in the base and alternate scenarios. Scenarios 2A ("gas price increase, high economic growth"), 2B ("gas price increase, extreme"), and 2D ("tax incentive present") all had neodymium consumption rise linearly over time. All three scenarios had a higher level of demand than the base case. Neodymium consumption increased in scenario 2C ("material composition change") but was the lowest of all the scenarios, as was the change in consumption from year to year (or the slope of these lines). While 2C had the lowest consumption of neodymium, scenario 2B ("extreme gas price increase") had the highest. Table 6.7 is a summary of each scenario's future neodymium consumption.

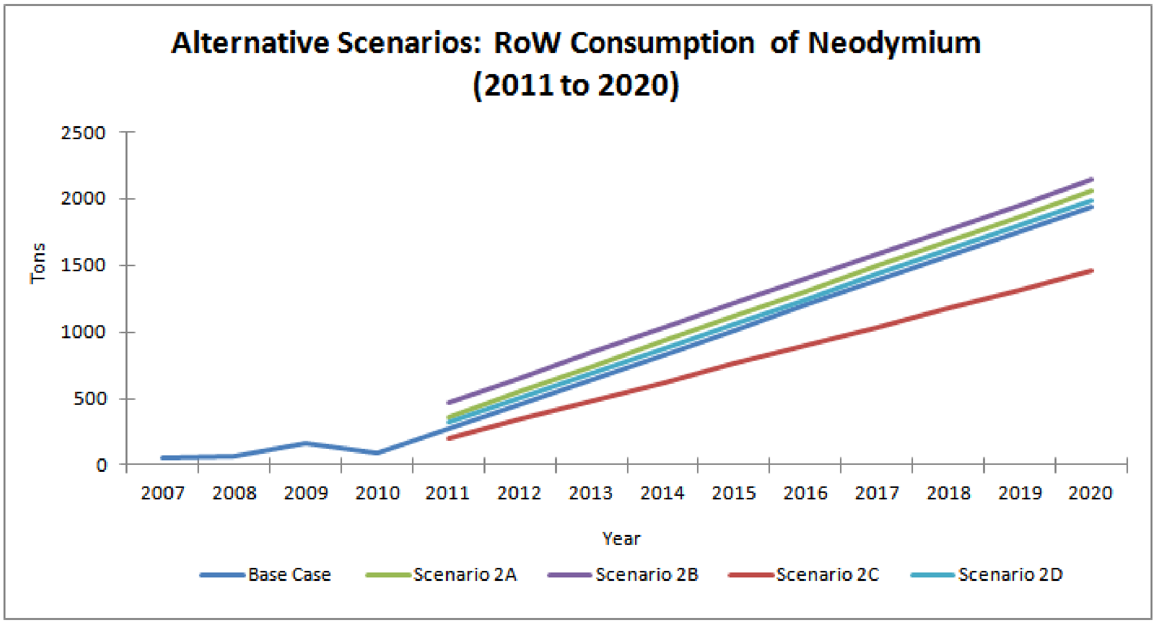

Figure 6.12 Alternative RoW consumption of neodymium in hybrid vehicles (2011 to 2020).

Consumption of dysprosium and terbium grows at the same rate as neodymium in the base case and scenarios 2A, 2B, and 2D. Unlike neodymium, the consumption of these rare earths in scenario 2C grows at a constant rate. This happens because neither material is removed when praseodymium is substituted for neodymium. Figures 6.13 and 6.14 and Tables 6.8 and 6.9 show short and mid-term consumption in each scenario. Praseodymium is only consumed in scenario 2C ("material composition change"); Figure 6.15 and Table 6.10 show growth over time.

Table 6.7 Alternative consumption of neodymium in RoW hybrid vehicles (2010, 2015, 2020).

| **Hybrid Vehicles** | **RoW Neodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 86 (123) | 1,012 (1,446) | 1,939 (2,770) |
| **Scen. 2A** | - | 1,118 (1,597) | 2,054 (2,934) |
| **Scen. 2B** | - | 1,213 (1,733) | 2,140 (3,057) |
| **Scen. 2C** | - | 759 (1,084) | 1,454 (2,077) |
| **Scen. 2D** | - | 1,059 (1,513) | 1,986 (2,837) |

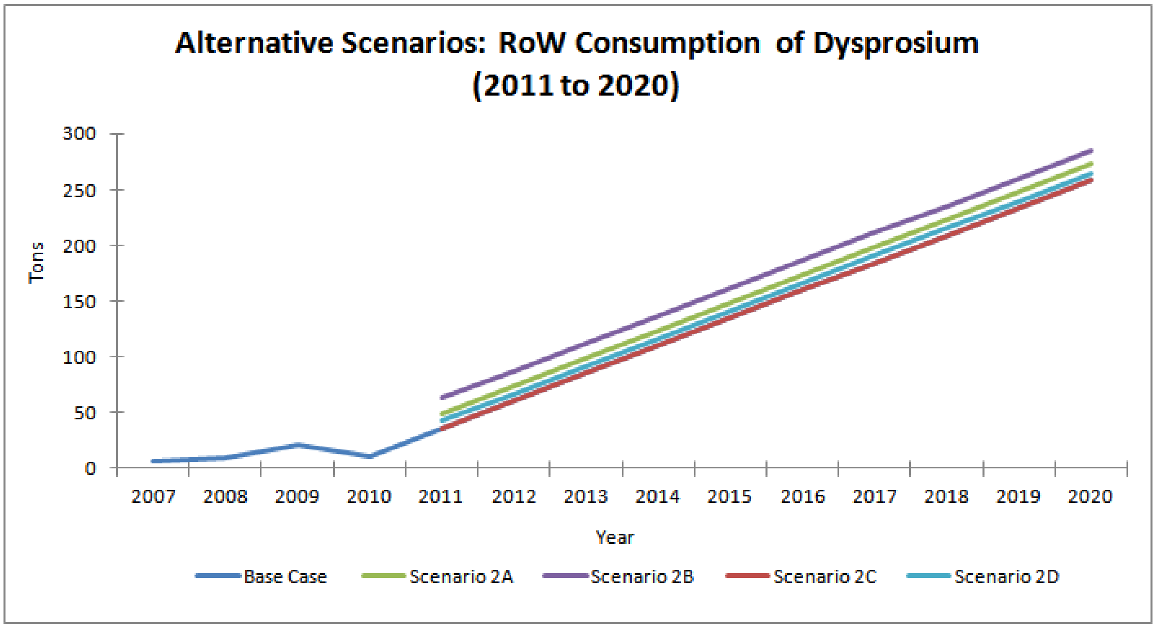

Figure 6.13 Alternative RoW consumption of dysprosium in hybrid vehicles (2011 to 2020).

Table 6.8 Alternative consumption of dysprosium in RoW hybrid vehicles (2010, 2015, 2020).

| **Hybrid Vehicles** | **RoW Dysprosium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 11 (16) | 135 (193) | 259 (370) |
| **Scen. 2A** | - | 149 (213) | 274 (391) |
| **Scen. 2B** | - | 162 (231) | 285 (407) |
| **Scen. 2C** | - | 135 (193) | 259 (370) |
| **Scen. 2D** | - | 141 (201) | 265 (379) |

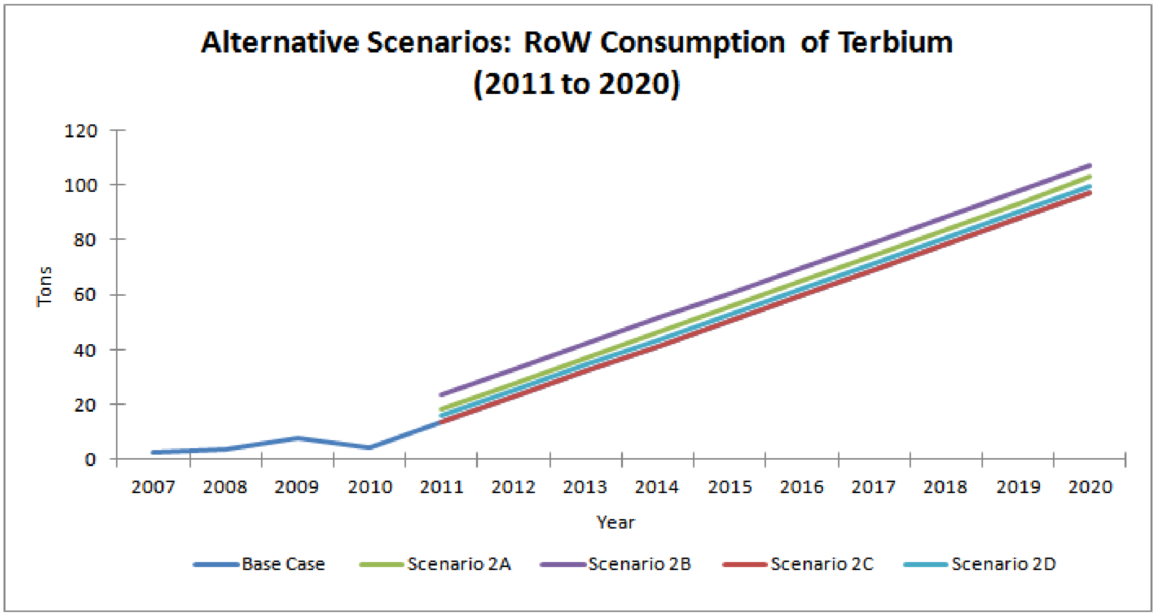

Figure 6.14 Alternative RoW consumption of terbium in hybrid vehicles (2011 to 2020).

Table 6.9 Alternative consumption of terbium in RoW hybrid vehicles (2010, 2015, 2020).

| Hybrid Vehicles | RoW Terbium (met. ton.) | | |
|---|---|---|---|
| | 2010 | 2015 | 2020 |
| **Base Case** | 4 (6) | 51 (73) | 97 (139) |
| **Scen. 2A** | - | 56 (80) | 103 (147) |
| **Scen. 2B** | - | 62 (89) | 107 (153) |
| **Scen. 2C** | - | 51 (73) | 97 (139) |
| **Scen. 2D** | - | 53 (76) | 99 (141) |

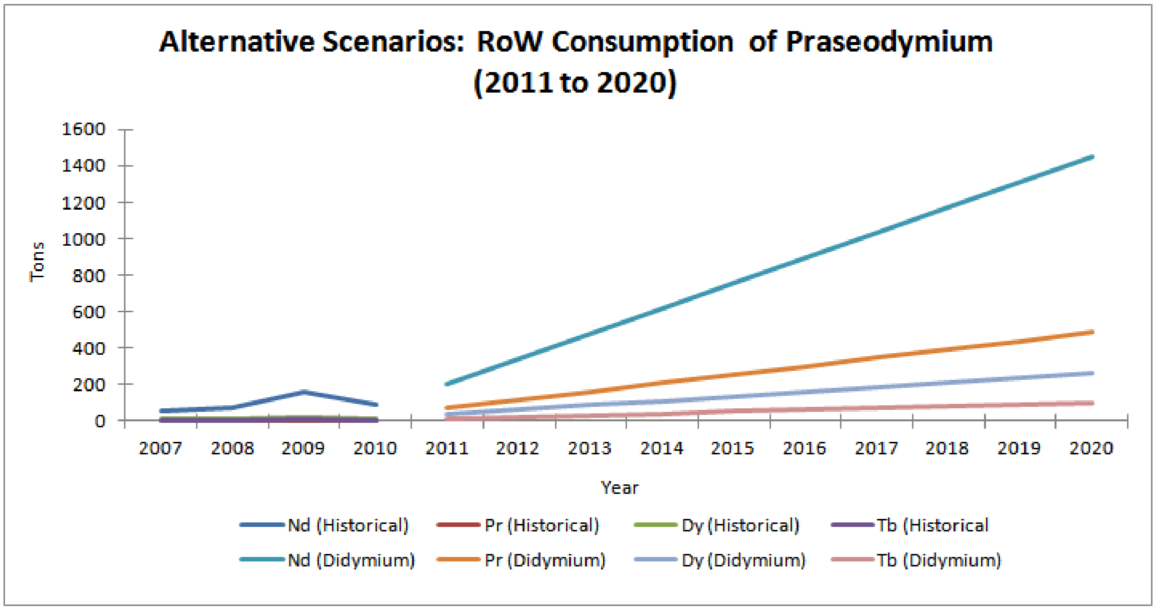

Figure 6.15 Alternative RoW consumption of praseodymium in hybrid vehicles (2011 to 2020).

Table 6.10 Alternative consumption of praseodymium in RoW hybrid vehicles (2010, 2015, 2020).

| **Hybrid Vehicles** | **RoW Praseodymium (met. ton.)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 2A** | - | - | - |
| **Scen. 2B** | - | - | - |
| **Scen. 2C** | - | 253 (361) | 485 (693) |
| **Scen. 2D** | - | - | - |

## 6.3 Further Discussion: Hybrid Electric Vehicles

It is necessary to discuss three issues that may affect the implied consumption of neodymium, dysprosium, terbium, and praseodymium in hybrid vehicles. First, material substitution could potentially decrease the quantity of certain rare earths used in each magnet. Second, there is a high likelihood that component and end-good substitution will also occur in hybrid vehicles. Producers of hybrid and full-electric vehicle producers are already switching over to lithium-ion batteries instead of nick-metal-hydride (Bauer et al. 2011, 29) because lithium is relatively more abundant and cheaper than rare earths. Demand for rare earth permanent magnets would decrease as a result because magnets in the battery are removed when the type of battery is changed.

A third issue that may affect consumption of rare earth magnet metals in hybrid vehicles is the presence of recycling. Section 5.3 described different materials like new and old manufacturing scrap that can be recycled in order to decrease new demand. Hybrid vehicles can be assumed to have a standard lifespan of around ten years (Bauer et al. 2011, 90); it is safe to presume that the contribution from old hybrid vehicles to magnet recycling is negligible in the short to medium-term. Recycling of other scrap materials may help reduce consumption if more efficient processes and techniques for doing so become available. Patents are the major barrier to recycling because the bulk of this technology is the intellectual property of Japanese firms.

# CHAPTER SEVEN

# DISCUSSION: RESULTS, GOVERNMENT POLICIES, CONSUMPTION CONSTRAINTS

Chapter seven presents three final points of discussion for this thesis. First, it looks at the final results from the scenarios of future consumption that were created in this paper. Alternate scenarios of rare earth consumption in each technology and each region of the world (U.S. and rest of world) will be compared to determine which region could contribute the most to overall consumption. This will answer the research question hypothesized in chapter one. Further discussion will link these scenarios to potential government solutions for reducing consumption.

The chapter ends by examining the link between resource extraction constraints in the short to very-long run periods and constraints on the consumption of technological goods. Essentially, the constraints on rare earth supply will negatively affect the market-clearing consumption of wind turbines and hybrid vehicles. Evaluating the direct consumption of rare earth materials from different upstream supply stages is difficult, so the demand for new wind turbines and hybrid vehicles was used as a proxy for determining rare earth consumption by magnet manufacturers. Constraints on the materials produced in the first stage of supply lead to limitations on the equilibrium demand (consumption) for the downstream technologies that rely upon these materials. Naturally, this could affect the present study's results so it is a useful topic for discussion.

## 7.1 Discussion of Results

Creating different scenarios of future wind turbine and hybrid electric vehicle consumption leads to several notable results. First, demand for wind turbines and their rare earths in the U.S.

would grow exponentially between 2011 and 2020; the same demand in non-U.S. countries would grow in a steeply linear fashion over the same period. Less neodymium was demanded in scenarios 1A, 1C, and 1D than in the base case, while scenario 1B had much greater demand. The demand for dysprosium and terbium was either equivalent or less than the base case in scenarios 1A, 1C, and 1D – scenario 1B had larger demand than in the base case. Praseodymium demand was only positive and non-zero in scenario 1C.

Scenario 1B examined how an increase in the market penetration of permanent magnet wind turbines would affect the consumption of rare earth magnet metals. It is important to note that this, and only this, scenario had greater demand for neodymium, dysprosium, and terbium than in the base case. Obviously, if more wind turbines with rare earths are being used each year, ceteris paribus, a larger amount of rare earths would subsequently be consumed. The consumption of rare earth magnet metals (at least in wind turbines) is clearly sensitive to the market penetration rate of wind turbines. This is especially true in developing countries where wind power is a relatively new technology and countries with numerous optimal locations for offshore wind power (such as China, Japan, and parts of Europe).

Second, the SAS-generated equation of best fit for hybrid vehicle demand in the U.S. declines steadily from 2011 to 2020 and then remains constant. Non-U.S. demand for hybrid vehicles over the same time period would increase linearly. Hybrid vehicle sales are unlikely to fully cease because of the governmental push to incentivize hybrid purchases and there will always be a niche market for them. The market share of hybrid vehicles would decrease because of the emergence of relatively cheap and more efficient plug-in and full-electric vehicles. Scenario 2B was the only scenario to project that new U.S. hybrid vehicle sales would grow modestly rather than decline.

The scenarios in chapters five and six began by estimating potential demand for the metal, alloy, and powder forms of rare earths. These were generalized as the total magnet weight per unit of each technology. Estimates were then improved through the inclusion of factors representing waste production during the permanent magnet manufacturing process. Low manufacturing efficiencies are directly accounted for, allowing the estimates to more accurately reflect reality. These numbers were then converted into rare earth oxide equivalents using known conversion efficiency rates. Data required to convert rare earth oxides into elemental amounts is extremely limited so this conversion step was excluded from the scope of this paper. Future studies can delve into this issue further when superior information becomes available (Avalon Rare Metals Inc. 2011).

A summary of implied neodymium consumption for each technology is provided in Table 7.1. Since the consumption of neodymium in wind turbines and hybrid vehicles was given in chapters five and six, Table 7.1 shows magnet manufacturer demand (the value not in parentheses) and its REO equivalent (in parentheses). U.S. wind turbine consumption of neodymium in 2010 was 95 tons and 573 tons in the RoW. Neodymium consumption in non-U.S. countries could be higher than in the U.S. during the short to medium term. Total future consumption in the world ranged from 516 to 3,800 tons in 2015 and 780 to 9,435 tons in 2020[6].

Similar 2010 consumption of neodymium in all hybrid vehicles was estimated at 173 tons in the U.S. and 154 tons in the RoW. Short to medium-term consumption was estimated to be between 1,468 and 2,675 tons in 2015 and in 2020 to range from 2,707 to 4,328 tons. This large span, from one thousand to several thousand tons, is a byproduct of treating the scenarios as mutually-exclusive events. A simultaneous improvement in mechanical efficiencies and increase

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[6] Lower bound was calculated by adding the two lowest demand values in all scenarios for both technologies in a given year. Upper bound calculated the same way but with two biggest demand values.

in market penetration could result in higher or lower demand, depending on which effect is stronger – the range of values accommodates results from all scenarios.

Table 7.1 Evolution of alternative world neodymium consumption
(2010 to 2015 to 2020).

| Wind Turbines | U.S. Neodymium (metric tonnes) | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 76 (95) | 251 (314) | 429 (536) |
| **Scen. 1A** | - | 0 | 0 |
| **Scen. 1B** | - | 629 (786) | 1,717 (2,146) |
| **Scen. 1C** | - | 189 (236) | 321 (402) |
| **Scen. 1D** | - | 107 (134) | 184 (230) |

| Hybrid Vehicles | U.S. Neodymium (metric tonnes) | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 139 (173) | 121 (152) | 119 (148) |
| **Scen. 2A** | - | 271 (339) | 284 (355) |
| **Scen. 2B** | - | 407 (509) | 406 (507) |
| **Scen. 2C** | - | 90 (113) | 89 (111) |
| **Scen. 2D** | - | 189 (236) | 187 (234) |

| Wind Turbines | RoW Neodymium (metric tonnes) | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 459 (573) | 964 (1,205) | 1,459 (1,823) |
| **Scen. 1A** | - | 906 (1,132) | 887 (1,109) |
| **Scen. 1B** | - | 2,411 (3,014) | 5,831 (7,289) |
| **Scen. 1C** | - | 723 (904) | 1,093 (1,366) |
| **Scen. 1D** | - | 413 (516) | 624 (780) |

| Hybrid Vehicles | RoW Neodymium (metric tonnes) | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 123 (154) | 1,446 (1,807) | 2,770 (3,463) |
| **Scen. 2A** | - | 1,597 (1,996) | 2,934 (3,668) |
| **Scen. 2B** | - | 1,733 (2,166) | 3,057 (3,821) |
| **Scen. 2C** | - | 1,084 (1,355) | 2,077 (2,596) |
| **Scen. 2D** | - | 1,513 (1,891) | 2,837 (3,546) |

Results in Table 7.1 lead to one major conclusion about future neodymium consumption. A significant source of global neodymium consumption could be hybrid electric vehicle sales in non-U.S. countries. This aligns with conclusions from reports like (Bauer et al. 2010, 2011), (Hykawy, Thomas and Casasnovas 2010), and (Roskill 2011). The U.S. is but one of many countries pursuing alternative energy transportation technologies; thus, while their overall consumption of neodymium is relatively high compared to other countries, its total global market share is small. In addition, although direct-drive and hybrid wind turbines use numerous large permanent magnets, there is a limit on the number of new installations that can be built, relegating wind turbines to a secondary role in future global neodymium demand.

The rise of hybrid electric vehicle demand is likely to occur for several reasons. Developing nations such as China and India are expanding their use of renewable energy production and transportation technologies as part of an effort to quell their burgeoning emissions of greenhouse gases. European nations have strong national programs that incentivize the use of hybrid electric vehicles for consumers, with the goal of helping reduce national greenhouse gas emissions. Additionally, rising gasoline prices across the globe have given consumers further economic incentive to switch to hybrid vehicles.

It was originally expected that the expansion of wind turbine capacity in the U.S. and non-U.S. countries would be the primary driver of neodymium consumption. Wind turbines require much larger magnets than hybrid vehicles and extensive government subsidies are provided for their installation and power production. China, specifically, has maintained strong economic growth and commercial investment despite other countries' economies being mired in recession. Developed nations are oriented towards improving their environmental quality through a reduction in greenhouse gas emissions using wind power. Ultimately, as population levels stabilize and growth rates slow, a smaller amount of new power production capacity is required; however, sales of hybrid vehicles will continue as gas prices rise and consumers replace their vehicles with cheaper alternatives. Hybrid vehicle demand could be the driving factor behind consumption of neodymium, dysprosium, and terbium in permanent magnets.

Evolution of alternative world dysprosium consumption is provided in Table 7.2. Reporting methodology here (and in the other tables) is similar to Table 7.1, where the first value represents the permanent magnet manufacturers' demand and parenthetical values represent the rare earth oxide equivalent of that demand. Total world consumption of dysprosium in wind turbines was 90 tons in 2010; in the alternate scenarios, consumption ranged from 70 to 507 tons in 2015 and grew over the short to medium-term. Consumption in 2020 had a lower limit of 104 tons and an upper limit of 1,257 tons. Recent 2010 consumption in hybrid vehicles was 43 tons, ranged from 261 tons to 357 tons in 2015, and increased through 2020 to between 483 and 577 tons. Similar to neodymium, dysprosium consumption growth will primarily be attributed to non-U.S. countries (especially China) in both the wind power and hybrid vehicle markets.

Table 7.2 Evolution of alternative world dysprosium consumption
(2010 to 2015 to 2020).

| **Wind Turbines** | **U.S. Dysprosium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 10 (13) | 33 (41) | 57 (71) |
| **Scen. 1A** | - | 0 | 0 |
| **Scen. 1B** | - | 84 (105) | 229 (286) |
| **Scen. 1C** | - | 33 (41) | 57 (71) |
| **Scen. 1D** | - | 14 (18) | 24 (30) |

| **Hybrid Vehicles** | **U.S. Dysprosium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 19 (23) | 16 (20) | 11 (20) |
| **Scen. 2A** | - | 36 (45) | 39 (48) |
| **Scen. 2B** | - | 54 (68) | 38 (68) |
| **Scen. 2C** | - | 16 (20) | 11 (20) |
| **Scen. 2D** | - | 26 (32) | 24 (30) |

| **Wind Turbines** | **RoW Dysprosium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 61 (77) | 129 (161) | 194 (243) |
| **Scen. 1A** | - | 121 (152) | 119 (148) |
| **Scen. 1B** | - | 321 (402) | 777 (971) |
| **Scen. 1C** | - | 129 (161) | 194 (243) |
| **Scen. 1D** | - | 56 (70) | 83 (104) |

| **Hybrid Vehicles** | **RoW Dysprosium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 16 (20) | 193 (241) | 370 (463) |
| **Scen. 2A** | - | 213 (266) | 391 (489) |
| **Scen. 2B** | - | 231 (289) | 407 (509) |
| **Scen. 2C** | - | 193 (241) | 370 (463) |
| **Scen. 2D** | - | 201 (252) | 379 (472) |

New sales of hybrid electric vehicles in non-U.S. countries are the main source of terbium consumption in permanent magnets. In 2010, total terbium consumption in wind turbines was 34 tons, which increased through 2020. Consumption in 2015 was between 25 and 189 tons and in 2020, ranged from 39 to 471 tons. Hybrid vehicles contributed 16 tons of consumption in 2010 and grew up to 98 to 136 tons in 2015 and 180 to 216 tons in 2020. These values are summarized in Table 7.3.

Praseodymium consumption is the lowest of the four magnetic rare earths because it is not believe to be currently used in these permanent magnets. World praseodymium consumption in wind turbines and hybrid vehicles was zero in 2010 but could increase due to greater material substitution rates. Praseodymium consumption from wind turbines in 2015 and 2020 ranged from 0 to 381 tons and 0 to 589 tons, respectively. Hybrid vehicle consumption ranged from 0 to 490 tons (2015) and 0 to 904 tons (2020); U.S. demand for this metal in hybrid vehicles would have smaller amounts of new growth as time passes. There is the potential for praseodymium consumption to increase as new supplies come online and neodymium prices increase, but these events probably will probably occur outside of the short to medium-term time frame.

Table 7.3 Evolution of alternative world terbium consumption
(2010 to 2015 to 2020).

| **Wind Turbines** | **U.S. Terbium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 4 (5) | 9 (16) | 21 (27) |
| **Scen. 1A** | - | 0 | 0 |
| **Scen. 1B** | - | 31 (39) | 86 (107) |
| **Scen. 1C** | - | 13 (16) | 21 (27) |
| **Scen. 1D** | - | 6 (7) | 9 (11) |

| **Hybrid Vehicles** | **U.S. Terbium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 7 (9) | 6 (7) | 6 (7) |
| **Scen. 2A** | - | 14 (18) | 14 (18) |
| **Scen. 2B** | - | 20 (25) | 20 (25) |
| **Scen. 2C** | - | 6 (7) | 6 (7) |
| **Scen. 2D** | - | 10 (13) | 10 (13) |

| **Wind Turbines** | **RoW Terbium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 23 (29) | 49 (61) | 73 (91) |
| **Scen. 1A** | - | 46 (57) | 44 (55) |
| **Scen. 1B** | - | 120 (150) | 291 (364) |
| **Scen. 1C** | - | 49 (61) | 73 (91) |
| **Scen. 1D** | - | 20 (25) | 31 (39) |

| **Hybrid Vehicles** | **RoW Terbium (metric tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 6 (7) | 73 (91) | 139 (173) |
| **Scen. 2A** | - | 80 (100) | 147 (184) |
| **Scen. 2B** | - | 89 (111) | 153 (191) |
| **Scen. 2C** | - | 73 (91) | 139 (173) |
| **Scen. 2D** | - | 76 (95) | 141 (177) |

Overall demand for the three primary rare earth magnet metals (neodymium, dysprosium, and terbium) is expected to increase in the short to mid-term period. For example, the maximum amount of neodymium that the world could require in 2020 is estimated to approximately be 14 times greater than in 2010, or 13,763 tons. The low estimate was 3,487 tons, which is 3.5 times greater than the 2010 demand. Both dysprosium and terbium follow similar patterns of growth. Praseodymium was not assumed to be a standard material for the permanent magnets found in wind turbines and hybrid vehicles. This is evidenced by it only being used in the material composition scenarios where didymium alloy was substituted for the traditional Nd-Dy-Tb mix. As such, the praseodymium consumption values in Table 7.4 represent the upper limits of praseodymium usage in the future (2011 to 2020).

Table 7.4 Evolution of alternative world praseodymium consumption
(2010 to 2015 to 2020).

| **Wind Turbines** | **U.S. Praseodymium (met. tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 1A** | - | - | - |
| **Scen. 1B** | - | - | - |
| **Scen. 1C** | - | 63 (79) | 107 (134) |
| **Scen. 1D** | - | - | - |

| **Hybrid Vehicles** | **U.S. Praseodymium (met. tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 2A** | - | - | - |
| **Scen. 2B** | - | - | - |
| **Scen. 2C** | - | 30 (38) | 30 (38) |
| **Scen. 2D** | - | - | - |

| **Wind Turbines** | **RoW Praseodymium (met. tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 1A** | - | - | - |
| **Scen. 1B** | - | - | - |
| **Scen. 1C** | - | 241 (302) | 364 (455) |
| **Scen. 1D** | - | - | - |

| **Hybrid Vehicles** | **RoW Praseodymium (met. tonnes)** | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Base Case** | 0 | 0 | 0 |
| **Scen. 2A** | - | - | - |
| **Scen. 2B** | - | - | - |
| **Scen. 2C** | - | 361 (452) | 693 (866) |
| **Scen. 2D** | - | - | - |

It makes perfect sense that the total global consumption of these metals will continue to grow even through a global recession and public resistance to renewable energy. Problems associated with traditional means of generating power and fuelling personal and commercial transportation have simply become too large to ignore. Natural limitations to the amount of fossil fuel reserves and resources will eventually be met and Middle Eastern suppliers could become completely unreliable, possibly because of external war, internal strife, or economic collapse. Each of these factors drives up the price of traditional fuels and coerces governments and individuals into pursuing a path of "green" action that minimizes their costs and maximizes their welfare.

Despite the overall increase in rare earth magnet metal usage, there will be some decline in the demand from hybrid vehicles in the United States. Hybrid vehicles can be considered a luxury good, even for developed nations, and there are no government programs forcing their purchase as there are with wind turbines. This is why hybrid vehicle use began to decline in 2007, in line with the housing and financial crises, and why the decline will continue in the short to medium-term. Hybrid vehicle sales are unlikely to reach zero in the short and medium terms however; new purchases will continue but the annual amount will decline moderately and stabilize in the base scenario.

Even Toyota has admitted to the possibility of slowed growth in the hybrid vehicle market both in the U.S. and non-U.S. countries. On September 24, 2011 (Mukai and Hagiwara 2012), the car maker announced possible cuts in forecasts for their new all-electric vehicle from "thousands [two years ago]" to "about 100 units". As well, Toyota only expects to sell 1.2 million hybrids worldwide in 2012. While this is double their total global sales in 2011, the bulk of new sales will come from developing and large markets rather than from the United States. A slowdown in global economic growth and the ongoing economic woes of the U.S. are two of the most probable reasons for lower than expected hybrid vehicle sales.

Although the United States has a strong influence on the demand of many goods, it does not wield significant power in the rare earth market. Non-U.S countries account for approximately 86% of rare earth consumption from wind turbines and 92% of consumption from hybrid vehicles between 2010 and 2020 – the U.S. is not and will not be a major player in the rare earth market. China represents the majority of this demand. U.S. wind turbine usage is growing, but new hybrid sales are declining (leading to a smaller influence on global consumption). This accentuates the fact that U.S. demand should not be expected to significantly affect overall consumption.

An attempt must be made at comparing the results from this work's analysis with those found in relevant literature[7]. Chapter three covers these documents at length – they are from the following groups: Byron Capital Markets (Hykawy, Thomas and Casasnovas 2010), U.S. Department of Energy (Bauer et al. 2010, 2011), Roskill Information Services (Roskill 2011), and the Environmental Science & Technology publication (Alonso et al. 2012). Results from Alonso et al.'s research were not used because no specific demand quantities were given and demand was reported in terms of total rare earth elements (as opposed to the traditional REO equivalent). Hykawy, Thomas and Casasnovas projected demand to 2015 while the others projected it to 2020 and beyond.

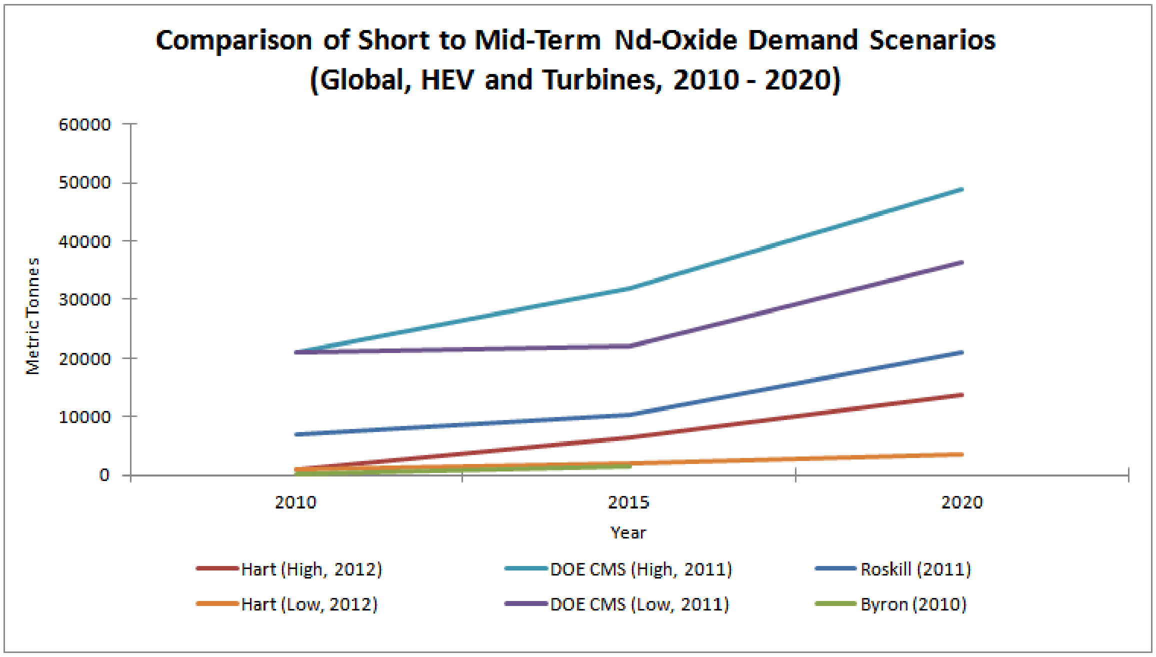

Figure 7.1 Comparison of alternative short to mid-term Nd-oxide consumption (Global, HEV and turbines, 2010 – 2020).

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[7] Data tables with actual values are given in appendix C.

Figure 7.1 shows a comparison of the possible neodymium-oxide consumption between this thesis, (Roskill 2011), (Hykawy, Thomas, and Casasnovas 2010), and (Bauer et al. 2011). There are three important things to note. First, the upper and lower ranges of global consumption, derived from the scenarios in chapters five and six, were used for this exercise. Second, Roskill only had one demand scenario based on their market analysis. Third, both high and low estimates from (Bauer et al. 2011) were used.

Bauer et al. had the highest demand for neodymium, followed by Roskill, this thesis, and Hykawy, Thomas, and Casasnovas. The projections created by Bauer et al. have a possible difference on the order of one magnitude from this thesis' results while Roskill's values are approximately one third to three times higher than those in the present work. Demand is greater in both reports because they used higher rates of market penetration for permanent magnet wind turbines. For example, Bauer et al. used a 15% rate for the "low penetration" case of onshore turbines, 25% for offshore turbines, and 75% for both "high penetration" cases. This thesis increased the rate 1.5% per year from 5% to 20% by 2020. Wind turbine market penetration was only altered in one scenario; the others assumed a flat 5%. While the 20% value is comparatively acceptable, others have concluded that permanent magnet wind turbines will be deployed in greater numbers over the next ten years. Electric vehicle calculations in (Bauer et. al 2011) and (Roskill 2011) also included electric bikes. Electric bikes are very popular in China but less so in the rest of the world and thus were not included in this analysis. Their inclusion would increase the effect of China's influence on global consumption of rare-earth magnet metals.

In Figure 7.2, a comparison of dysprosium-oxide consumption scenarios is shown. Bauer et al.'s "high penetration" case has the highest consumption of dysprosium oxide. However, the "low penetration" case, which was initially greater than Roskill's projection, eventually gets overtaken by Roskill's estimated demand. It is assumed by Bauer et al. that permanent magnets will have much smaller amounts of dysprosium content than Roskill does (2% as opposed to 4%). Roskill's expectations of strong growth in dysprosium-oxide demand means the amount demanded will exceed the DOE scenario.

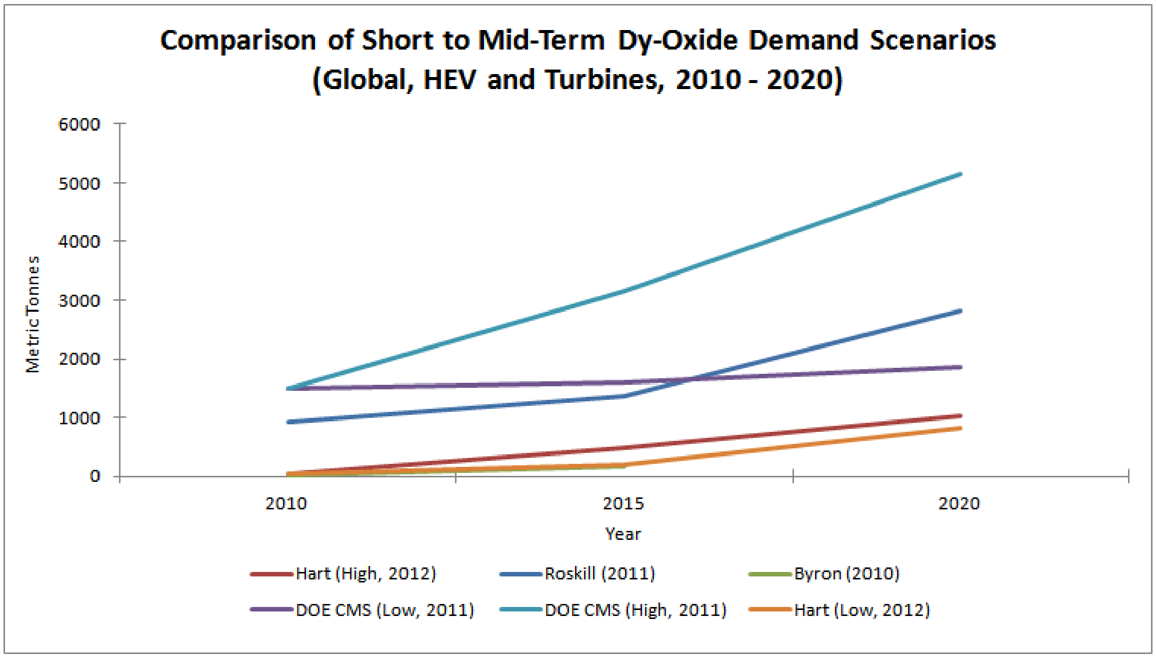

Figure 7.2 Comparison of alternative short to mid-term Dy-oxide consumption (Global, HEV and turbines, 2010 – 2020).

Compared to the other projections, the estimates in this thesis are approximately one order of magnitude less than in Bauer et al.'s "high penetration" case, but one-fifth the size of Roskill's estimates and three-quarters the size of those in the DOE's "low penetration" case. This is also because of the lower market penetration rate for permanent magnet wind turbines used in this thesis. Hykawy, Thomas, and Casasnovas' estimates are the smallest because they believe that new wind turbines will not use dysprosium because they are naturally cooled by the surrounding air (dysprosium enables magnets to function properly at high operating temperatures).

Future terbium consumption was only estimated in this thesis and the Roskill publication. Bauer et al. did not find that terbium would be a critical material, at least in terms of permanent magnet demand, and Byron Capital Markets simply does not believe that terbium will be used in these magnets. Roskill estimated that terbium consumption would increase steadily until 2015 and then grow faster between 2015 and 2020. Medium-term demand, as projected by this thesis, is approximately one-fifth of that in Roskill's estimates (see Figure 7.3). In the future, it is possible that terbium could be replaced by cheaper, more abundant metals such as dysprosium, praseodymium, or iron; however, there is no indication that such a substitution will occur soon.

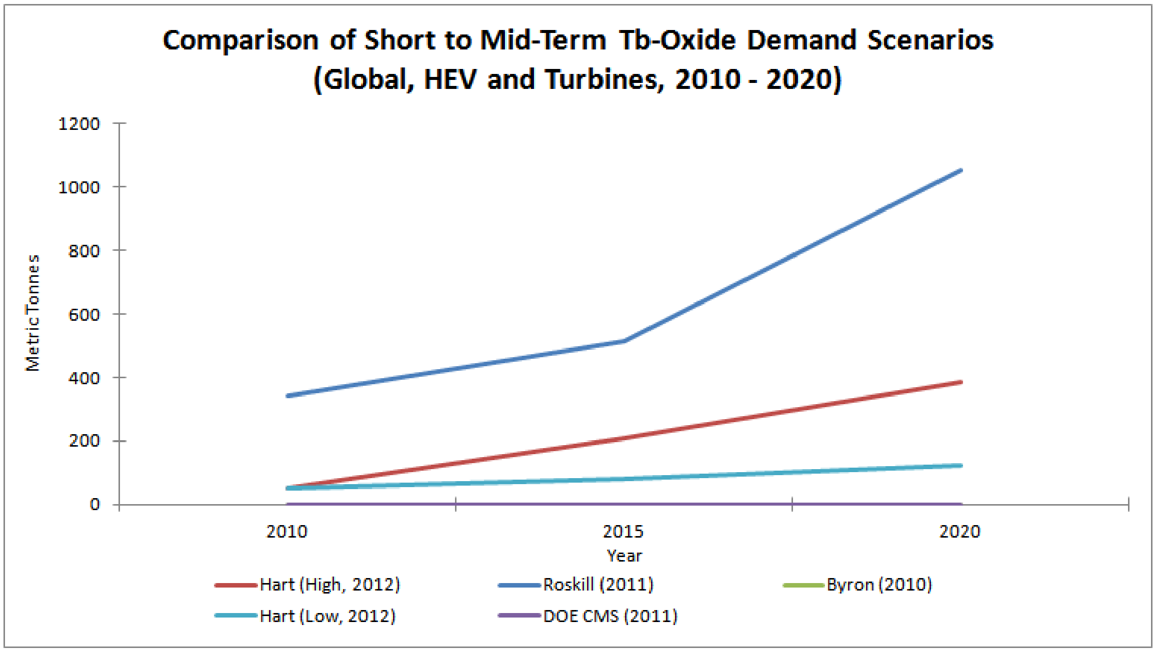

Figure 7.3 Comparison of alternative short to mid-term Tb-oxide consumption (Global, HEV and turbines, 2010 – 2020).

Finally, estimates of future praseodymium-oxide consumption were only produced in (Hykawy, Thomas and Casasnovas 2010) and the present work. The lower boundary of demand for this thesis was zero, while the upper bound was much larger than Hykawy, Thomas, and Casasnovas' projection (approximately one order of magnitude). Bauer et al. did not estimate praseodymium demand because it was deemed "not critical"; this was due to the fact that praseodymium is "generally used as a substitute for other [rare earth elements] … not as a primary material" (Bauer et al. 2011, 46). Their estimates were assumed to be zero. Roskill states that "around 2-2,500 metric tonnes of praseodymium were thought to have been consumed [in Nd-Fe-B permanent magnets] in 2010" (Roskill 2011, 207). It is unclear if didymium (neodymium and praseodymium) magnets were used in wind turbines or hybrid vehicles, so Roskill's estimates were assumed to be zero for comparison purposes.

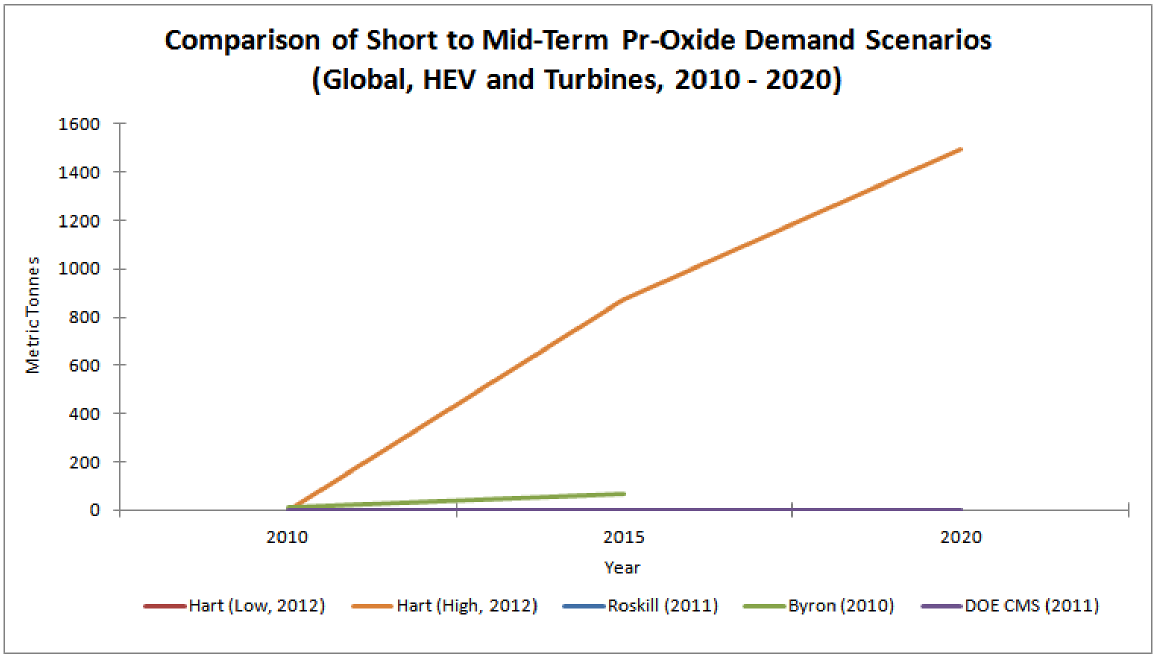

Figure 7.4 Comparison of alternative short to mid-term Pr-oxide consumption (Global, HEV and turbines, 2010 – 2020).

### 7.2 Discussion of Government Policies

Each scenario generated in this paper represents a single possibility of how demand might be shaped in the future. Having this type of analysis on hand is good for private firms considering entrance into the rare earth industry at any point of production, firms already in the industry, but more importantly the government. The results from each scenario serve a greater purpose than to simply say that demand will grow – they also supply governments with possible methods for reducing demand. While there is no indication of a market failure that requires either supply or demand-side intervention, this analysis remains useful for future research into the field of wind turbine, hybrid vehicle, and rare earth magnet metal markets. Much emphasis is placed on supply-side responses to potential failures of the rare earth market while little work has been done to highlight possible demand-side solutions.

This is akin to Ronald Reagan's war on drugs, where the main goal was to reduce the supply of drugs in the United States. Staving off the burgeoning epidemic of addiction that demanded more drugs was secondary to eliminating supply. Following a similar path of action to affect the supply of rare earths won't result in a swelling prison population or billions of taxpayer dollars, but it may not be the best option. Increasing the availability of rare earths from non-Chinese sources is certainly one method of alleviating supply concerns. However, directly reducing demand from consumers of hybrid vehicles, wind turbines, and rare earths through political means may be an equally viable solution.

The scenarios in this paper represent a variety of singular changes in the consumption of each technology and their rare earths. Despite this singularity, it is clear that there exist different options for government intervention. These changes could alter the consumption patterns of end-users and producers of intermediate goods, reducing their risk of exposure to external market shocks. One policy option would be to fund scientific research and development efforts targeted at reducing rare earth use in each technology. Government funding could be in the form of subsidies, grants, and loans for participants that meet specific performance criteria in regards to research output and monetary requirements.

Research efforts would focus on improving mechanical efficiencies and altering the material composition of permanent magnets. Private companies, which have generally lead the way in terms of scientific advancement, could take technologies like GE's ScanWind wind turbine and build upon their design if provided adequate funding by the government. Reducing the cost of and improving performance for next-generation wind turbines would allow for a more widespread use of this technology and decrease the overall amount of magnetic rare earths used.

Governments might also want to fund research into alternative material compositions for neodymium-iron-boron permanent magnets. Technical knowledge and expertise to make these magnets is limited to Chinese and Japanese firms however. If neodymium prices were high, a substitution towards praseodymium might be a prudent choice of action. Each rare earth comprises a large portion of a didymium magnet's cost and would still be expensive; a cost-benefit analysis could help determine whether decreasing the amount of an expensive material would offset the increased cost of a substitute material. Substitution is limited though and believed to only be good in amounts lower than 5% of the total weight. Dysprosium and terbium could also be substituted for neodymium in greater amounts but are unlikely to do so because they are both more expensive than it.

Material substitution, of course, can also be accomplished by changing the type of magnet to a completely different material such as a ceramic or ferromagnetic substance. Work in this field is being undertaken at various government-sponsored research facilities in the United States, including the following programs (Constantinides, "Status and Outlook of Rare Earth Permanent Magnets" 2011, 24):

- Beyond Rare Earth Magnets (BREM), funded by the United States Department of Energy, through the Ames Laboratory, its sister sites, and Arnold Magnetic Technologies
- FOA-472 "Rare Earth Alternatives in Critical Technologies (REACT)", funded by the United States Department of Energy and carried out at multiple university and national laboratories

Should governments choose a demand-side response to future market failures, they would be wise to develop a path of action that accomplishes two primary tasks. First, their policies would help reduce consumption of base components by the manufacturers of hybrid vehicles and wind turbines. Second, the magnets produced under these policies would have the same or similar functional performance as magnets that are currently being produced. Changes to the material composition of permanent magnets and improving technological efficiencies in wind turbines and hybrid vehicles may be two of the better paths of action as they resulted in the lowest amounts of neodymium, dysprosium, and terbium demanded for wind turbines. Praseodymium will once again have to be substituted for neodymium, but it is possible that a balance could be struck where the lowest cost amount of each material would be employed (possibly through the use of optimization and operations research techniques).

Only one scenario that was analyzed for hybrid electric vehicles can provide guidance for helping reduce the amount of rare earth magnets demanded in the future. Material substitution, or scenario 2C, had lower demand for neodymium, terbium, and dysprosium but lead to an increased demand for praseodymium. Manufacturers of some hybrid and all-electric vehicles have started using LIB, which represent a component/end-good substitution. Heavy government funding for research efforts into lithium-ion technology has proved advantageous, as the technology has advanced much quicker with the support.

A cost-savings analysis would show whether or not these substitutions would be beneficial to producers of hybrid vehicles and their customers. The other three scenarios (2A, 2B, 2D) all saw greater demand for hybrid vehicles over the base case, which is not necessarily bad thing. If the goal is to reduce carbon emissions, increasing the number of hybrid vehicles being employed through tax incentives and the natural effects of rising substitute price is a boon to your cause.

The best thing about this model and the policy options that are presented is the potential to update them with new data. Sales of hybrid vehicles or installation of new wind turbine data from future years can be entered and will help to revise future projections. Private, public, and government organizations can update this model with newer data in order to determine more accurate projections of future rare earth magnet metal consumption. While it is designed to be a static model, new data would at least provide base estimates for what consumption could look like in the coming years.

## 7.3 Discussion of Constraints on Short-term Rare Earth Consumption

It has been previously discussed that the use of the term "demand" in this paper is loose and more accurately described by consumption. Consumption represents the market-clearing equilibrium found at the intersection of supply and demand for the good in question. One concept that has been conveniently left out of this paper's discussion is the idea of natural constraints on rare earth supplies and how this would affect consumption of magnetic rare earths, hybrid vehicles, and wind turbines. The belief is that naturally-imposed constraints on the supply of magnetic rare earths would negatively affect the equilibrium level of consumption for hybrid vehicles and wind turbines.

In his unpublished book, Dr. John Tilton proposes a theory in Chapter 3 "Metal Supply" (Tilton 2010) that there is a natural capacity constraint on the supply of a metal given its price. Figure 7.5 illustrates that the short and long-run supplies of a metal increase almost asymptotically, to the point where any tiny increase in the quantity supplied increases the price by disproportionate amount. Tilton's theory presents the idea that in the short and long-run periods, the amount of metal supplies from a specific deposit or set of deposits will be naturally limited by the current technology, price of the material being mined, and quality of in-situ resources. In the very long run, however, supply has no constraints due to capacity or known resource issues – it simply continues at a level price.

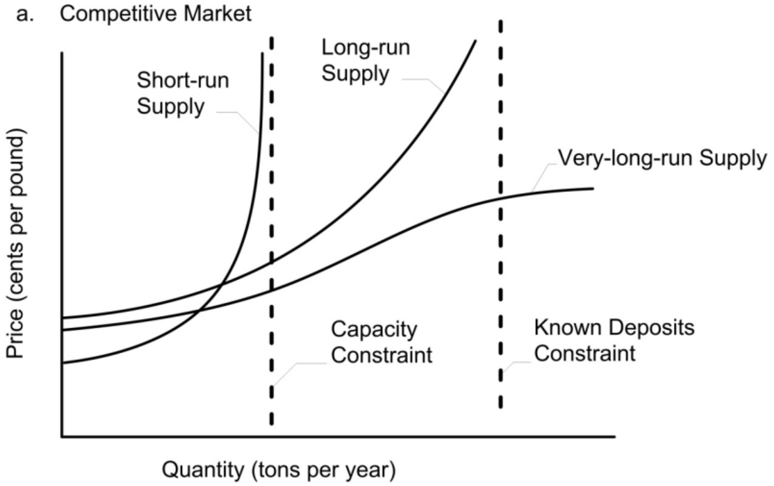

Figure 7.5 Supply of a metal over the short run, long run, and very-long run.

There are analogous capacity and "known deposit" constraints on rare earth supplies. China is the only place where rare earths are being actively mined and produced. Two non-Chinese mines are currently operating (Mt. Pass in California and Mt. Weld in Australia) but their output is small and largely producing light rare earths. The current operational capacity of China's mines is such that if global consumption increased by an unexpected amount in the short-term and prices increased, the new quantity supplied would be very small. This is the short-term capacity constraint on magnetic rare earths that would limit or even halt the number of new hybrid vehicles built and sold and the number of new wind turbines built and erected. Ultimately, this reduces the market-clearing quantity of each technology sold and would likely lead to decreased consumption in future years.

In the long run, new mines will begin producing materials and supply will expand. The equilibrium consumption level of hybrid vehicles, wind turbines, and their rare earths will no longer be hindered by capacity constraints at specific mines because there are multiple mines producing a large amount of material. Eventually, the number of low-cost, high-grade resources will diminish and then cease completely. The price of raw materials will rise enough that low-grade resources will become economical to mine. Naturally-imposed restrictions on the growth of hybrid vehicle and wind turbine demand, due to a lack of rare earths for the production of permanent magnets, will be lifted. This is well beyond the time scope of this thesis and will not affect its conclusions.

# CHAPTER EIGHT

# CONCLUSION

The main question that this thesis sought to answer was the following: how will United States and world consumption of rare earth magnet metals evolve in the short to medium term (2011 – 2020) and why. In the base scenarios, rare earth metal usage in U.S. and non-U.S. wind turbines largely grew at an exponential rate, in line with the demand for wind turbines themselves. This was postulated to be the result of federal government subsidies such as the renewable energy production tax credit, state-mandated renewable energy portfolios requiring wind energy, and increasing prices for traditional fossil fuels.

Hybrid electric vehicles pose a slightly different situation; their use increased exponentially between 1999 and 2007 but new sales began to decline from 2008 onward in the U.S. as it was hit by economic recession. In non-U.S. countries, external estimates projected that hybrid vehicle demand will continue on an exponential path. Higher RoW demand was driven by strong economic growth in developing nations such as China and vehement government support for hybrid vehicles in Europe, South America, and Asia. It was estimated that between 2011 and 2020, there would be an overall increase in the amount of neodymium, dysprosium, terbium, and possibly praseodymium consumed in the United States and the rest of the world. Wind turbines appear to be a secondary factor behind consumption of rare earth permanent magnets. U.S. and international governments mandate the use of renewable energy of which wind is one of the cheapest and most reliable alternatives. This has caused the consumption of wind turbines and their associated metals to explode. However, although wind turbines use more rare earths per unit than hybrid vehicles, there will be fewer new turbines than hybrid vehicles sold.

Hybrid vehicle sales in non-U.S. countries (particularly China, Japan, and Europe) are likely to drive the consumption of magnetic rare earths. Unyielding support by federal governments and an educated public continue to push the adoption of electric vehicle technologies in these places. Since hybrid vehicles are considered a luxury good in the U.S., their use is limited to consumers that can afford the high initial purchase cost. Base scenario demand in the U.S. would decline due to the hardship felt by consumers as the economy falters. People have financial incentives to purchase these vehicles yet are not forced to do so. With less disposable income and no government pressure to purchase them, people will choose cheaper alternatives such as gasoline automobiles or public transit. Unlike wind turbines, hybrid vehicles have not been mandated for use in the United States; rather, the government sets unofficial goals for total hybrid vehicle use and does not strictly enforce them through legislation.

As stated earlier, the results of the scenarios presented in this thesis are not absolute. There are many unknown factors that could lead to alterations in the projected demand for wind turbines and hybrid vehicles. One such event occurred recently, with news that the all-electric Chevy Volt had been experiencing battery fires during safety tests (Hirsch, “Probe of Chevrolet Volt fires ends” 2012). Although GM has begun to rectify this issue, many consumers will see headlines about vehicle fires and become unnecessarily concerned about sticking with gas-powered cars. This could negatively affect the number of hybrid vehicles demanded, despite the fact that new modifications to the Volt have been deemed safe and that other “tried-and-true” hybrid and full-electric vehicles are already on the market.

This is but one example of a demand-changing factor that was beyond the scope of this thesis. Many unknown variables exist that could affect the consumption of wind turbines or hybrid vehicles, indirectly affecting the demand for the four magnetic rare earths. Changes in prices for raw rare earth materials or the own price of a turbine or vehicle could result in demand for these technologies and materials growing or shrinking, depending on the direction of the price change. The probability of an event like an Israeli strike on Iranian nuclear facilities occurring is relatively high - though apocalyptic, this is a very plausible scenario that would lead to the eradication of many countries and their demand for green energy technologies. Any of these situations or the plethora of other possibilities that there are could occur, thus altering the results of this paper – it cannot cover every scenario and only the ones most likely to occur have been explored.

Unfortunately, like any research paper, this one too suffers from several shortcomings. First, its methodology does not include all of the potential factors that influence demand for wind turbines and hybrid electric vehicles. Some are known and some are unforeseeable (as previously discussed) and there are simply too many factors to include. Second, though rare earths have been used for decades, wind turbines and hybrid vehicles in their current formats are relatively new technologies. Even the biggest data set in this paper has only twenty data points, which is far smaller than other technologies or minerals such as the gasoline automobile or copper. The accuracy of SAS-generated predictions of base scenario consumption benefit from larger sample sizes. This small sample size is unlikely to produce results that are anywhere near 100% accurate.

The paper's final shortcoming is that the scenarios created represent singular, mutually-exclusive events. Future consumption of neodymium in wind turbines is examined in alternate scenarios by using different assumptions about material composition, economic growth, and other factors. For example, the effect of a material composition change alone is first examined; the conditions that resulted in this change are then "reset", so to speak, and the effect of a change in market penetration is estimated. These events were assumed to be independent of each other for this paper's analysis.

In reality, it is possible that any combination of these scenarios, or perhaps all of them, could occur simultaneously. Neodymium consumption could increase due to higher rates of market penetration for direct-drive wind turbines, but could be reduced by technological changes that increase a turbine's power output without altering the amount of permanent magnets required. It is unclear as to what the exact results are when these happen at the same time.

Each of these shortcomings provides the chance for other economists, social scientists, or policy and scientific research institutions to improve upon the model in this paper. Similar to Bauer et al.'s "Critical Materials Strategy" or Gareth Hatch's "Critical Rare Earths" publications, there are many strong points to this analysis, but many options for further research. One example would be to amalgamate the scenarios through a mix-and-match process and examine multiple events at once. Another example would be to create a dynamic model that accounts for time-specific variables and observes the effect of micro and macroeconomic changes as they occur. Finally, future researchers would simply have more points of data available in order to improve on the model developed here. While very important, these issues are well beyond this paper's scope and are likely to be covered and cleverly negated in future studies.

Demand for renewable energy technologies is going to continue in the years to come. Barring catastrophic events such as nuclear war or global economic meltdown, the cumulative demand for these technologies will continue increasing until natural capacity constraints have been met. There are many policy options available to governments that could shrink their national consumption of these technologies and their rare-earth components. Each path would seek to reduce consumption, causing a domino effect that could results in an alleviation of potential (or actual) supply concerns.

As a result, governments and private firms will have a longer period of time with which they can explore for and develop new mines. Passing such policies in a time of crisis would require the presence of strong, well-funded local and national governments so as to avoid the failures of short-sighted policies. As stated earlier, demand drives supply, not the other way around. Hyped up concerns regarding a lack of supply are potentially fixed by cleverly shaping demand as opposed to wild-eyed development of the sea bed, the Moon, and every middling pile of sand on Earth in hopes of striking it rich.

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# APPENDICES

## Appendix A: SAS Output - Wind Turbine and Hybrid Vehicle Analysis

Figure A-1 New wind turbines in the U.S. (Historical, best fit, base scenario, 1999 to 2020).

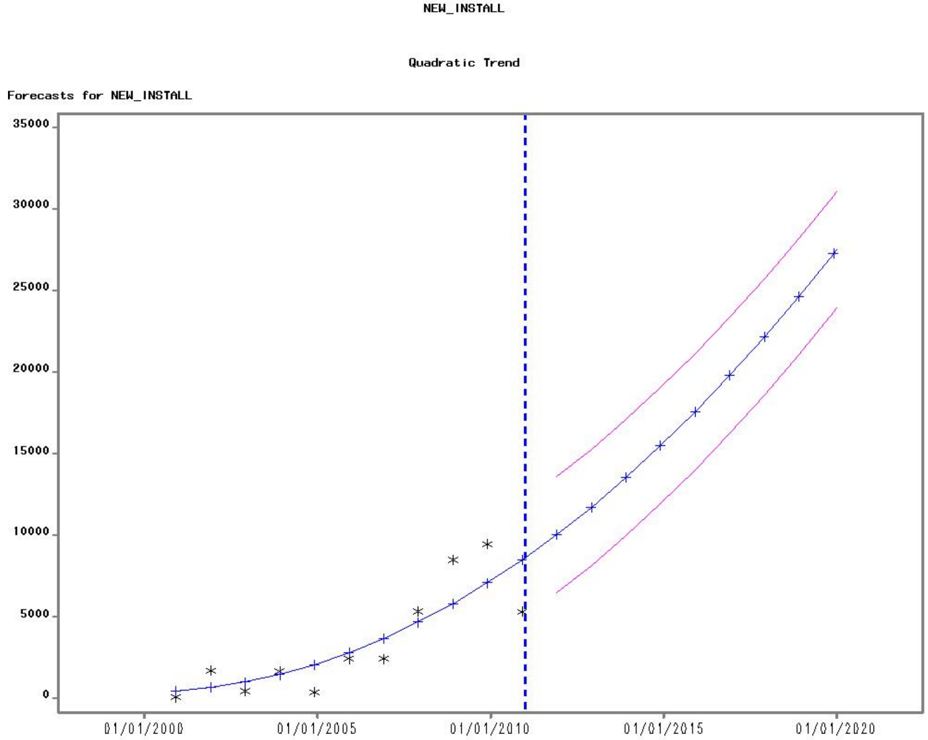


Figure A-2 New wind turbines in the RoW (Historical, best fit, base scenario, 1990 to 2020).

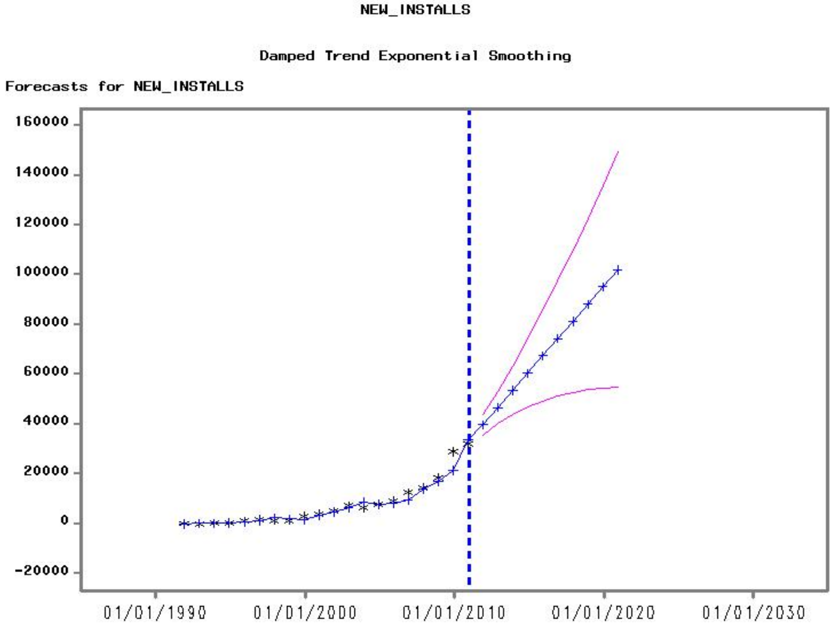


Figure A-3 New HEV in the U.S. (Historical, best fit, base scenario, 1999 to 2020).

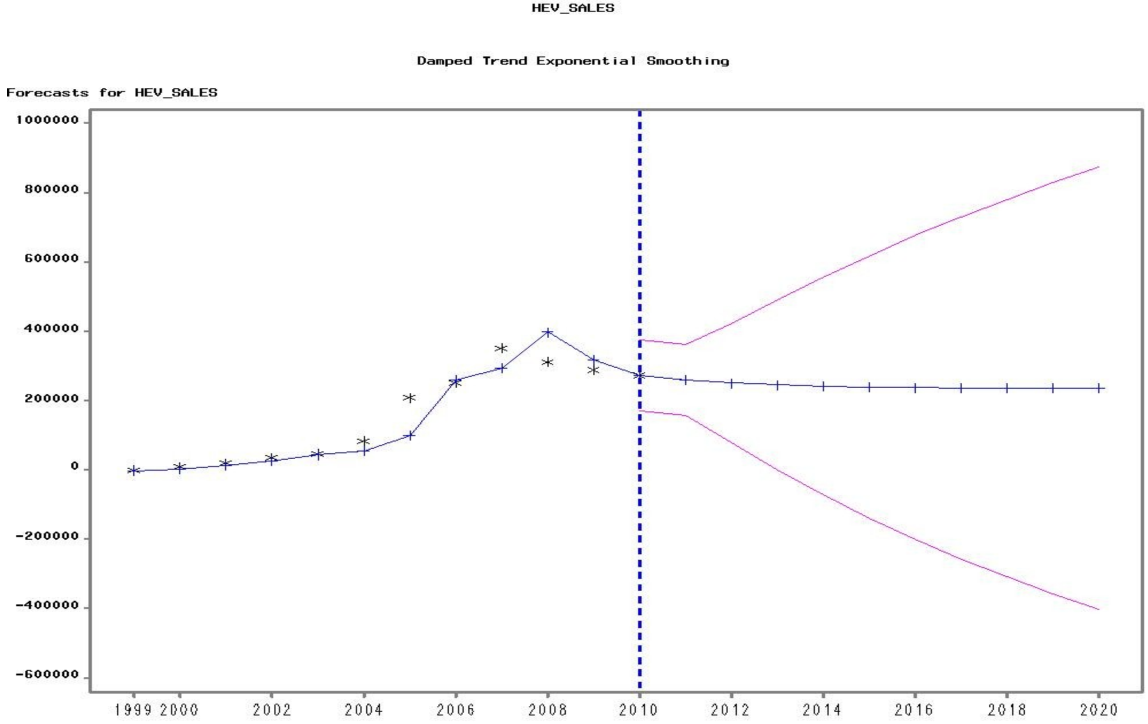
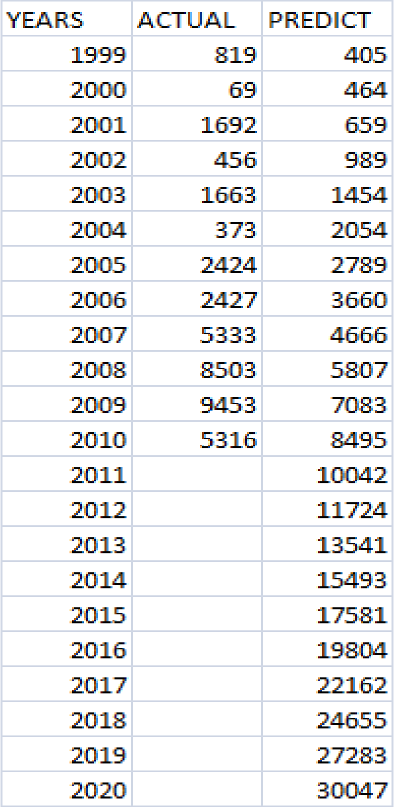
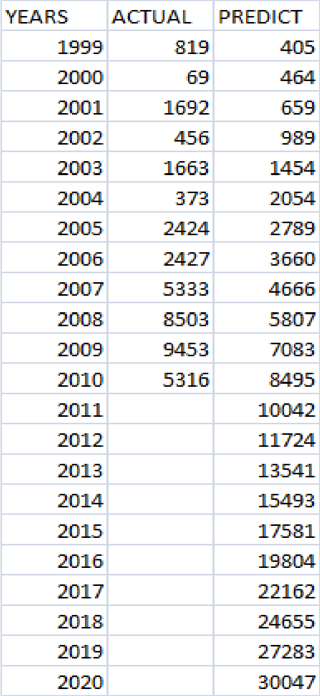


Table A-1 SAS Projections of new wind turbines in the U.S. (2011 to 2020).



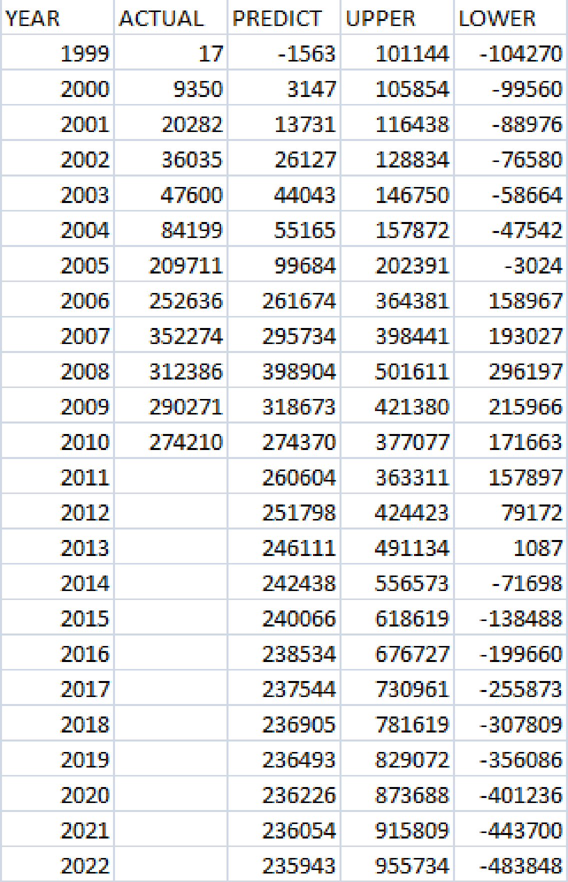
| YEARS | ACTUAL | PREDICT |
|---|---|---|
| 1999 | 819 | 405 |
| 2000 | 69 | 464 |
| 2001 | 1692 | 659 |
| 2002 | 456 | 989 |
| 2003 | 1663 | 1454 |
| 2004 | 373 | 2054 |
| 2005 | 2424 | 2789 |
| 2006 | 2427 | 3660 |
| 2007 | 5333 | 4666 |
| 2008 | 8503 | 5807 |
| 2009 | 9453 | 7083 |
| 2010 | 5316 | 8495 |
| 2011 | | 10042 |
| 2012 | | 11724 |
| 2013 | | 13541 |
| 2014 | | 15493 |
| 2015 | | 17581 |
| 2016 | | 19804 |
| 2017 | | 22162 |
| 2018 | | 24655 |
| 2019 | | 27283 |
| 2020 | | 30047 |

Table A-2 SAS Projections of new wind turbines in the RoW (2011 to 2020).



| YEARS | ACTUAL | PREDICT |
|---|---|---|
| 1999 | 819 | 405 |
| 2000 | 69 | 464 |
| 2001 | 1692 | 659 |
| 2002 | 456 | 989 |
| 2003 | 1663 | 1454 |
| 2004 | 373 | 2054 |
| 2005 | 2424 | 2789 |
| 2006 | 2427 | 3660 |
| 2007 | 5333 | 4666 |
| 2008 | 8503 | 5807 |
| 2009 | 9453 | 7083 |
| 2010 | 5316 | 8495 |
| 2011 | | 10042 |
| 2012 | | 11724 |
| 2013 | | 13541 |
| 2014 | | 15493 |
| 2015 | | 17581 |
| 2016 | | 19804 |
| 2017 | | 22162 |
| 2018 | | 24655 |
| 2019 | | 27283 |
| 2020 | | 30047 |

Table A-3 SAS Projections of new hybrid vehicle sales in the U.S. (2011 to 2020).



| YEAR | ACTUAL | PREDICT | UPPER | LOWER |
|---|---|---|---|---|
| 1999 | 17 | -1563 | 101144 | -104270 |
| 2000 | 9350 | 3147 | 105854 | -99560 |
| 2001 | 20282 | 13731 | 116438 | -88976 |
| 2002 | 36035 | 26127 | 128834 | -76580 |
| 2003 | 47600 | 44043 | 146750 | -58664 |
| 2004 | 84199 | 55165 | 157872 | -47542 |
| 2005 | 209711 | 99684 | 202391 | -3024 |
| 2006 | 252636 | 261674 | 364381 | 158967 |
| 2007 | 352274 | 295734 | 398441 | 193027 |
| 2008 | 312386 | 398904 | 501611 | 296197 |
| 2009 | 290271 | 318673 | 421380 | 215966 |
| 2010 | 274210 | 274370 | 377077 | 171663 |
| 2011 | | 260604 | 363311 | 157897 |
| 2012 | | 251798 | 424423 | 79172 |
| 2013 | | 246111 | 491134 | 1087 |
| 2014 | | 242438 | 556573 | -71698 |
| 2015 | | 240066 | 618619 | -138488 |
| 2016 | | 238534 | 676727 | -199660 |
| 2017 | | 237544 | 730961 | -255873 |
| 2018 | | 236905 | 781619 | -307809 |
| 2019 | | 236493 | 829072 | -356086 |
| 2020 | | 236226 | 873688 | -401236 |
| 2021 | | 236054 | 915809 | -443700 |
| 2022 | | 235943 | 955734 | -483848 |

## Appendix B: SAS Output - Regression Results

Equation Set B-1 Multi-variate regression, HEV demand as function of $P_{gas}$ and Tax Credit.

$$Q_{D,HEV} = \alpha + \beta_1 x_1 + \beta_2 x_2$$

where:

$$\alpha = \text{intercept}$$

$$x_1 = \text{price of substitute good (gasoline)} = P_{gas}$$

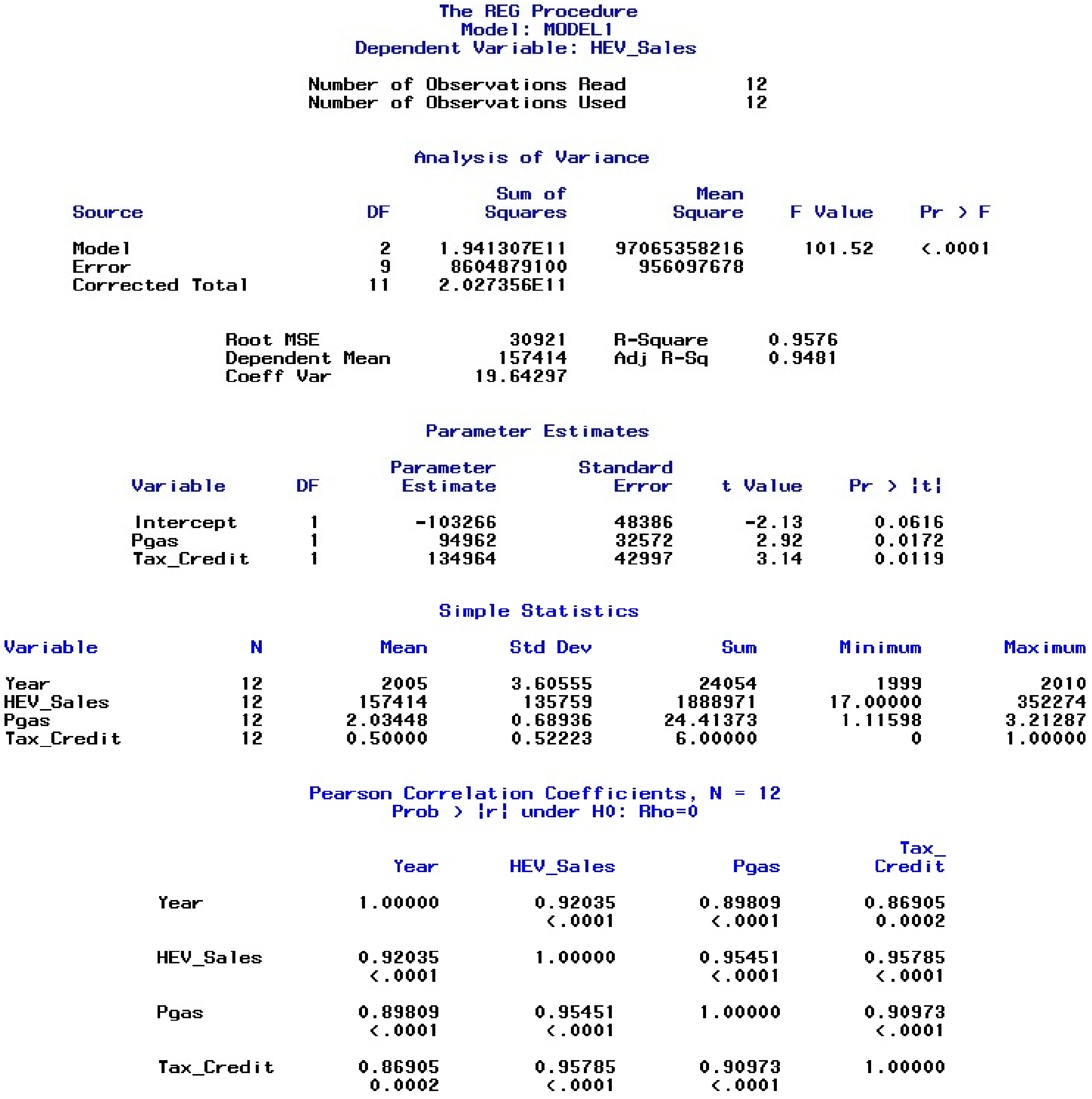
$$\beta_1 = \text{price of substitute good (gasoline) coefficient} = \beta_{gas}$$

$$x_2 = \text{tax credit dummy} = \text{TaxCred}, \begin{Bmatrix} x = 0, \text{no tax credit} \\ x = 1, \text{tax credit present} \end{Bmatrix}$$

$$\beta_2 = \text{tax credit coefficient} = \beta_{\text{TaxCred}}$$

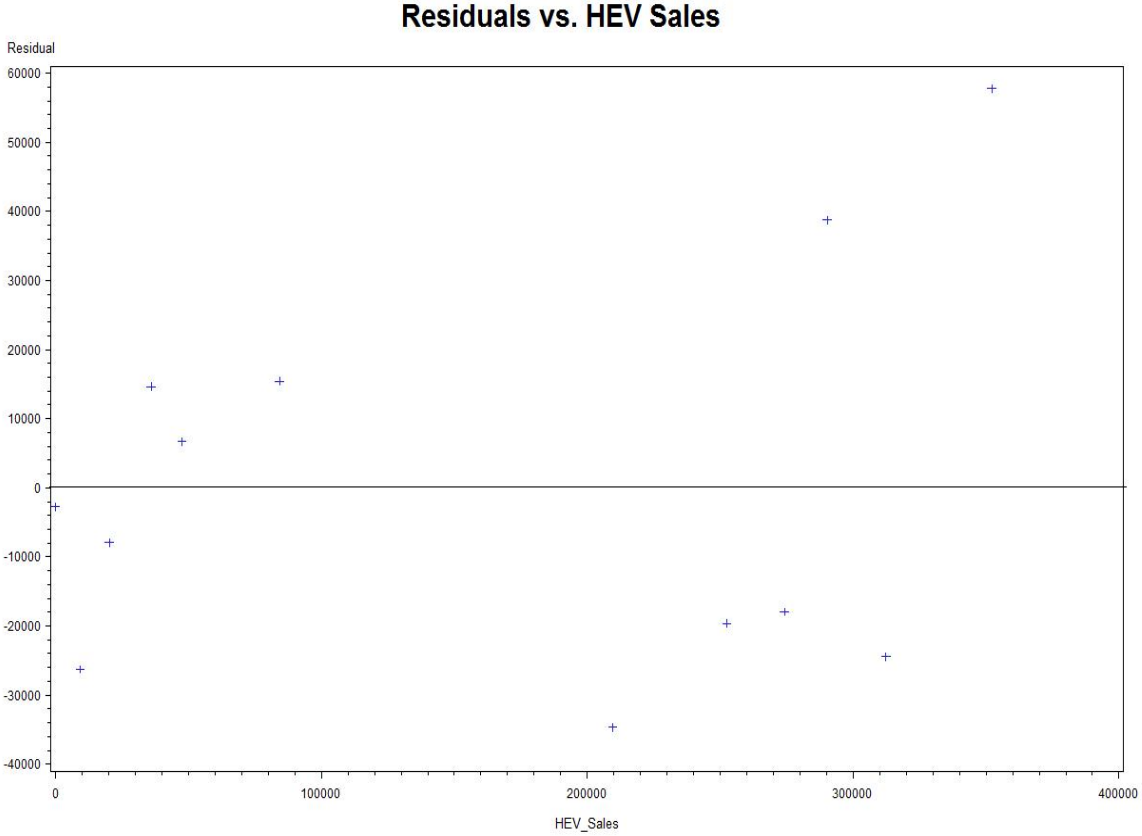
$$Q_{D,HEV} = \alpha + \beta_{gas} P_{gas} + \beta_{TaxCred} TaxCred$$

Figure B-1 Regression results and statistics.



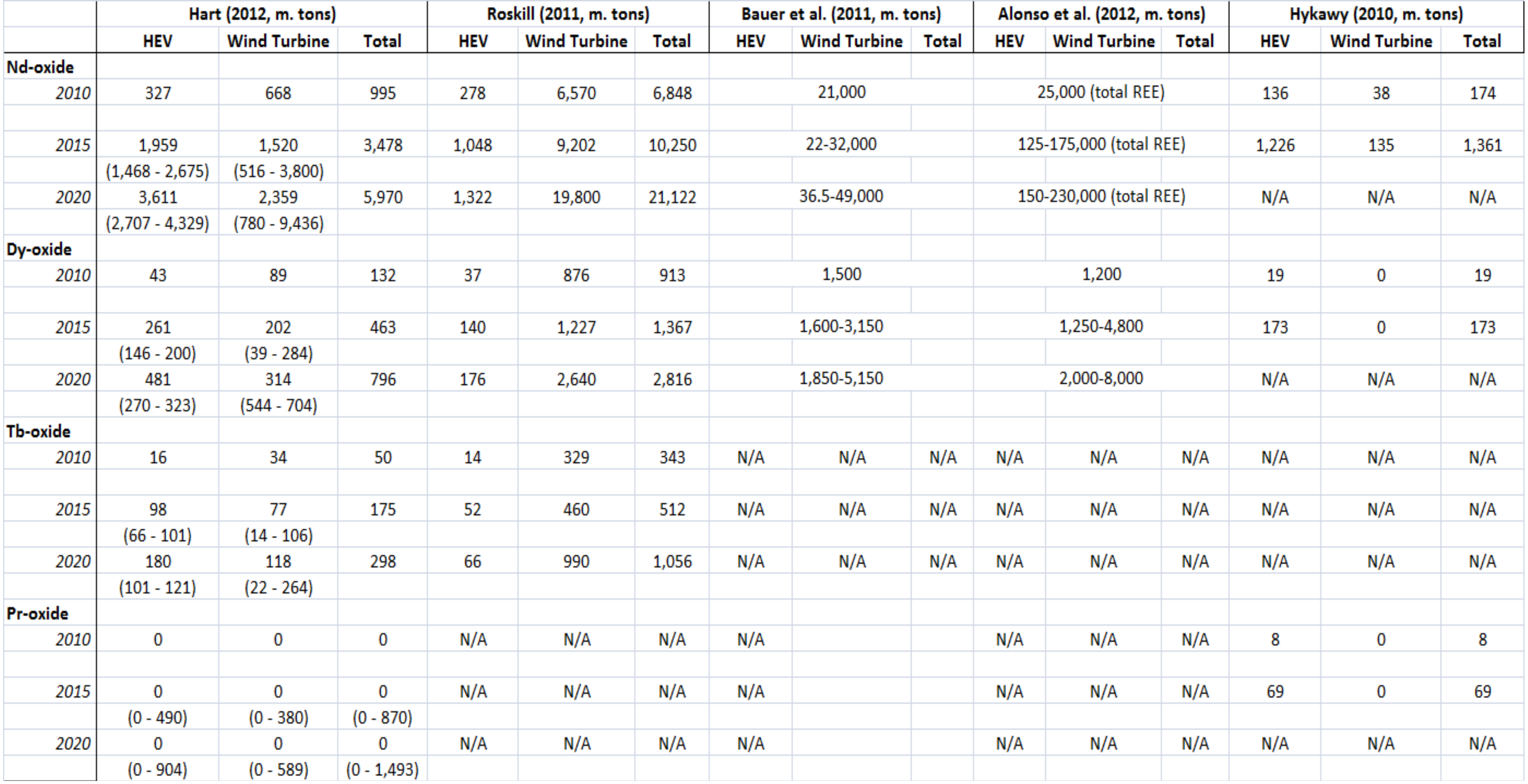
```
                              The REG Procedure
                                Model: MODEL1
                        Dependent Variable: HEV_Sales

                     Number of Observations Read          12
                     Number of Observations Used          12

                             Analysis of Variance

                                    Sum of           Mean
      Source                   DF          Squares         Square    F Value    Pr > F

      Model                     2      1.941307E11    97065358216     101.52    <.0001
      Error                     9       8604879100      956097678
      Corrected Total          11      2.027356E11

                   Root MSE                  30921    R-Square     0.9576
                   Dependent Mean           157414    Adj R-Sq     0.9481
                   Coeff Var              19.64297

                             Parameter Estimates

                               Parameter       Standard
         Variable      DF       Estimate          Error    t Value    Pr > |t|

          Intercept     1        -103266          48386      -2.13      0.0616
         Pgas           1          94962          32572       2.92      0.0172
         Tax_Credit     1         134964          42997       3.14      0.0119

                               Simple Statistics

Variable             N          Mean       Std Dev           Sum       Minimum        Maximum

Year                12          2005       3.60555         24054          1999           2010
HEV_Sales           12        157414        135759       1888971      17.00000         352274
Pgas                12       2.03448       0.68936      24.41373       1.11598        3.21287
Tax_Credit          12       0.50000       0.52223       6.00000             0        1.00000

                     Pearson Correlation Coefficients, N = 12
                            Prob > |r| under H0: Rho=0

                                                                       Tax_
                              Year      HEV_Sales           Pgas       Credit

           Year            1.00000        0.92035        0.89809      0.86905
                                           <.0001         <.0001       0.0002

           HEV_Sales       0.92035        1.00000        0.95451      0.95785
                            <.0001                        <.0001       <.0001

           Pgas            0.89809        0.95451        1.00000      0.90973
                            <.0001         <.0001                      <.0001

           Tax_Credit      0.86905        0.95785        0.90973      1.00000
                            0.0002         <.0001         <.0001
```

Figure B-2 Graph of residuals vs. HEV sales (time series).



## Appendix C: Data tables for comparison of projections from relevant publications

Table C-1 Comparison of Nd, Dy, Tb, and Pr-oxide demand in the short (2015) and mid-term (2020).



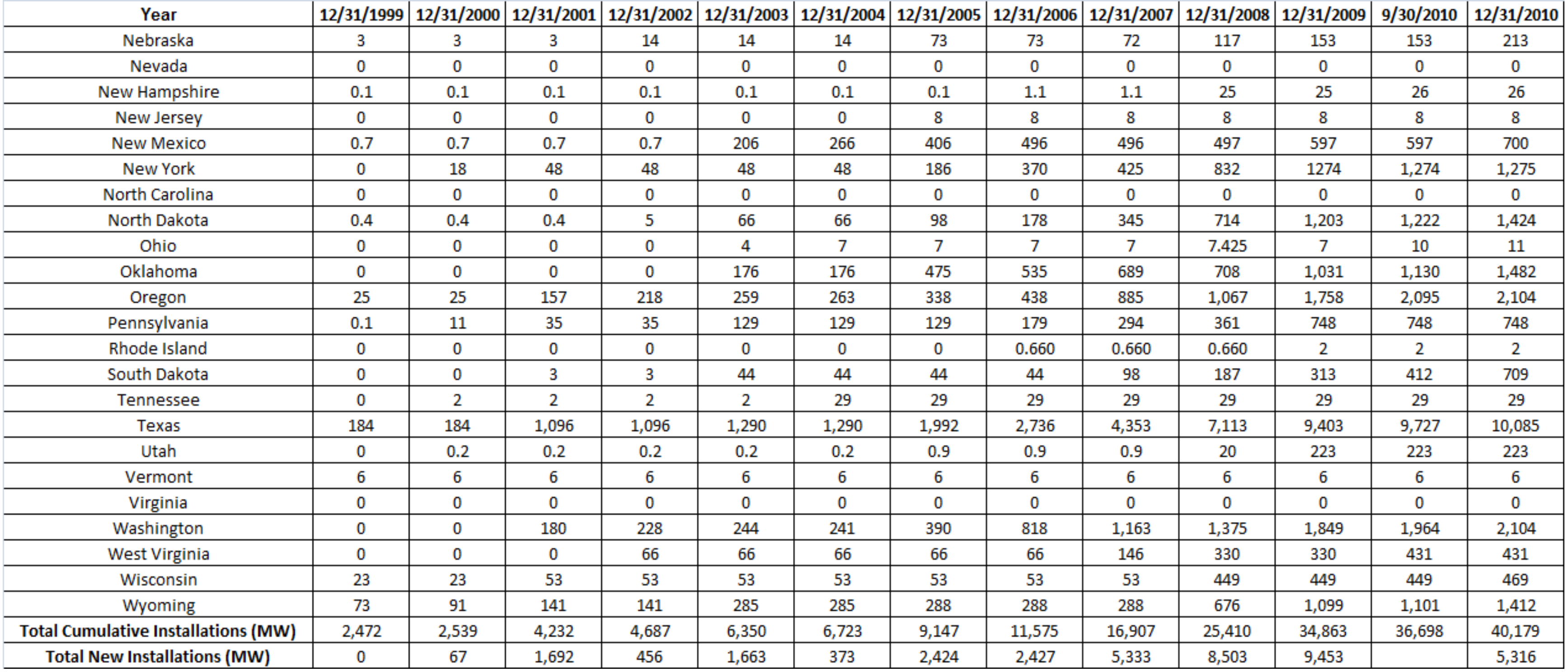
| | Hart (2012, m. tons) | | | Roskill (2011, m. tons) | | | Bauer et al. (2011, m. tons) | | | Alonso et al. (2012, m. tons) | | | Hykawy (2010, m. tons) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HEV | Wind Turbine | Total | HEV | Wind Turbine | Total | HEV | Wind Turbine | Total | HEV | Wind Turbine | Total | HEV | Wind Turbine | Total |
| **Nd-oxide** | | | | | | | | | | | | | | | |
| *2010* | 327 | 668 | 995 | 278 | 6,570 | 6,848 | 21,000 | | | 25,000 (total REE) | | | 136 | 38 | 174 |
| | | | | | | | | | | | | | | | |
| *2015* | 1,959 | 1,520 | 3,478 | 1,048 | 9,202 | 10,250 | 22-32,000 | | | 125-175,000 (total REE) | | | 1,226 | 135 | 1,361 |
| | (1,468 - 2,675) | (516 - 3,800) | | | | | | | | | | | | | |
| *2020* | 3,611 | 2,359 | 5,970 | 1,322 | 19,800 | 21,122 | 36.5-49,000 | | | 150-230,000 (total REE) | | | N/A | N/A | N/A |
| | (2,707 - 4,329) | (780 - 9,436) | | | | | | | | | | | | | |
| **Dy-oxide** | | | | | | | | | | | | | | | |
| *2010* | 43 | 89 | 132 | 37 | 876 | 913 | 1,500 | | | 1,200 | | | 19 | 0 | 19 |
| | | | | | | | | | | | | | | | |
| *2015* | 261 | 202 | 463 | 140 | 1,227 | 1,367 | 1,600-3,150 | | | 1,250-4,800 | | | 173 | 0 | 173 |
| | (146 - 200) | (39 - 284) | | | | | | | | | | | | | |
| *2020* | 481 | 314 | 796 | 176 | 2,640 | 2,816 | 1,850-5,150 | | | 2,000-8,000 | | | N/A | N/A | N/A |
| | (270 - 323) | (544 - 704) | | | | | | | | | | | | | |
| **Tb-oxide** | | | | | | | | | | | | | | | |
| *2010* | 16 | 34 | 50 | 14 | 329 | 343 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | | | | | | | | | | | | | | | |
| *2015* | 98 | 77 | 175 | 52 | 460 | 512 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | (66 - 101) | (14 - 106) | | | | | | | | | | | | | |
| *2020* | 180 | 118 | 298 | 66 | 990 | 1,056 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | (101 - 121) | (22 - 264) | | | | | | | | | | | | | |
| **Pr-oxide** | | | | | | | | | | | | | | | |
| *2010* | 0 | 0 | 0 | N/A | N/A | N/A | N/A | | | N/A | N/A | N/A | 8 | 0 | 8 |
| | | | | | | | | | | | | | | | |
| *2015* | 0 | 0 | 0 | N/A | N/A | N/A | N/A | | | N/A | N/A | N/A | 69 | 0 | 69 |
| | (0 - 490) | (0 - 380) | (0 - 870) | | | | | | | | | | | | |
| *2020* | 0 | 0 | 0 | N/A | N/A | N/A | N/A | | | N/A | N/A | N/A | N/A | N/A | N/A |
| | (0 - 904) | (0 - 589) | (0 - 1,493) | | | | | | | | | | | | |

## Appendix D: Summary of historical data

Table D-1 Historical U.S. Wind Capacity, states A-M (megawatts, MW).

| | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW | Sum of MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **12/31/1999** | **12/31/2000** | **12/31/2001** | **12/31/2002** | **12/31/2003** | **12/31/2004** | **12/31/2005** | **12/31/2006** | **12/31/2007** | **12/31/2008** | **12/31/2009** | **9/30/2010** | **12/31/2010** |
| Alaska | 0.7 | 0.8 | 0.8 | 0.9 | 0.9 | 1.2 | 1.5 | 1.7 | 1.7 | 4 | 9 | 9 | 9 |
| Arizona | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 63 | 63 | 128 |
| Arkansas | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 |
| California | 1,616 | 1,616 | 1,683 | 1,823 | 2,025 | 2,095 | 2,149 | 2,376 | 2,439 | 2,537 | 2,798 | 2,739 | 3,177 |
| Colorado | 22 | 22 | 61 | 61 | 223 | 231 | 231 | 291 | 1,067 | 1,068 | 1,244 | 1,248 | 1,299 |
| Connecticut | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Delaware | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| Florida | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Georgia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Hawaii | 1.6 | 1.6 | 1.6 | 9 | 9 | 9 | 9 | 42 | 63 | 63 | 63 | 63 | 63 |
| Idaho | 0 | 0 | 0 | 0 | 0.2 | 0.2 | 75 | 75 | 75 | 76 | 147 | 164 | 353 |
| Illinois | 0 | 0 | 0 | 0 | 50 | 51 | 107 | 107 | 699 | 915 | 1,547 | 1,848 | 2,046 |
| Indiana | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 131 | 1,036 | 1,238 | 1,339 |
| Iowa | 242 | 242 | 324 | 423 | 472 | 634 | 836 | 932 | 1,273 | 2,791 | 3,604 | 3,670 | 3,675 |
| Kansas | 1.5 | 1.5 | 114 | 114 | 114 | 114 | 264 | 364 | 364 | 921 | 1,021 | 1,026 | 1,074 |
| Maine | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 9 | 42 | 47 | 175 | 200 | 266 |
| Maryland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 70 |
| Massachusetts | 0.3 | 0.3 | 1.0 | 1.0 | 1.0 | 1.0 | 1 | 4 | 5 | 6 | 15 | 17 | 18 |
| Michigan | 0.6 | 0.6 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 144 | 138 | 143 | 164 |
| Minnesota | 273 | 291 | 320 | 338 | 558 | 600 | 745 | 896 | 1,300 | 1,753 | 1,810 | 1,818 | 2,192 |
| Missouri | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 62 | 163 | 309 | 457 | 457 |
| Montana | 0.1 | 0.1 | 0.1 | 0.4 | 1.1 | 1.1 | 137 | 146 | 153 | 271 | 375 | 386 | 386 |

Table D-2 Historical U.S. Wind Capacity, states N-Z and total U.S. (megawatts, MW).



| Year | 12/31/1999 | 12/31/2000 | 12/31/2001 | 12/31/2002 | 12/31/2003 | 12/31/2004 | 12/31/2005 | 12/31/2006 | 12/31/2007 | 12/31/2008 | 12/31/2009 | 9/30/2010 | 12/31/2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nebraska | 3 | 3 | 3 | 14 | 14 | 14 | 73 | 73 | 72 | 117 | 153 | 153 | 213 |
| Nevada | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| New Hampshire | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 1.1 | 1.1 | 25 | 25 | 26 | 26 |
| New Jersey | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| New Mexico | 0.7 | 0.7 | 0.7 | 0.7 | 206 | 266 | 406 | 496 | 496 | 497 | 597 | 597 | 700 |
| New York | 0 | 18 | 48 | 48 | 48 | 48 | 186 | 370 | 425 | 832 | 1274 | 1,274 | 1,275 |
| North Carolina | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| North Dakota | 0.4 | 0.4 | 0.4 | 5 | 66 | 66 | 98 | 178 | 345 | 714 | 1,203 | 1,222 | 1,424 |
| Ohio | 0 | 0 | 0 | 0 | 4 | 7 | 7 | 7 | 7 | 7.425 | 7 | 10 | 11 |
| Oklahoma | 0 | 0 | 0 | 0 | 176 | 176 | 475 | 535 | 689 | 708 | 1,031 | 1,130 | 1,482 |
| Oregon | 25 | 25 | 157 | 218 | 259 | 263 | 338 | 438 | 885 | 1,067 | 1,758 | 2,095 | 2,104 |
| Pennsylvania | 0.1 | 11 | 35 | 35 | 129 | 129 | 129 | 179 | 294 | 361 | 748 | 748 | 748 |
| Rhode Island | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.660 | 0.660 | 0.660 | 2 | 2 | 2 |
| South Dakota | 0 | 0 | 3 | 3 | 44 | 44 | 44 | 44 | 98 | 187 | 313 | 412 | 709 |
| Tennessee | 0 | 2 | 2 | 2 | 2 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 |
| Texas | 184 | 184 | 1,096 | 1,096 | 1,290 | 1,290 | 1,992 | 2,736 | 4,353 | 7,113 | 9,403 | 9,727 | 10,085 |
| Utah | 0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.9 | 0.9 | 0.9 | 20 | 223 | 223 | 223 |
| Vermont | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| Virginia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Washington | 0 | 0 | 180 | 228 | 244 | 241 | 390 | 818 | 1,163 | 1,375 | 1,849 | 1,964 | 2,104 |
| West Virginia | 0 | 0 | 0 | 66 | 66 | 66 | 66 | 66 | 146 | 330 | 330 | 431 | 431 |
| Wisconsin | 23 | 23 | 53 | 53 | 53 | 53 | 53 | 53 | 53 | 449 | 449 | 449 | 469 |
| Wyoming | 73 | 91 | 141 | 141 | 285 | 285 | 288 | 288 | 288 | 676 | 1,099 | 1,101 | 1,412 |
| **Total Cumulative Installations (MW)** | 2,472 | 2,539 | 4,232 | 4,687 | 6,350 | 6,723 | 9,147 | 11,575 | 16,907 | 25,410 | 34,863 | 36,698 | 40,179 |
| **Total New Installations (MW)** | 0 | 67 | 1,692 | 456 | 1,663 | 373 | 2,424 | 2,427 | 5,333 | 8,503 | 9,453 |  | 5,316 |

Source: (U.S. Department of Energy, “Installed Wind Capacity” 2010)

Table D-3 Historical RoW Wind Capacity, part 1 (megawatts, MW).

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USA | 1484 | 1709 | 1680 | 1635 | 1663 | 1,612 | 1,590 | 1,592 | 1,946 | 2,472 | 2,539 | 4,232 | 4,687 | 6,350 | 6,723 | 9,147 | 11,575 | 16,907 | 25,410 | 34,863 | 40,179 |
| China | 0 | 0 | 0 | 0 | 0 | 38 | 79 | 166 | 190 | 265 | 265 | 402 | 459 | 567 | 764 | 1,260 | 2,599 | 5,912 | 12,210 | 25,810 | 44,733 |
| Germany | 62 | 112 | 180 | 335 | 643 | 1,130 | 1,548 | 2,080 | 2,870 | 4,445 | 6,113 | 8,754 | 11,994 | 14,609 | 16,629 | 18,415 | 20,622 | 22,247 | 23,897 | 25,777 | 27,214 |
| Spain | 0 | 5 | 50 | 60 | 70 | 140 | 249 | 512 | 660 | 1,522 | 2,235 | 3,337 | 4,825 | 6,202 | 8,263 | 10,027 | 11,623 | 15,145 | 16,689 | 19,149 | 20,676 |
| India | 0 | 39 | 39 | 79 | 185 | 576 | 816 | 950 | 968 | 1,077 | 1,167 | 1,456 | 1,702 | 2,125 | 3,000 | 4,430 | 6,270 | 7,850 | 9,587 | 11,807 | 13,066 |
| Italy | 0 | 0 | 0 | 0 | 0 | 22 | 60 | 100 | 154 | 282 | 427 | 690 | 788 | 904 | 1,265 | 1,717 | 2,123 | 2,726 | 3,736 | 4,850 | 5,797 |
| France | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 87 | 148 | 239 | 390 | 757 | 1,567 | 2,454 | 3,404 | 4,492 | 5,660 |
| United Kingdom | 0 | 0 | 0 | 0 | 0 | 0 | 270 | 320 | 331 | 343 | 406 | 474 | 552 | 649 | 907 | 1,353 | 1,962 | 2,389 | 2,974 | 4,051 | 5,204 |
| Portugal | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 131 | 195 | 299 | 522 | 1,022 | 1,716 | 2,130 | 2,862 | 3,357 | 3,702 |
| Denmark | 343 | 413 | 458 | 487 | 539 | 637 | 857 | 1116 | 1380 | 1748 | 2,390 | 2,497 | 2,889 | 3,110 | 3,118 | 3,122 | 3,136 | 3,125 | 3,163 | 3,465 | 3,752 |
| Sweden | 0 | 0 | 0 | 0 | 0 | 0 | 105 | 117 | 148 | 195 | 231 | 264 | 345 | 399 | 442 | 500 | 571 | 788 | 1,048 | 1,560 | 2,163 |
| Turkey | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 19 | 19 | 20 | 20 | 20 | 65 | 207 | 333 | 797 | 1,274 |
| Poland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 18 | 27 | 57 | 63 | 73 | 153 | 276 | 544 | 725 | 1,107 |
| Japan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 136 | 302 | 338 | 580 | 809 | 1,049 | 1,309 | 1,528 | 1,880 | 2,083 | 2,304 |
| South Korea | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 8 | 13 | 18 | 68 | 99 | 176 | 192 | 278 | 348 | 379 |
| Canada | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 137 | 198 | 236 | 322 | 444 | 684 | 1,460 | 1,846 | 2,372 | 3,319 | 4,009 |
| Australia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | 73 | 105 | 198 | 380 | 708 | 817 | 817 | 1,494 | 1,877 | 1,880 |
| New Zealand | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 36 | 36 | 36 | 168 | 168 | 171 | 322 | 325 | 497 | 506 |
| Chile | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 2 | 2 | 20 | 20 | 168 | 170 |
| Brazil | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 22 | 29 | 29 | 29 | 237 | 247 | 339 | 600 | 920 |
| Mexico | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 84 | 85 | 85 | 417 | 521 |
| Egypt | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 68 | 98 | 145 | 145 | 230 | 310 | 390 | 435 | 550 |
| Iran | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 12 | 15 | 21 | 47 | 67 | 82 | 82 | 100 |
| Morocco | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 54 | 54 | 54 | 64 | 64 | 125 | 124 | 253 | 286 |
| Netherlands | 0 | 0 | 0 | 0 | 0 | 0 | 299 | 325 | 359 | 410 | 449 | 486 | 693 | 912 | 1,079 | 1,219 | 1,558 | 1,746 | 2,225 | 2,229 | 2,237 |
| Ireland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 137 | 186 | 339 | 496 | 746 | 805 | 1,027 | 1,260 | 1,428 |
| Greece | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 297 | 375 | 473 | 573 | 758 | 873 | 990 | 1,086 | 1,208 |
| Austria | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 140 | 415 | 606 | 819 | 965 | 982 | 995 | 995 | 1,011 |
| Belgium | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35 | 68 | 96 | 167 | 194 | 287 | 415 | 563 | 911 |
| Taiwan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 104 | 188 | 280 | 358 | 436 | 519 |
| Romania | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 3 | 8 | 7 | 14 | 591 |
| Norway | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 97 | 101 | 160 | 267 | 325 | 333 | 429 | 431 | 441 |
| Bulgaria | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 36 | 70 | 120 | 177 | 375 |
| Hungary | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 3 | 18 | 61 | 65 | 127 | 201 | 295 |
| Czech Republic | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 9 | 17 | 28 | 54 | 116 | 150 | 192 | 215 |
| Finland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43 | 52 | 82 | 82 | 86 | 110 | 143 | 146 | 197 |
| Estonia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 3 | 32 | 32 | 59 | 78 | 142 | 149 |
| Costa Rica | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 70 | 70 | 70 | 71 | 74 | 74 | 74 | 123 | 123 |
| Tunisia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 10 | 20 | 20 | 21 | 21 | 21 | 30 | 54 |
| Lithuania | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 6 | 48 | 51 | 54 | 91 | 154 |
| Ukraine | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 46 | 57 | 72 | 77 | 86 | 89 | 90 | 90 | 87 |
| Nicarauga | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 40 |
| Luxembourg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 22 | 35 | 35 | 35 | 35 | 35 | 35 | 42 |

Table D-4 Historical RoW Wind Capacity, part 2 (megawatts, MW).

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Argentina | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 26 | 26 | 27 | 28 | 30 | 30 | 29 | 54 |
| Phillipines | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 25 | 25 | 25 | 25 | 33 | 33 |
| Jamaica | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 21 | 21 | 21 | 21 | 30 | 30 |
| Latvia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | 26 | 27 | 27 | 27 | 27 | 27 | 28 | 31 |
| Croatia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 6 | 17 | 17 | 18 | 28 | 89 |
| South Africa | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 16 | 17 | 17 | 17 | 17 | 22 | 8 | 10 |
| Guadeloupe | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 21 | 21 | 21 | 21 | 21 | 21 |
| Uruguay | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.6 | 21 | 21 | 31 |
| Colombia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Switzerland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 9 | 12 | 12 | 12 | 14 | 18 | 42 |
| Russia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 11 | 11 | 14 | 16 | 13 | 9 | 9 | 9 |
| Guyana | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 14 | 14 | 14 | 13 | 14 | 14 |
| Vietnam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 31 |
| Cuba | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 2 | 7 | 7 | 12 |
| Israel | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 6 |
| Slovakia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 5 | 5 | 5 | 5 | 3 | 3 | 3 |
| Pakistan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 6 | 6 |
| Faroe Islands | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.15 | 4 | 4 | 4 | 4 | 4 | 4 |
| Cape Verde | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.78 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| Ecuador | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.1 | 4 | 2.5 | 2.5 |
| Mongolia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.4 | 1.3 | 1.3 |
| Nigeria | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| Belarus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.9 | 1.9 |
| Antarctica | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 1.6 | 1.6 |
| Jordan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| Indonesia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.8 | 0.8 | 1.0 | 1.2 | 1.4 | 1.4 |
| Martinique | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Falkland Islands | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Eritrea | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Peru | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Kazakhstan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Namibia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.5 | 0.5 | 0.5 | 0.2 |
| Syria | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 |
| Dominican Republic | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.2 |
| North Korea | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.2 |
| Algeria | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| Bolivia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Malta | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Slovenia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Former Rep. of Macedonia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Iceland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Liechtenstein | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cyprus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 82 |
| **Total Capacity (MW)** | 1,889 | 2,278 | 2,407 | 2,596 | 3,100 | 4,155 | 5,873 | 7,278 | 9,006 | 12,759 | 16,691 | 23,469 | 31,206 | 39,282 | 47,514 | 59,060 | 74,093 | 93,968 | 120,872 | 159,375 | 196,775 |
| **New Capacity (MW)** | | 389 | 129 | 189 | 504 | 1,055 | 1,718 | 1,405 | 1,728 | 3,753 | 3,932 | 6,777 | 7,737 | 8,076 | 8,233 | 11,546 | 15,033 | 19,875 | 26,904 | 38,503 | 37,400 |

Source: (Global Wind Energy Council 2011), (Wilkes and Moccia 2011)

Table D-5 Historical U.S. Hybrid Vehicle Sales (1999 to 2010).

| Hybrid Electric Vehicle (HEV) Sales by Model | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vehicle** | **1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **Total** |
| Honda Insight | 17 | 3,788 | 4,726 | 2,216 | 1200 | 583 | 666 | 722 | 0 | 0 | 20,572 | 20,962 | 55,452 |
| Toyota Prius | | 5,562 | 15,556 | 20,119 | 24,600 | 53,991 | 107,897 | 106,971 | 181,221 | 158,574 | 139,682 | 140,928 | 955,101 |
| Honda Civic | | | | 13,700 | 21,800 | 25,571 | 25,864 | 31,251 | 32,575 | 31,297 | 15,119 | 7,336 | 204,513 |
| Ford Escape | | | | | | 2,993 | 18,797 | 20,149 | 21,386 | 17,173 | 14,787 | 11,182 | 106,467 |
| Honda Accord | | | | | | 1,061 | 16,826 | 5,598 | 3,405 | 196 | - | - | 27,086 |
| Lexus RX400h | | | | | | | 20,674 | 20,161 | 17,291 | 15,200 | 14,464 | 15,119 | 102,909 |
| Toyota Highlander | | | | | | | 17,989 | 31,485 | 22,052 | 19,441 | 11,086 | 7,456 | 109,509 |
| Mercury Mariner | | | | | | | 998 | 3,174 | 3,722 | 2,329 | 1,693 | 890 | 12,806 |
| Lexus GS 450h | | | | | | | | 1,784 | 1,645 | 678 | 469 | 305 | 4,881 |
| Toyota Camry | | | | | | | | 31,341 | 54,477 | 46,272 | 22,887 | 14,587 | 169,564 |
| Nissan Altima | | | | | | | | | 8,388 | 8,819 | 9,357 | 6,710 | 33,274 |
| Saturn Vue | | | | | | | | | 4,403 | 2,920 | 2,656 | 50 | 10,029 |
| Lexus LS600hL | | | | | | | | | 937 | 907 | 258 | 129 | 2,231 |
| Saturn Aura | | | | | | | | | 772 | 285 | 527 | 54 | 1,638 |
| Chevy Tahoe | | | | | | | | | | 3,745 | 3,300 | 1,426 | 8,471 |
| GMC Yukon | | | | | | | | | | 1,610 | 1,933 | 1,221 | 4,764 |
| Chevy Malibu | | | | | | | | | | 2,093 | 4,162 | 405 | 6,660 |
| Cadillac Escalade | | | | | | | | | | 801 | 1,958 | 1,210 | 3,969 |
| Chrysler Aspen | | | | | | | | | | 46 | 33 | 0 | 79 |
| Dodge Durango | | | | | | | | | | | 9 | 0 | 9 |
| Ford Fusion | | | | | | | | | | | 15,554 | 20,816 | 36,370 |
| Mercury Milan | | | | | | | | | | | 1,468 | 1,416 | 2,884 |
| Lexus HS 250h | | | | | | | | | | | 6,699 | 10,663 | 17,362 |
| Sierra/Silverado | | | | | | | | | | | 1,598 | 2,393 | 3,991 |
| BMW ActiveHybrid 7 | | | | | | | | | | | | 102 | 102 |
| BMW X6 | | | | | | | | | | | | 205 | 205 |
| Ford Lincoln MKZ | | | | | | | | | | | | 1,192 | 1,192 |
| Honda CR-Z | | | | | | | | | | | | 5,249 | 5,249 |
| Mazda Tribute | | | | | | | | | | | | 570 | 570 |
| Mercedes ML450 | | | | | | | | | | | | 627 | 627 |
| Mercedes S400 | | | | | | | | | | | | 801 | 801 |
| Porsche Cayenne | | | | | | | | | | | | 206 | 206 |
| Total | 17 | 9,350 | 20,282 | 36,035 | 47,600 | 84,199 | 209,711 | 252,636 | 352,274 | 312,386 | 290,271 | 274,210 | 1,888,971 |

Source: (U.S. Department of Energy, “U.S. HEV Sales” 2011)