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# An introduction to the economics of rare earths

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# An Introduction to the Economics of Rare Earths*

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**Abstract**

The aim of this paper is to examine the supply risk of rare earths and its impact on low carbon technologies deployment. Bringing together seemingly disconnected strands of scientific literature, this multidisciplinary approach allows to provide an overarching overview of the economics of rare earths. In terms of supply risk, as opposed to the common belief, it is not China's dominant position per se, but its industrial policies which distort the rare earths market. On the demand side, the results of this paper disprove the widespread allegation that availability risk impedes deployment of offshore wind. Contrary to this, a potential supply shortage of rare earths would disrupt the further development of the automotive industry and its electrification. Ultimately, uncertainty about volatile prices and threat of supply shortages induce manufacturers to shift away from technologies containing rare earths, and thus render innovation in these economically non-viable.

**JEL classification:** L11, L72, O31, Q31, Q34, Q37, Q42, Q53
**Keywords:** rare earths, supply risk, wind turbines, advanced technology vehicles, innovation, social costs

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# 1 Introduction

Within the past couple of years, growing concerns over massively skewed world production and supply of rare earths have emerged in the specific context of clean energy technologies. This paper analyses the extent to which the risk of supply disruption constitutes a threat to the deployment of these technologies and how it induces their innovation.

Rare earths constitute a group of 17 chemical elements. As opposed to what the name suggests, they are neither rare nor earths. In fact, they are fairly abundant metals, though it is rather unusual to find them in large enough concentrations to make their mining and processing economically viable and environmentally friendly. According to Humphries (2010), almost 97% of global rare earths supplies and 50% of world reserves are owned by China. In line with this, it is often claimed that their geographical concentration poses a potential threat for their future supply. The latter is further exacerbated by China's active industrial policies in form of export quotas, strategic pricing, as well as ongoing consolidation of the industry. As a response to these fears, projects outside China have been recently taking off: resumption of operations by Molycorp in the US, establishment of Lynas in Australia, as well as refurbishment of a previously producing mine by Great Western Minerals Group in South Africa, just to mention the major ones. However, due to the lengthy period required for their development, substantial financial burden and lack of capabilities in terms of technically trained personnel it becomes clear that these production sites are in no shape to become significant competitors to China any time soon.

For what concerns the demand side, the growing deployment of low carbon technologies is expected to remain its main driver. In fact, increasing power generation capacity, along with decarbonising transport, are laid down by international institutions such as the Kyoto Protocol and the European Strategic Energy Technology Plan (SET-Plan). Moreover, UNCTAD encourages deployment of these technologies, claiming that they help eradicating energy poverty and contribute to the industrialisation effort by developing countries (Sampath et al., 2011). Further to this, estimates confirm that demand for dysprosium and neodymium, known for their exceptional magnetic properties which make them suitable for the lightweight motors and batteries used in low carbon technologies, is to increase by more than 2600% and 700% respectively, over the coming 25 years (Alonso et al., 2012a). Consequently, shortages of some of the rare earths are projected to occur already in 2015 (Bourzac, 2011).

On balance, low carbon technologies are intended to tackle climatic changes but their deployment seems to be adversely affected by resource scarcity. The question arises then, to what extent do potential supply shortages of rare earths pose barriers to low carbon technologies deployment. A lot of specialised literature exists on different aspects of rare earths, ranging from geology, chemistry and materials science to engineering and life cycle analysis. However, there seems to be a lack of comprehensive analysis in economic literature. Thus, the aim of the present paper is to bring these seemingly disconnected strands of literature together, in order to provide an overarching overview of the rare earths economics and to shed clarity on the far reaching consequences of demand-supply imbalances on innovation of low carbon technologies.

The multidisciplinary approach allows to provide a thorough overview of market forces in place, investigating the impact of China's industrial policies on the rare earths market on the one hand, and the key trends in offshore wind turbines and advanced technology vehicles, as the main drivers of increased demand for rare earths on the other. Following from this, conclusions can be drawn on price and sourcing volatilities inducing manufacturers to innovate or substitute across technologies. For this purpose, specialised literature from across various fields of rare earths is analysed. Data on production, supply and industrial uses is collected in order to determine the existence of supply risk. Subsequently, a database is created for offshore wind turbines and advanced technology vehicles, collecting information on current technology designs, capacities and global shares. Based on the information on rare earths intensity of respective topologies, the cumulative shares in rare earths consumption are determined. Finally, costs of rare earths within these technologies are estimated.

In order to be able to carry out this analysis, it is important to first understand the individual rare earth elements and their respective chemical properties and physical attributes. These, along with the multitude of their uses are reviewed in Section 2. Section 3 analyses forces on the supply side of the rare earths market in terms of both geopolitical and quantity risks. Here, also downstream responses to the threat of supply disruption are discussed, while upstream initiatives such as recycling, stockpiling, and materials and technology substitution are reviewed in Section 5. Section 4 discusses the role of rare earths in offshore wind turbines and advanced technology vehicles. Demand and supply are brought together in Section 6, where price trends and their impact on technologies' producers are considered. After a brief overview of social costs incurred by mining and processing of rare earths in Section 7, the paper concludes with Section 8.

## 2 Rare Earths

As per the definition of the International Union of Pure and Applied Chemistry (IUPAC), rare earth elements are lanthanoids with atomic numbers 57 to 71, as well as yttrium and scandium which exhibit sufficiently similar properties to be included in this group of transition metals distinguished by their special electron configurations (Connelly, 2005). Classified according to their ionic radii, rare earths constitute two subgroups: light (LREE) and heavy rare earths (HREE), with scandium not belonging to any of these two (see Table 1). An additional group of the medium rare earths (MREE) has emerged recently to denote samarium, europium and gadolinium (Hatch, 2011c). Other classifications may be considered based on physical, chemical, technological and geochemical attributes, as well as on industrial demand and prices of individual elements.

## 2.1 From Discovery to Processing

The history of rare earths dates back to 1787, when ytterbite ore was accidentally discovered by Lieutenant C. A. Arrhenius at Ytterby, Sweden. However, due to the chemical similarity of rare earths, it took another 7 years until J. Gadolin successfully isolated a previously undescribed "earth" from the ore. In the coming years, number of mineralogists, geochemists and crystallographers worked on the separation of metallic oxides present in yttria and ceria, both regarded originally as pure oxides. It was not until more than a century later that progress in fractional separation, publication of periodic law of chemical elements and experimental work on relationship of x-ray spectra to atomic numbers, allowed to establish the final number of "newly discovered elements" with the complex mixture of oxides (Gschneidner and Capellen, 1987; Moeller, 1963; Weeks, 1956). The latter were decomposed into simple oxides of the following rare earths metals: yttria was broken down into yttrium, terbium, erbium, ytterbium, lutetium, holmium, thulium and dysprosium; while ceria was decomposed into cerium, lanthanum, neodymium, praseodymium, samarium, gadolinium, europium and promethium.

The multitude of investigators, who often managed to isolate same elements independently from each other, resulted in a confusion of names throughout the history. The final version of universally accepted names were mostly derived from Greek - so is for example the meaning of dysprosium "the difficult to access" - while some others were given in honour of scientists who investigated upon them - gadolinium named after Gadolin - or by geographical location - lutetium for the ancient name of Paris, the birthplace of one of the investigators - as well as inspired by astronomy - cerium after planetoid Ceres - and mythology - prometheum (whose spelling was later amended to promethium), from Prometheus - (Gschneidner and Capellen, 1987; Moeller, 1963; Weeks, 1956). The name of the group of elements instead, is considered a historical misnomer which arose from rare earths having been first obtained in form of oxides (a modern term for earths) from seemingly rare minerals. Some of the alternative names for this transition group are: lanthanides (derived from lanthanum - the first rare earth element in series), lanthanide elements, lanthanons, or f-type transition elements to denote their ground-state electronic configurations of atoms. It is precisely their electronic configurations, large atomic radii and their position within the periodic table what ranks them among metals rather than earths (Moeller, 1963).

In terms of their rarities, individual elements are found in Earth's crust in different quantities. According to the Oddo-Harkins effect, even-numbered elements are more abundant than the adjacent odd-numbered elements, resulting from the formers' lower neutron-capture cross sections preventing them to take up an additional neutron and thus be transformed to a higher element (Cornell, 1993). So is cerium and lanthanum constituting the bulk, while lutetium on the other end of the series has low concentrations within the group. Furthermore, lighter elements prove to be more abundant than heavier ones, as a consequence of their different synthesis by atomic fusions in the cores of stars, with heavy elements being made under higher temperatures and pressures in supernovae only (Cotton, 2007). Table 1 collects figures from various studies on rare earths elements' continental crust abundance in percentage of parts per million in mass (ppm). Note that these differ in absolute terms in function of the method of estimation used and assumptions made about the genesis of the lower crust. Nevertheless, the order of magnitude is roughly identical across estimations, confirming that rare earths in the upper part of the table are more abundant, and that those with odd atomic numbers are less common than those with even atomic numbers. Moreover, based on crustal abundance data for most common chemical elements by Moeller (1963); Taylor (1964); Wedepohl (1995), rare earths prove to be not less abundant than other common elements. In fact, cerium - the most abundant rare earth - is in the same range as nickel and zinc and more common than copper. At the same time the least abundant lutetium and thulium are more than 100 times more abundant than gold.

While conclusion can be drawn on the relative abundance of rare earths when compared to other industrial metals, one needs to keep in mind that rare earths are rarely concentrated in minable deposits. They are obtained from lanthanide minerals in form of oxides (REO), which contain a mixture of all rare earths elements (with the exception of promethium). Principal sources of the cerium group are bastnäsite, monazite and cerianite, while the yttrium group is most commonly retrieved from euxenite, xenotime and gadolinite (Cotton, 2007; Moeller, 1963). Despite them being contained in as many as 200 minerals (Walters and Lusty, 2011), not all of them can be commercially processed due to cost, geographical location as well as the nature of minerals themselves (Moeller, 1963). A selection of those that do, along with their REO content, is reported by Castor and Hedrick (2006). Similarly, an overview of primary and secondary deposits and their capacities can be found in Walters and Lusty (2011); Castor and Hedrick (2006); Long et al. (2010). It is important to note how the significance of these minerals has changed over time for rare earths mining. Monazite which occurs in granitic rocks, used to be the most important source of LREE until it has been lately shifted away from due to its content of radioactive thorium (Cornell, 1993) (USGS, 2013). The same holds for xenotime in placer accumulations of Australia and Malaysia. Contrary to this, bastnäsite mined from carbonatite deposits contains negligible amount of thorium and is currently the most important deposit of rare earths on western hemisphere - in Mountain Pass, California. At the same time Chinese ionic clays, namely the iron deposits of Bayan Obo,

**Table 1:** Abundance of Rare Earths in Continental Crust, ppm (10'000 ppm = 1%)

| Z* | Element | Symbol | (1) | (2) | (3) | (4) |
|---|---|---|---|---|---|---|
| | | **LREE - The Cerium Group** | | | | |
| 57 | Lanthanum | La | 30 | 29 | 30 | 35 |
| 58 | Cerium | Ce | 60 | 70 | 60 | 66 |
| 59 | Praseodymium | Pr | 8.2 | 9.0 | 6.7 | 9.1 |
| 60 | Neodymium | Nd | 28 | 37 | 27 | 40 |
| 61 | Promethium† | Pm | - | - | NA | 0.0 |
| 62 | Samarium | Sm | 6.0 | 8.0 | 5.3 | 7.0 |
| 63 | Europium | Eu | 1.2 | 1.3 | 1.3 | 2.1 |
| 64 | Gadolinium | Gd | 5.4 | 8.0 | 4.0 | 6.1 |
| | | **HREE - The Yttrium Group** | | | | |
| 39 | Yttrium | Y | 33 | 29 | 24 | 31 |
| 65 | Terbium | Tb | 0.9 | 2.5 | 0.65 | 1.2 |
| 66 | Dysprosium | Dy | 3.0 | 5.0 | 3.8 | 4.5 |
| 67 | Holmium | Ho | 1.2 | 1.7 | 0.8 | 1.3 |
| 68 | Erbium | Er | 2.8 | 3.3 | 2.1 | 3.5 |
| 70 | Ytterbium | Yb | 3.0 | 0.33 | 2.0 | 3.1 |
| 69 | Thulium | Tm | 0.48 | 0.27 | 0.3 | 0.5 |
| 71 | Lutetium | Lu | 0.50 | 0.8 | 0.35 | 0.8 |
| 21 | Scandium | Sc | 22 | NA | 16 | NA |

*Atomic number; †Promethium has no stable isotopes and is not found in nature.
*Source:* Data complied from (1) Taylor (1964), (2) Jackson and Christiansen (1993), (3) Wedepohl (1995), (4) Cotton (2007).

have become the largest source of rare earths in the world. Only a few of the mines are operated for the recovery of rare earths themselves, the latter being mostly retrieved as by-products or joint-products of iron ore (China), titanium (Russia), uranium (Canada), zirconium and niobium (some mines in Australia), or thorium (Brazil) (Walters and Lusty, 2011). This implies that their mining decisions are driven primarily by the demand for principal products, rather than by the actual demand for rare earths.

As a consequence of the diversity of rare earths deposits, both extraction techniques and physical and chemical processing techniques depend on the mineralogy and chemical composition of deposits. The extraction techniques vary from more economic and currently most practised surface mining, through underground mining, to in-situ mining suitable for near-surface deposit of softer ion absorption clays. The complexity of processing methods also influences the competitive advantage of deposits, processing of ion absorption clays being more cost efficient than that of hard-rock deposits, for example. Similarly, HREE are often more complex to process than minerals containing LREE. In general, techniques for processing multiple mineral phases prove to be more complex and costly to carry out than for many industrial metals concentrated in a single mineral phase. An outline of these can be found in Walters and Lusty (2011);

Castor and Hedrick (2006); Cotton (2007); Moeller (1963); Long et al. (2010). The result are high purity compounds, with different purities used for different applications, ranging from mischmetal in alloy metallurgy to rare earth metals with purities of up to 99.9999% required in magnetic applications (Cotton, 2007; Walters and Lusty, 2011).

## 2.2 Their Industrial Use

The commercial production of rare earths' compounds started after the WWII, with the availability of improved separation techniques, such as ion-exchange, partition and liquid-liquid extraction (Gschneidner and Capellen, 1987). This turned the former minor metals into metals of large industrial uses. Rare earths have been sold in various forms, from mineral concentrates, mixed chemicals, oxides and metals, to magnets, phosphors and powders, in line with the developments in their end uses overtime (Walters and Lusty, 2011). According to the estimates reported by Henderson (1984), in 1980 more than one third of the production by volume was used in form of mischmetal in metallurgic applications. Catalytic applications for fluid cracking catalysts (FCCs) in petroleum refining and in polyesterification processes constituted another third. By 2010 these have significantly lost on importance by dropping to 18% and 20% by volume, respectively (Kingsnorth, 2011). The usage for glass-polishing compositions and as colouring agents in ceramics remained altogether very similar over time. The recent use of rare earth phosphors seems to be linked to the discovery of their luminescence property, which further allowed for commercialisation in medical applications (laser, X-ray, MRIs), as well as in electronics (cathode ray tube television, energy-efficient fluorescent lamps). Being used in all kind of visual display devices these days, phosphors account for more than 30% of consumption by value according to Kingsnorth (2009). Furthermore, with perfectioning of hydrometallurgical processes for extraction of raw materials and improved methods for purification of rare earths, increased purities of elements allowed for their wide application in high-tech products, cell phones, hard disk drives (HDD), microphones and digital music players. In terms of their volume, both phosphors and high-techs continue constituting only a negligible part of the market, though their relative value is high. For illustration, merely a small fraction of a gram is sufficient to guarantee quality sound, high resolution coloured screen or vibration function in a smartphone, as compared to several hundred kilograms required for MRIs (Molycorp, 2010; Tasman, 2010). Other uses of rare earths are in defence applications, such as radars and sonars, as well as in nuclear energy applications and fertilisers.

Last but not least, despite the fact that the most important physical properties of rare earths - ferromagnetism and superconductivity - were discovered already in the 1930s, it was only several decades later that samarium and neodymium based permanent magnets started to replace conventional aluminium-nickel-cobalt (Al-

NiCo) magnets. According to Kingsnorth (2009), these constitute nowadays more than 20% of rare earths by volume and almost 40% by value. Main applications of rare earth magnets are in clean-energy technologies such as electric vehicles and direct drive wind turbines. Similarly, in today's age of miniaturisation of high-tech sector, their superior coercivity and higher energy products are essential to keep up effectiveness and efficiency of devices while continuously shrinking their size and weight.

An overview of an unusually wide range of consumer products making use of rare earths is provided in Table 2, along with the breakdown of particular elements employed. It becomes obvious that despite their similar chemical properties, rare earth are applied in different combinations, forms and purities within different technologies. The most extensively used ones are those with lower atomic numbers. Some of the HREE such as dysprosium, terbium, yttrium are used in smaller quantities to enhance the properties of the LREE, such as coercivity and magnetic flux. Holmium, erbium, thulium, ytterbium, lutetium and scandium instead, can be considered as minor metals, the lack of their uses in mass production being conditioned by the their relative scarcity (Technology Metals Research, 2010).

Rare earths play a key role in enabling digital technology, improving energy efficiency, enhancing environmental protection as well as are indispensable for health and medical technologies. In all these fields, a growing demand is expected to occur driven by economic growth from emerging economies on the one hand, and from new technologies under development on the other. Linking the market demand of individual elements from all these technologies back to the proportions in which they can be found in deposits, to the accessibility of their geological locations and to the complexity of their processing, two things become obvious: first, the demand for the rare earths is not uniform. This implies higher prices for less abundant oxides contained in minerals the processing of which is more complex. This is further exacerbated by the fact that rare earths are often mined as by-product and their production rates depend on the production rates of base metals. Second, in order to keep up the supply of the most commercialised rare earths, such as dysprosium and neodymium, an oversupply of some less utilised oxides such as samarium and yttrium which are contained in ores will necessarily occur.

**Table 2:** Main Rare Earth Applications.

| Field | Technology | Rare Earths Application | La | Ce | Pr | Nd | Sm | Eu | Gd | Y | Tb | Dy | Er |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy Efficiency | Lighting | Phosphors in Compact Fluorescent Light bulbs (CFLs) | (x) | (x) | (x) | | | x | (x) | x | | (x) | |
| Clean Water | Water Purification | Cerium Chloride for Waste water, Recreational Water | | x | | | | | | | | | |
| Healthcare | Magnetic Resonance Imaging (MRI) | Magnets and Contrasting Agents in MRI Scans | | | x | x | | | x | | (x) | (x) | |
| Transportation | Hybrid and Electric Vehicles | Nickel Metal Hydride (NiMH) battery | x | (x) | (x) | (x) | | | | | | | |
| | | Magnets in Electric Motors | | | x | x | | | | | (x) | (x) | |
| | | Hybrid Vehicles Braking | | | x | x | | | | | (x) | (x) | |
| | Others | Auto Catalysts | (x) | x | | (x) | | | | | | | |
| | | Polish for Glass, Mirrors and UV Cut Glass | | x | | x | | | | | | | |
| | | Magnets Used in Small Motors to Power Windows, Seats, Sunroofs ...etc. | | | x | x | | | | | (x) | (x) | |
| | | Component Sensors | | | | | | | | x | | | |
| | | Phosphors in LCD Screens | | | | | | x | | x | x | | |
| Clean Energy | Wind Turbines | Permanent Magnet Generators | | | x | x | | | | | (x) | (x) | |
| National Defence | Satellite Systems, Small Motors | Magnets and Phosphors to Aid Satellite Positioning, Communication Transmission and Reception, Small Motors for Guided Missiles | | | x | x | x | x | | x | (x) | (x) | |
| | LCD screens for Computers, Night Vision Goggles, and Laser Technology | Phosphors | | | | | | x | | x | x | | |
| Oil Industry | Fluid Cracking Catalysts (FCC) | Stabilisator of Structure and Chemistry of Zeolites Used as a Molecular Filter | x | (x) | (x) | (x) | | | | | | | |
| Mobile Devices | Laptops, Tablets, Mobile Phones, iPods | Magnets in Speakers (within Earphones/Headphones) | | | x | x | | | | | (x) | (x) | |
| | | Magnets in Vibration Function | | | x | x | | | | | (x) | (x) | |
| | | Phosphor Coating for Cathode Ray Tubes (CRT), Plasma (PDP) and Computer Monitors | (x) | (x) | (x) | | | x | (x) | x | x | (x) | |
| | | Polishing Powders for Cathode Ray Tubes (CRT), Plasma (PDP) and Liquid Crystal Display (LCD) Glass | x | x | x | | | | | | | | |
| Computing | Computer Hard Disk Drives (HDD), CD-ROMs and DVDs | Magnets | | | x | x | | | | | (x) | (x) | |
| | | High Strength Glass Substrates | x | x | | (x) | | (x) | (x) | (x) | | | |
| Other Advanced Communication Technologies | Fibre Optics Cables | Doping Agents | | | | | | x | | x | x | | x |

Note: x = main rare earths, (x) = may be added in smaller quantities
*Source:* Information compiled from Lynas, 2010; Molycorp, 2010; Tasman, 2010.

## 2.3 The Criticality of "Not So Rare" Metals

The multitude of their uses in green technologies, consumer goods and military applications ranks rare earths among strategically important raw materials. The terms strategic and critical are often used interchangeably for raw materials, however it is advisable to distinguish between them: strategic denoting military uses while critical meaning availability risk to national economy stemming from international supply. According to the Strategic and Critical Materials Stockpiling Revision Act of 1979, strategic and critical materials are those which a) "would be needed to supply the military, industrial, and essential civilian needs [of the United States] during a national emergency, and b) are not found or produced [in the United States] in sufficient quantities to meet such need" (United States Public Laws, 1979). The first part of this definition points to the dependence on raw materials of growing economic importance. The second part is about the availability risk. According to the material science literature, the two main mechanisms behind material availability risk are physical constraint and institutional inefficiency. The former is a well researched concept which concerns physical scarcity from long term perspective. It has been derived from Malthusian and Ricardian considerations of physical constraints on resource availability in terms of physical exhaustion and of quality of supply (Alonso et al., 2007). The concept of institutional inefficiency instead, has not been given enough emphasis within resource and environmental economics due to its short-term nature. It arises from local trigger by markets', firms' and governments' failures, which may cause supply disruptions globally and result in permanent changes to the supply chain or to materials used therein (Alonso et al., 2007). Authors consider concentration within supply chain as the most important measure of institutional inefficiency, in terms of both geographic structure of supply and production and of institutional structure based on production and consumption.

For what concerns the particular case of rare earths, based on the preceding discussion on abundance, as well as taking into consideration that the static depletion index for REO based on reserves is 1219 years (as compared to 38 years for copper)[1], physical constraint does not seem to be an issue. From an institutional inefficiency viewpoint, looking at the geographical distribution one cannot speak of concentration of rare earths reserves either (see Figure 3). Nevertheless, not all exploitable deposits are currently economically viable, located in reliable geopolitical jurisdictions with sound processing in place (Berry, 2013). The more pressing issue proves to be the geographic and institutional structure of production, in terms of concentration of primary production and of control. The fact that China is the single major producer of rare earths (see Figure 4) exercising control over the global market, might lead to a serious global supply disruption should a political disturbance occur on the local level.

[1]Own calculations based on 2013 estimates published by U.S. Department of Interior - U.S. Geological Survey (2014).

The high threat of supply risk of rare earths has now been confirmed by the EU Raw Materials Initiative (EC, 2010) which ranked rare earths as a group highest in terms of supply risk and environmental country risk, due to concentration of supply in China and the EU's 100% dependence on imports. Similarly, Bauer et al. (2010, 2011) on behalf of the U.S. Department of Energy conclude on short and medium term criticality of 5 rare earths - dysprosium, terbium, europium, neodymium and yttrium - based on their importance to clean energy and supply risk. Furthermore, a study by Moss et al. (2011) within the framework of EU's Strategic Energy Technology Plan (Set-Plan) confirms the high risk position of dysprosium and neodymium both in terms expected demand growth from green technologies and in terms of short term limitations to expanding the supply. These are further exacerbated by high concentration of production and political risk of the supplier country. Finally, the Japanese Scheme for Critical Raw Materials acknowledges the tight supply of rare metals caused by both rapid increase in their consumption as well as by supplier countries' export policies. However, in addition to the political risk and concentration, the report envisages long term physical constraint in terms of depletion of land-based resources of dysprosium in the coming decades (Kawamoto, 2008).

To conclude with, based on both theory and results of studies, rare earths are considered highly vulnerable to institutional inefficiencies. The threat of supply risk arises from the political risk and concentration of supply. In line with this, the next section analyses supply risk of rare earths offering a geopolitical perspective and discusses the Chinese hegemony in terms of quantity risk in depth.

# 3 Supply Risk

The major cause of global supply chain disruptions besides natural catastrophes and factory disasters is the geopolitical risk when sourcing raw materials from remote regions characterised by lack of political stability (Advisen Ltd, 2013). The latter includes events such as labour disputes (e.g. case of platinum (Chong, 2013)), civil wars and political upheavals (e.g. Zaire in 1978 (Alonso et al., 2007)) international terrorism (e.g. government's response to 9/11 (Sheffi, 2001)), as well as other dynamics impacting the long term stability of the region. What these events have in common is the local character with global ramifications on the entire supply chain. The 1977 - 1979 "cobalt crunch" is an example of a local event which permanently changed materials, technologies, and sourcing routes within the global cobalt supply chain. Cobalt being a primary input to aerospace and defence industries was considered strategic to the US - its major importer. Political unrest in Zaire (now Democratic Republic of Congo), coupled with tight cobalt supplies and increased demand from industrial economies resulted in a temporary disruption of cobalt supply and a price increase by 330%. These developments triggered both upstream and downstream responses across the supply chain, such as extending production capacities to Zambia, recycling and substitution (Alonso et al., 2007; Shedd, 1999). For example, in samarium-cobalt (SmCo) permanent magnets for electrical equipment, cobalt was substituted by cobalt-free permanent magnets based on neodymium and iron compound which were developed in 1983.[2] On the one hand, this substitution resulted in a superior magnet technology and reduction of vulnerability to volatile cobalt prices and to resource dependence on Zaire (Gschneidner and Capellen, 1987). On the other hand though, it indirectly shifted the world dependence from politically unstable Zaire to communist China. In fact, neodymium-iron-boron (NdFeB) magnets deployment has been driving the demand for some of the rare earths, the majority supplier of which is China.

### 3.1 Geopolitical Security and Resource Dependence

Besides the present increased demand of rare earths being an indirect consequence of the cobalt supply chain disruption back in the 1970s, there are several parallels between the two minerals: both are to a large extent by-products, what makes their supply be largely inelastic; the production of cobalt then and of rare earths now is heavily concentrated with 2/3 of world cobalt production originating from the Copper Belt, while more than 95% of rare earths in 2010 were mined in China; finally both are labelled as critical and strategic materials. In addition, similar to the cobalt prices set by producers and sales carried out under long term contracts before 1990s, also in the case of rare earths there have been no spot markets with independent traders until recently (Shedd, 1999). Bearing in mind the far reaching consequences of cobalt supply disruptions, it proves important to analyse the geopolitics of rare earths.

To start with China, its intention to use rare earths as a tool of foreign policy was implicitly revealed in 1992 when Deng Xiaoping, leader of the China, stated out: "There is oil in the Middle East; there is rare earth in China" (Hurst, 2010). The parallels are not only in respective reserves of raw materials, but also in how the two influence international relations through the control of these. Thinking back to the Arab Oil embargo in early 1970s, the oil crisis manifested itself by shortfall of automotive gasoline and dramatic increases in prices of gasoline and heating fuels. OPEC's control of oil was serving to achieve political and economic goals of oil producing Arab states by exercising pressure on industrialised oil importing countries. In a similar fashion, though to a lesser extent, China has used its control of rare earths exercising pressure on resource dependent countries. In early 2000s China tightened the supply of rare earths by introducing export quotas and setting limits to number of companies allowed to export (Ting and Seaman, 2013). Cutting back supply escalated with the 2010 maritime in-

[2]Note that these magnets still contain up to 5% of cobalt in order to improve the otherwise low Curie temperatures when compared to SmCo magnets (Cobalt Development Institute, 2006).

cident between China and Japan, when a Chinese fishing trawler collided with Japanese coast guard vessels in the waters which are since long object of territorial dispute between the two countries. Consequently, China used its position as a diplomatic leverage and imposed an "administrative halt" on rare earths exports to Japan (Bradsher, 2010a). Though there has been little doubt that this informal act by Chinese customs relates back to the detention of the Chinese captain by Japanese coast guards (Wong, 2010; Reilly, 2012), some claim that there is no clear evidence for or against the embargo (Johnston, 2013). Even if exports resumed within two months time from the incident, China's diplomatic assertiveness has significantly impacted both East Asian and international environment: while Japan's manufacturing is highly dependent on sourcing rare earths from China, the world is dependent on importing manufactures from Japan. The world's largest economies responded by financing new rare earths projects outside China, as well as R&D for improved extraction, resource efficient use, recycling and substitutes. The EU-US-JP Trilateral Critical Materials Initiative is an example of a joint initiative to reduce countries' resource dependence on China (DOE, 2011; EC, 2013; NEDO, 2012). As per Japan, it is now in process of exploring seabed deposits, which among other minerals also contain rare earth ores (Mori, 2013; Evans-Pritchard, 2013). This however is susceptible to trigger a vicious circle of geopolitical instability in the region. In fact, these mineral reserves are found in Japan's Exclusive Economic Zone (EEZ) - another disputed seabed the waters of which are of overlapping claims to both China and Japan (Kawamoto, 2008).

To summarize, considering the importance of rare earths in low carbon technologies as well as in defence appliances, a potential supply disruption threatens country's energy and national security. It is thus expected that rare earths turn into new elements of geopolitical power - a role previously conferred to oil. However, for the moment China's rare earth diplomacy has not exercised strong leverage on import-dependent countries to pursue its own strategic goals to the extent Arab countries has done during the energy crisis in 1970s. What is more, China has denied the use of rare earth as a bargaining tool (Huixia, 2010). Nonetheless, geopolitics is not to be underestimated in that it plays a significant role in determining supply and demand. Also, it is shaped by balance of power between mineral rich and mineral poor countries (de Ridder, 2013). It proves thus important to consider the mineral policies of exporting countries on the one hand and policy responses to concerns about supply disruptions in importing countries on the other. In this light, China's industrial policies are considered next, followed by the downstream responses by importing countries. The upstream strategies are described in Section 5.

### 3.2 Quantity Risk

From the above discussion it becomes obvious that concentration alone does not constitute an issue to rare earths supply risk. Rather, it is China's abuse of power over resources in terms of its protectionist policies. In fact, rare earths were declared as "protected and strategic materials" more than two decades ago (Tse, 2011) and China introduced rare earth industrial policy measures to hold them back for domestic purposes. Firstly, resource nationalism in China has seen foreign companies being banned from engaging in any part of the rare earths supply chain other than forming joint ventures with domestic companies (MOFCOM, 2012h). Secondly, both domestic and joint venture companies became subjected to production quotas (MLR, 2013) and export quotas (MOFCOM, 2012a). Consequently, the number of companies permitted to export was gradually decreasing from 41 in 2007 to 24 only in 2013.[3] Thirdly, increased state control on supply chain was achieved by merging several companies into one "megacompany" (MOFCOM, 2012d), by banning new rare earth mining licenses (MOFCOM, 2012e) and by eliminating smuggling (MOFCOM, 2012i). Fourthly, creation of joint pricing platform (MOFCOM, 2012b) and of national pricing system (MOFCOM, 2012f), accompanied by benevolent production halts (MOFCOM, 2012c) and decision to set up a stockpile (MOFCOM, 2012g), strengthen China's pricing power. Taken together, the protectionist policies demonstrate a clear alignment of China's natural resource policies with its national interests. However, this state interventionism paralysed the usual market forces - supply and demand - causing resource-dependent countries to lose influence over raw materials, what ultimately lead to increased geopolitical and economic risks. It is important to note that not all aspects of supply risk are relevant to all rare earths equally. The extent depends on the future demand, scarcity as well as complexity of their processing.

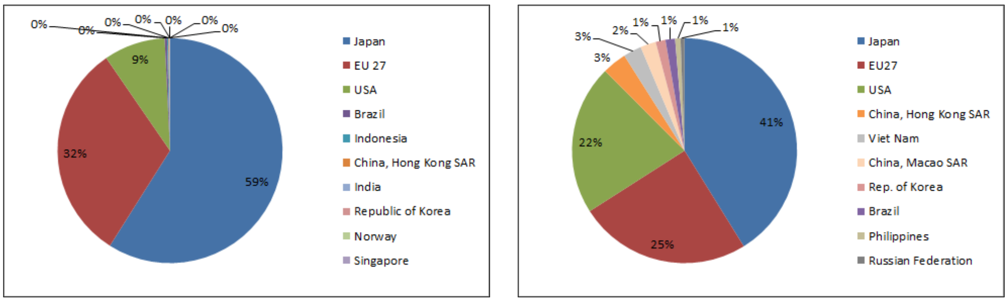
#### 3.2.1 Mined in China

Global import data of rare earths compounds and metals compiled from UN Statistics Division, 2013 sheds light into the severity of resource dependence of rare earths importing countries. In 2012, Japan was the largest importer with 13'829 tonnes, followed by the US with 10'161 tonnes. France and Estonia imported half as much - 5'520 tonnes and 5'044 tonnes, respectively - tightly followed by Germany with 4'814 tonnes and Malaysia with 4'332 tonnes of rare earth products. Not only are these countries import-dependent, they also tend to source majority of rare earths from China, as illustrated in Figure 1. While the three major importers - Japan, the EU and to some extent the US - have already been dependent on China back in 1992, by 2012 the relative proportions of Chinese exports to Japan and the EU decreased, while to the US they in-

[3] Considering parent companies.

creased substantially. Also, by 2012 additional countries started to source rare earths from China: Russia, Brazil and Australia which discontinued domestic production in the 1990s (see Figure 4), as well as South Korea and Hong Kong which started to manufacture rare earth-intensive technologies.

**Figure 1:** Comparison of Chinese Export Destinations: a) 1992 and b) 2012.



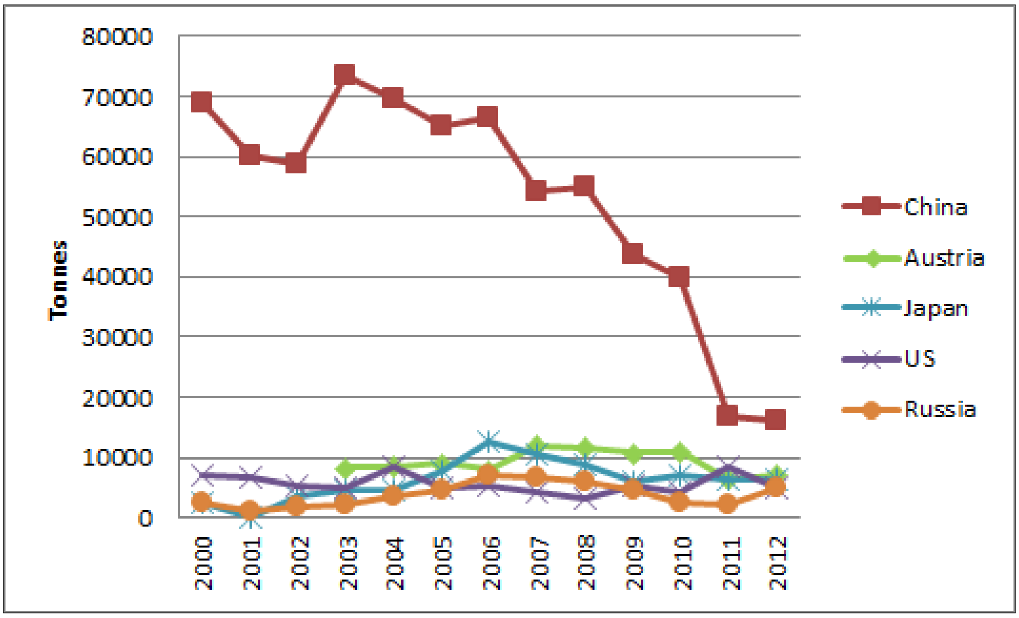

**(a)** 1992 **(b)** 2012

Note: Following Harmonized System codes were taken into consideration: HS280530, HS284610, HS284690. *Source:* Based on data collected from UN Comtrade Database (UN Statistics Division, 2013).

Overall, China exported 16'266 tonnes of rare earth products in 2012, 83% of these as compounds and the rest in form of metals. The other top five global rare earth exporters were Austria, Japan, Russia and the US. While the latter two were historically primary producers of rare earths, Austria and Japan import rare earths and process these further to produce metal alloys and chemical products for export. Figure 2 shows that since 2000 China has been by far the largest supplier of rare earths, though its exports have been decreasing gradually ever since 2003, from almost 10 times more than the second largest supplier in 2000 to below 2.5 times more in 2012.

In order to gain a long term perspective, it proves important to examine the availability of reserves worldwide. Considering the dynamic nature of reserves, Figure 3 shows a snapshot for years 1995 and 2013. China's percentage share of reserves remained constant overtime at approximately 40%. Note that estimates vary from 22% to 50% depending on the calculation method used (Humphries, 2010). Though China's reserves in absolute terms increased overtime by 28%, there was a drop of 37% when considering the sub-period of rapid exploitation in 1995-2002. Other substantial deposits can be found in Brazil (16%), the Commonwealth on Independent States (CIS) (14%) and the US (10%), with the global share of other countries below 5%. It follows from this, that while China possesses the largest single deposit of rare earths, there exist substantial deposits in other parts of the world too. However, the economic viability of reserves in terms of concentration of ore and ease of processing is not to be neglected. The surficial clay deposits of Jiangxi (China) are much less complex to mine and process than the bulk ore from Strange Lake (Canada) or Xenotime in Lahat (Malaysia) (Long et al., 2010). Another concern is the decreasing quality of

**Figure 2:** World Rare Earth Export, by Country, 2000-2012.

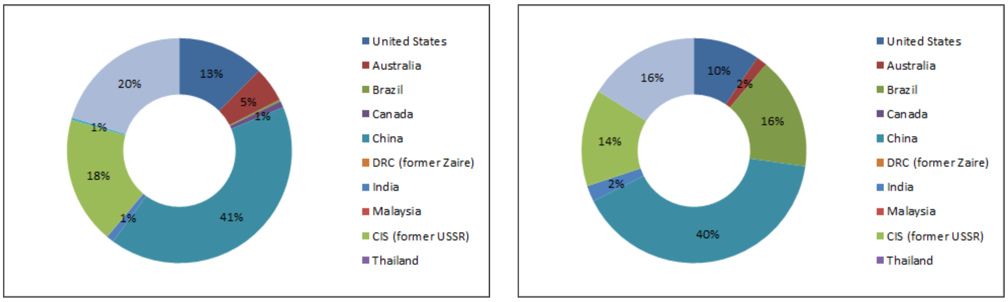



Note: Following Harmonized System codes were taken into consideration: HS280530, HS284610, HS284690. *Source:* Based on data collected from UN Comtrade Database (UN Statistics Division, 2013).

mined ores which requires more costly and energy intensive extraction (Cho, 2012). Also, there are long lead times for new mines development and higher environmental standards in Western countries which require more sustainable mining and processing techniques. Finally, considering the relative distribution of scarcer HREE-rich minerals, 80% of world's deposits are contained in Chinese ion adsorption clays of South-east Guangdong and Jiangxi Provinces (USGS, 2013) (Walters and Lusty, 2011). Instead, LREE can be retrieved in substantial concentrations from Mountain Pass (the US), Mount Weld (Australia), besides the Bayan Obo (China) deposit which is the largest of its kind in the world. All these taken together, guarantee China to remain the rare earth's super power beyond the medium term.

In terms of global production trends, various producer countries were leading the rare earths market historically: while in the first half of the 20th century the market was dominated by REO mined from Brazilian, Indian and South African monazite bearing placers, in the second half of the century production shifted to Mountain Pass bastnäsite deposits in the US. China entered the market in late 1970s and after a transition period in mid-1980s it became market leader thanks to cheap labour force, less stringent environmental regulation, but also well trained technical staff in processing and engineering. Lower prices of Chinese REO resulted in squeezing the US and most of other producing countries out of the market by early 2000s (USGS, 2013) (Haxel et al., 2002). Figure 4 illustrates China's hegemony in global production of rare earths over the past 20 years.

**Figure 3:** Comparison of World Rare Earth Reserves, by Country: a) 1996 and b) 2013.



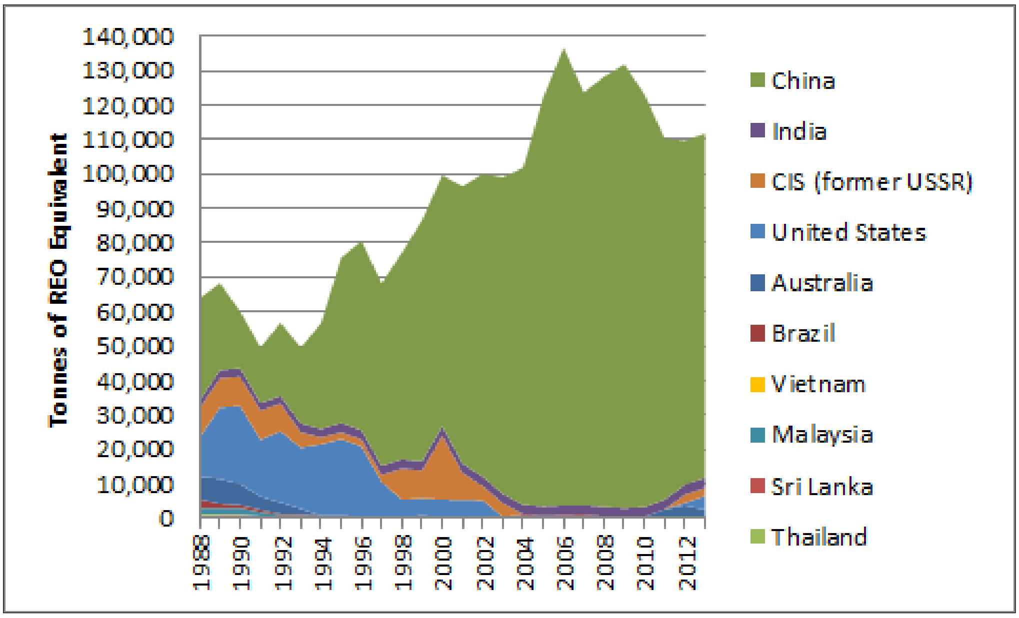

**(a)** 1995 **(b)** 2013

*Source:* Based on data collected from USGS, 2014.

The data is to be interpreted with caution in that it is based on estimates, and might be incomplete in terms of minerals and country coverage. It also does not to account for production from stockpiled material (Walters and Lusty, 2011). During the period examined (1988-2013), China increased its rare earths production by 237%, while the rest of the world decreased production by 66%. Taken together the global production increased by 75%, peaking in 2006 with 136'657 tonnes. Taking a closer look at Figure 5 it becomes obvious that as opposed to the expectations, China's monopoly has been eroding, its share in world production having shrank from 98% in 2009 to 89% in 2013. While China still dominates the market by far, some new players have been entering the global rare earth market. For the moment, the American Molycorp and the Australian Lynas, as well as production sites in India and Russia constitute the competitive fringe. With further increase in their mining capacities and expected development of new projects outside China, a further erosion in China's monopoly is foreseen to occur in medium to long term.

Two things need to be noted when talking about Chinese rare earths production. First, the Chinese Government has been setting yearly production quotas, putting forward the environmental damage. To-date these have always been exceeded by production companies. For example, the quota set by the China Ministry of Land and Resources in 2006 was 86'620 (Tse, 2011), the estimated production exceeding it by 55% at 133'000 tonnes. According to Tse (2011), the discrepancy between sustained high production levels and quotas can be explained by competition among local governments which derive substantial financial resources from rare earth producers. By 2013, quotas smoothly increased to 93'800 tonnes (MLR, 2013) with a substantially lower production, exceeding the former by a 7% only. Quotas limit especially the production of HREE by allocating only 17'900 tonnes to ionic clays, what is less than 20% of the overall production allowed. Second, in an attempt to consolidate the industry and minimize environmental damage, China has been tightening supply by shutting down illegal mines. During past years, altogether 110 mines were closed down

**Figure 4:** World Mine Production, by Country, 1988-2013.

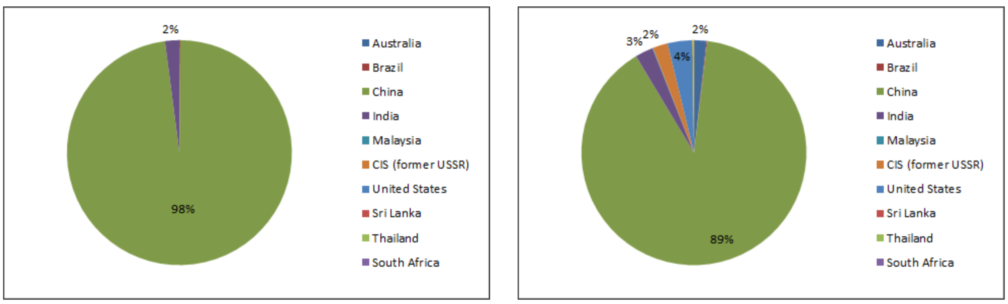



*Source:* Based on estimates collected from USGS, 2013; USGS, 2014.

in the South-Eastern provinces (MIIT, 2012; MOFCOM, 2012k). According to estimates, 22’320 tonnes of rare earths were smuggled out of the country in 2011, what represents 130% of the legally exported quantity (MOFCOM, 2012j). Most of the illicit materials are claimed to be transported through Taiwan and Hong Kong for further processing in Japan and Vietnam (Want China Times, 2010).

The country has also introduced rare earth export quotas, aiming at satisfying the increasing domestic demand on the one hand and at conserving exhaustible natural resources in line with the 10th Five-Year Plan on the other (MIIT, 2012). These became a further source of market distortion globally and triggered the

**Figure 5:** Comparison of World Mine Production, by Country: a) 2009 and b) 2013.

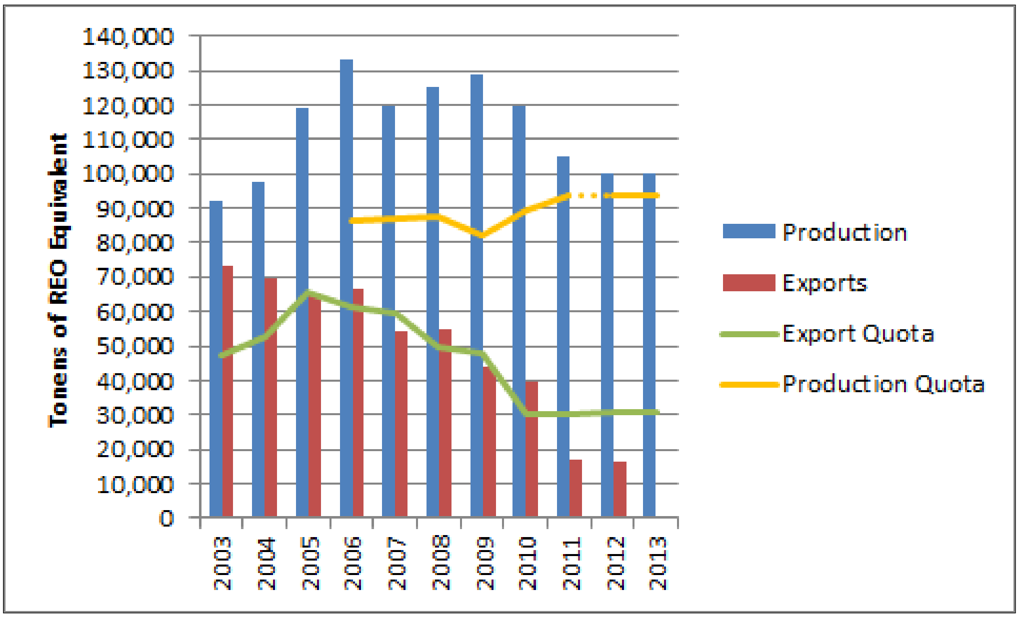



**(a)** 2009 **(b)** 2013

*Source:* Based on estimates collected from USGS, 2013; USGS, 2014.

EU, Japan and the US to log a joint complaint to the WTO (2012). Similarly as in case of Chinese export restraints on bauxite and other industrial materials, the WTO has recently judged the imposition of export duties and quotas on rare earths incompatible with its rules, in that they violate free trade in favour of China's domestic industry. Nonetheless, China now envisages to appeal against this decision (Jolly, 2014). In order to conclude on the extent to which export quotas hamper international trade in reality, Figure 6 offers an overview of production, exports and respective quotas during the past 10 years. The collected data and notes are summarised in Table 8 in Appendix A. Export quotas have been decreasing ever since 2005 - a reduction by 50% to-date - with the largest annual drop in 2010 by 37%. Since then, only minimal changes in quotas occurred. However, note that from 2011 also alloys with a much less rare earth content are counted towards the quota (MOFCOM, 2012l). There is no consensus on how the inclusion of ferro-alloys would impact the quotas, views of experts diverging from no large impact at all (Hatch, 2011a), through 6% of tightening (Bradsher, 2010b), till 40% net decline of rare earth metals and oxides exported (MetalBulletin, 2011). For the moment though this seems to pose no further constraints on satisfying the demand.

**Figure 6:** Chinese Rare Earths Production and Exports, and Respective Quotas, in tonnes, 2000-2013.




*Source:* Based on data collected from UN Statistics Division, 2013; MOFCOM, 2014; USGS, 2013; USGS, 2014 and Tse (2011).

Examining export quotas jointly with actually exported quantities of rare earths sheds light on how the earlier tight supply turned into a surplus in recent years.[4]

[4]There seems to be a discrepancy between export quotas as reported by MOFCOM, 2014 and actual exports as collected from UN Statistics Division, 2013. Unfortunately, Chinese customs data were not available for comparison.

In fact, while during the initial years of tightening quotas have limited the actual exports, the majority of quotas remained unfilled in the subsequent years. Chinese exports to rest of the world shrunk by 70% since the 2008 financial crisis. Due to the weak post-financial crisis global demand but also due to West running down huge accumulated rare earths stocks during 2010-2011 (Kingsnorth, 2013b), Chinese exports decreased to only a little above the half of the authorised quantities in 2011 and 2012. As of now, there is no trade data available for 2013, yet some sources anticipate this trend to reverse with recovery of major rare-earth importing economies and with depletion of stockpiled material (Kingsnorth, 2013b; Topf, 2013c). Just like with production quotas, also in case of export quotas there is a split between LREE and HREE. Since 2012, when China started to report the quotas separately for the two groups, the HREE are capped to roughly 12% of the total. According to China's rare earth development plan, the country intends to maintain tight supply for some of the critical rare earths (dysprosium and terbium) in the future as well (Tse, 2011). Lifton (2013) argues that China itself is about to loose self-sufficiency in some of the HREE since "they don't have any more deposits [...] and the other is, they don't want to strain what they've got". Hence, China started to look at global deposits to secure its future sources of supplies. Acquisition of stake in Australian Arafura, as well as attempted purchase of controlling stakes in both Lynas and Molycorp are examples of China's expansion attempts to foreign mining territories. There are also signs of China's interest in North Korean rare earths (Schearf, 2014; Wee, 2014).

In conclusion, the present "abundance" of rare earths in terms of unfilled quotas is not to be underestimated considering the economic recovery of Japan, the EU and the US - the major importers of Chinese rare earths. While LREE might be back in balance in short term due to new non-Chinese suppliers entering the market, the skewed distribution of HREE-rich deposit reserves in China and the threat of their depletion, along with tight production and export quotas are expected to cause substantial supply shortages in the near future, especially for the elements labelled critical.

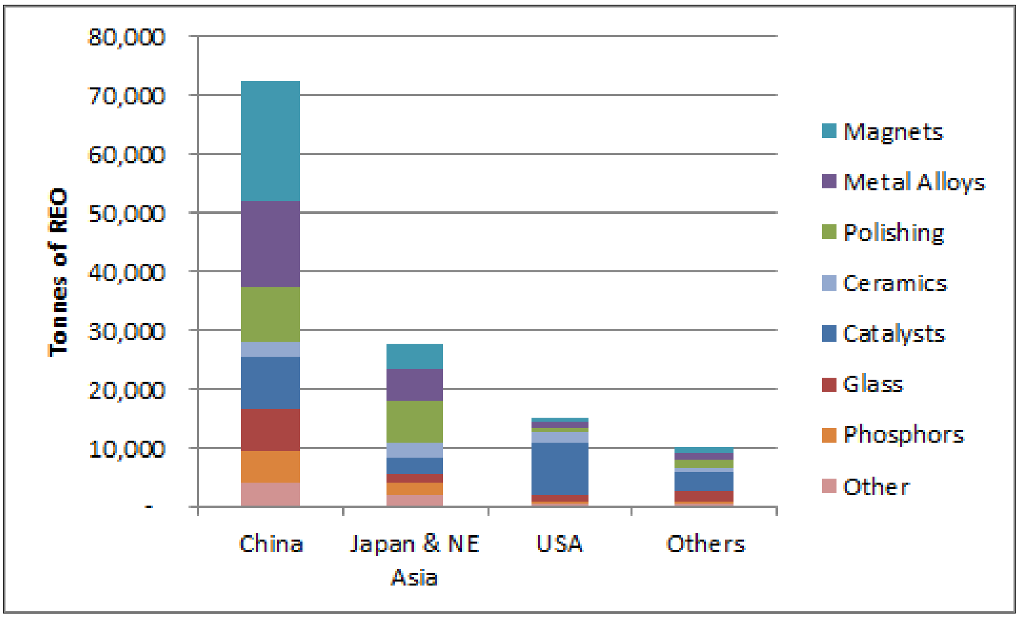
### 3.2.2 Made in China

Economically speaking, the industrial policies discussed above benefit domestic producers in that they make more supply available at lower prices. This is in line with China's resource nationalism, whereby export quotas are set to satisfy country's own need of rare earths for manufacturing. For industrial upgrading in China speaks also the fact that export quotas were only set for REO and for some metals and alloys but not for products higher in the supply chain.

Looking at the Figure 6, the increasing wedge between production and export quotas indicates rising domestic consumption of rare earths. Indeed, while the

Chinese consumption was smooth in the 1990's, there was a dramatic increase in the first decade from 19'000 tonnes in 2000 to almost 73'000 tonnes in 2007 - an increase by some 280% (Zhanheng, 2010). According to estimates by Kingsnorth (2011) adapted in Figure 7, China was the major consumer of rare earths with 58% of estimated global demand, followed by Japan and the North East Asian countries with 22%, the US with 12%, 8% of the global demand in the rest of the world.

**Figure 7:** Estimated Global Rare Earths Consumption (in tonnes), by Country and Sector, 2010.

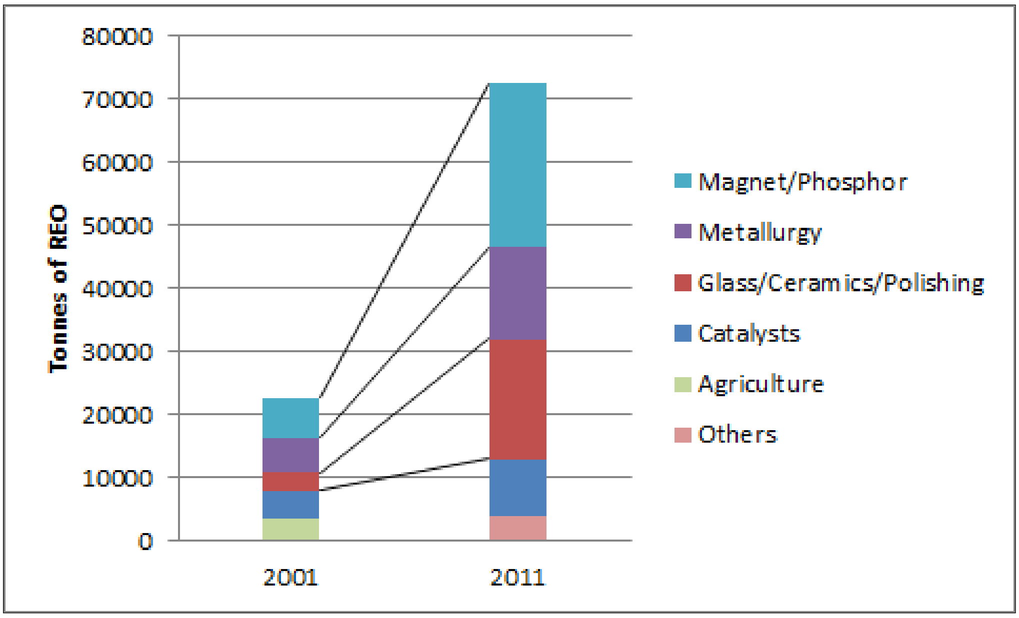



*Source:* Adapted from (Kingsnorth, 2011).

As can be seen in Figure 8, this increase has been mainly driven by increased production of magnets and phosphors. According to data for 2010, China manufactured 79% of all magnets, two thirds of alloys, glass and phosphors and half of the world's phosphor powders. For what concerns its dominance in magnets, China supplies 80'000 tonnes of NdFeB annually, half of which is used domestically (Kosich, 2013). In spite of this, China currently holds no patents on neodymium magnets. These are controlled exclusively by the two inventors: Magnequench (previously General Motors, currently owned by Molycorp) which has rights on bonded and hot pressed magnets; and Hitachi (previously Sumitomo) with patents on sintered magnets. The latter owns over 615 of them and as of July 2013 licensed some to 2 companies in Japan, 3 in Europe, and 9 in China (Benecki, 2013). Concerning the latter, out of 200 Chinese manufacturers only a quarter holds these licences and can manufacture and sell them worldwide. Those without licenses have filed a complaint against Hitachi in August 2013 due to the latter extending patent expirations for process patents what in turn infringes patent rights from Chinese point of view and ultimately hinders

Chinese magnet exports (Kosich, 2013). The legal dispute is not expected to end soon, but should the court rule in favour of Chinese producers, this could lead to concentration of the entire rare-earths-to-permanent-magnets supply chain in Chinese hands. In fact, China already dominates the supply chain from extraction, through processing to production of most finished manufactures. Especially this latter stage shall assure China to achieve economic growth by exporting rare earths in higher value-added forms, which are worth more than in concentrate form.

**Figure 8:** Chinese Rare Earths Consumption (in tonnes), 2001 and 2011.




*Source:* Adapted from (Kingsnorth, 2011; Hong, 2006).

Chinese efforts to achieve industrial upgrading can be best understood by analysing its science and technology (S&T) policies. These are drawn up by the Ministry of Science and Technology and target long terms objectives of becoming an innovative nation by 2020 (Mancheri, 2012). The innovation efforts in rare earths started in the 1980s with the approval of the National High Technology Research and Development Program (also labelled as Program 863) which aimed at narrowing the technology gap between China and the developed world by leapfrogging those high-tech fields in which China had relative advantages. Among others, the program focused on rare earths due to their strategic significance and geological abundance within the country (Hurst, 2010). It was followed up on by National Basic Research Program in the 1990s (Program 973) - a basic research program targeting major strategic needs of the country. Currently, both fundamental and applied research on rare earths is carried out in four major laboratories, focusing mainly on rare earth chemistry, physics and exploration, as well as on environmental protection and on rare earth utilization in both traditional industry and as new functional materials. Besides this, the

Chinese Society of Rare Earths publishes the only periodic publications focusing on rare earths and organises conferences on rare earth development and application. In terms of research on various fields of rare earths chemistry, paper contributions by Chinese researchers have been increasing ever since 2001 (as opposed to those of Japanese and American researchers) and have made China to become the global center of research for rare earth science and technology (Adachi et al., 2010). These efforts not only made China to become a leader in the world rare earth ore production, they also allowed it to gradually move higher in the value chain. In fact, according to historical export data (UN Statistics Division, 2013), while there has been a gradual decrease in China's exports of rare earths in form of compounds and phosphors since early 2000s, the exports of magnets and motors, and later of high-tech products like cellular phones and electric motors have been picking up in recent years.

There are two conclusions to be drawn from this discussion. First, China owes its dominant position in the entire rare earths supply chain to its long term S&T policies. Second, the recent industrial policies not only threaten the availability of supply of rare earths compounds and metals to rest of the world, they also threaten to shift the entire supply chain to China.

### 3.2.3 Can the World Compete?

As discussed previously, abundant reserves of minerals containing rare earths are distributed globally. For example, bastnäsite is mined in Mountain Pass, California - currently the largest non-Chinese deposit of predominantly LREE. Lateritic material in Australia's Mount Weld and Brazilian Araxá is also enriched with deposits with high LREE/HREE ratios. Finally, LREE-dominated Monazite-rich laterite hard-rocks are being examined in under-explored areas of Africa. Instead, peralkaline ingenuous rocks in Russia's Kola Peninsula are a rich deposit of HREE (Walters and Lusty, 2011; Castor and Hedrick, 2006; Long et al., 2010). Also, discovery of the latter has been reported in Greenland, Sweden and Canada, as well as at seabed of Pacific Ocean. In general, the world's largest rare earth deposits were discovered in North Korea, though no official statistics exist (Els, 2013). As of 2011, there were in total 381 projects outside China located across 35 different countries (Hatch, 2011b). Table 9 in Appendix A lists a selection of the most advanced non-Chinese projects as identified by Hatch (2014), based on relative in-situ quantities and on relative physical distributions of specific REO. All these projects contain LREE-rich minerals, in particular lanthanum, cerium and neodymium oxides. But only a few of them are sources of HREE dysprosium, terbium, and yttrium oxides, namely Bokan, Norra Kär, Kutessay II, Kipawa, Strange Lake and Nechalacho Basal. The top five ranked projects in terms of critical rare earth oxide (CREO) rich deposits are Mount Weld, Steenkampskraal, Bokan, Strange Lake and Norra Kärr. Respective distributions and REO grades can be retrieved from (Hatch, 2014).

Most of these projects are currently still under development with stages varying from feasibility studies to initial drilling. Some of the industry experts do not expect the majority of the projects to develop into actual mines, forecasting a success rate of 1-2%, many of the junior projects already fighting insolvency (Hatch, 2011b; Kingsnorth, 2013a; Schlumpberger, 2013). Moreover, deployment of the few successful ones is not expected to occur before 2017 (Kingsnorth, 2013a). The main barriers to market entry are long lead times due to lengthy mine permitting procedures of up to 10 years (Clagett, 2013), environmental considerations in view of higher ecological standards in developed countries, but also financing (for illustration, capital costs for Nechalacho project were estimated at $1.575 billion (Avalon, 2014)), and lack of capabilities in terms of technically trained personnel with expertise and experience in various aspects of rare earths processing and engineering in western hemisphere (Gschneidner Jr, 2010).

For what concerns the already producing mines, Mount Weld and Mountain Pass are currently the largest projects with yearly productions capacities of 11'000 tonnes and 15'000 tonnes, respectively - both having the possibility to increase these further depending on the market conditions. However, looking at their annual sales figures at 5'626 tonnes and 13'118 tonnes of REO for 2013 respectively, both fall short of their production quotas (Lynas, 2014; Molycorp, 2014). While this is caused by currently low demands of cerium - the major product of the two - it is expected that the increased demand for permanent magnets and electric vehicle batteries will increase demand for lanthanum and neodymium - their other major REO products. Another source of non-Chinese rare earths is a the Indian Rare Earths project which is mining and processing monazite to yield cerium, neodymium, praseodymium and lanthanum in Kerala. Of the CIS countries, Russia and Kyrgyzstan are in possession of rare earths which however are currently not mined, though production occurs from stockpiles. Despite the low shares of global production of Lynas, Molycorp and Indian Rare Earths - only 2%, 4% and 3% respectively in 2013 - these are expected to remain the major sources of non-Chinese LREE and their share to increase in the future. CIS currently supplies 2% of global market and is expected to expand its operations in 2015 for production of HREE (Prentice et al., 2013). Currently there exist no HREE producers outside China.

Besides ensuring countries' internal availability of rare earths, additional trends have emerged as a response to Chinese industrial policies. On the level of countries, rare earths importers strive to diversify sources of supply by strengthening relations with rare earths producers in order to secure foreign resources. Especially Europe and Japan, which do not have access to domestic rare earths resources unlike the US, have been active in pursuing rare earths diplomacy by setting up cooperation with other countries to commonly explore rare earths. In case of the latter, joint projects with Vietnam (Toyota/Sojitz - Government of Vietnam), with India (Toyota - Indian Rare Earths) and with Kazakhstan (Sumitomo - Kazatomprom) are expected to come online by 2016 (Fontanella-Khan, 2010; Kingsnorth, 2013a; Sumitomo Corporation, 2012). The EU intends to pursue raw material diplomacy through policy and raw materials dialogues, such as the Africa-EU Joint Strategy 2011-2013 (European Commission, 2011).

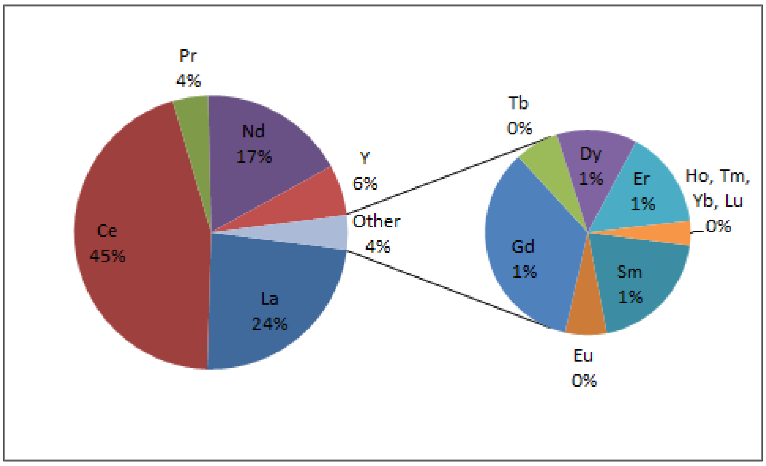
On the level of companies, two strategies are pursued. Some companies started to relocate their permanent magnet manufacturing facilities to China in order to secure stable and cheaper supply of rare earths (Hayes-Labruto et al., 2013). Indeed, as stated out by the vice-chairman of Inner Mongolia Autonomous Region: "imposing controls and reducing exports aim to attract more factories using rare earth metals from home and abroad to Inner Mongolia" (Dingding, 2009). In fact, China's double pricing of rare earths in favour of domestic companies and joint ventures (see Table 6) encourages moving production facilities, and with them also technological capabilities, to China. The latter then benefits from foreign technology and knowledge of permanent magnets in its own efforts to climb up the value chain of rare earth products. Other companies responded by creating various linkages across the supply chain. On the downstream side, Lynas assures a yearly supply of 9'000 tonnes to Sojitz, and Molycorp of 10'000 tonnes of rare earths to Mitsubishi (Watanabe and Suzuki, 2012). Similarly, through a strategic alliance with Lynas, Rhodia secures its supply of LREE (Brindal, 2010), while Toyota is to source HREE in the future from Matamec's Kipawa deposit (Miller, 2014). On the upstream side, Molycorp and Hitachi agreed to create a joint venture with the aim of producing rare earth alloys and magnets. This will assure Molycorp a fully integrated position across mine-to-magnets supply chain (Stynes, 2010). Furthermore, Avalon Rare Metals entered into an agreement with Solvay under which the latter will process its concentrates into REO, among others dysprosium, terbium, yttrium and lutetium Avalon Rare Metals (2014).

To sum up, the rest of the world tries to mitigate import dependence of rare earths on China by opening new mines, by tightening relations with countries in possession of rare earths-rich deposits and by closing strategic alliances on company level. While the former is a long term strategy, the latter two are viable in short term. In conclusion, from the discussion on industrial uses and on Chinese hegemony in both production and supply of rare earths, it becomes clear that tighter supply might adversely impact adoption of technologies which rely on these. In this light, the next section analyses the demand side as driven by low carbon technologies, in an attempt to establish to what extent potential supply shortages pose barriers to deployment of these technologies.

# 4 Demand Push

Increased demand for rare earths is the other side of the coin in the discussion of rare earths supply risk. Based on estimates by Kingsnorth (2013c), global demand for rare earths has increased from 85,000 tonnes in 2009 to 125,000 tonnes in 2013, and is forecasted to increase further to 150,000 - 170,000 tonnes in 2016 and to 200,000 - 240,000 tonnes in 2020. While this represents an increase by almost 200% for rare earths as a group, one has to keep in mind that individual rare earths differ in their uses across technologies. This in turn influences their respective demands. According to data in Figure 9, estimated individual demand is highest for cerium, lanthanum and neodymium. Together they constitute some 85% of estimated global demand in 2016. Based on information in Table 2, demand for these is driven predominantly by hybrid and electric vehicles and by wind turbines, as well as by mobile devices, catalysts, glass and water purification. Indeed, Kingsnorth (2013c) estimates yearly growth rates between 2013-2016 of 4-6% for catalysts and glass and of 8-12% for permanent magnets. The latter may further increase up to 20-25% annually by 2020. The large shares of LREE in the demand as a whole are due to the generally larger quantities these are used in within various technologies. On the contrary, shares of HREE in total demand are relatively small. In spite of this, one should not underestimate their functional criticality. For example, dysprosium only constitutes 1% of the total rare earth demand but is indispensable in permanent magnets due to its ability to increase latter's coercive force and magnetic flux density. In line with this, Alonso et al. (2012a) forecasts an increase of up 724%, 669% and 2630% during the coming 25 years, for neodymium, praseodymium and dysprosium, originating from production of wind turbines and electric vehicles which rely on permanent magnets.[5] Additionally, strong demand growth is driven by competitive pressures from other technologies making use of permanent magnets, such as mobile phones and computing.

**Figure 9:** Global Demand Forecast for Individual Rare Earths, Accuracy of Data +/- 20% (in tonnes), 2016.




*Source:* Adapted from Kingsnorth (2013c). Data are a courtesy of Professor Kingsnorth.

It becomes clear that an increased adoption of low carbon technologies, driven by institutional setting such as the EU's Strategic Energy Technology Plan (SET-

[5]These are upper bound projections in absence of reuse, recycling and efficiency-in-use improvements, assuming aggressive automotive electrification, all wind using permanent magnets, while other rare earths market demand growing at historical rates.

Plan) on the one hand, and by growth of emerging economies on the other, is to exercise pressure on some rare earths to a larger extent than on others. In this light, the present section examines the specific case of offshore wind turbines and of advanced technology vehicles - the two technologies which were identified by scientific literature as major drivers of change in rare earths demand, and which are incorrectly claimed by headlines of newspaper articles as impossible to be manufactured without rare earths content. The analysis is carried out by compiling an overview of existent offshore wind turbine and advanced technology vehicle designs and by establishing their respective rare earths contents in permanent magnets and batteries. For this purpose, specialised engineering literature is analysed. In the next step, current and future trends in deploying particular technology designs is determined. A database is created collecting information on installed offshore wind turbines in current and future projects, as well as on advanced technology vehicle models and battery types. Based on the information on the rare earths intensity of respective topologies, the cumulative shares in rare earths consumption are determined.

## 4.1 Offshore Wind Turbines

The central priority of the SET-Plan is to create a low-carbon economy and wind power is one of the technologies foreseen to contribute to this transition (Moss et al., 2011). Wind is the fastest growing renewable energy source, having increased 8-fold over the past 10 years (Global Wind Energy Council, 2014). But limited space for further development of wind energy onshore, availability of higher wind speeds and opportunities to launch industrial wind projects of magnitudes parallel to power stations, led to progressive siting of wind turbines offshore (Hau and Renouard, 2013). In line with this, recent R&D projects are focusing on challenges primarily in offshore technology, specifically on increasing their capacity, on alternative support structures, on farm layout optimization as well as on their protection (Sun et al., 2012). In terms of drive train innovations the focus lies on improvement of reliability of gearbox and on development of direct drive and hybrid drivetrain technologies. In that the later prove relevant in the context of rare earths supply risk, their topology is discussed in below.

In the evolution of wind turbine technology, early machines operated at constant speed with gearbox and squirrel cage generator (SCIG) and were later replaced by variable speed machines with doubly-fed induction generators (DFIG) (Kostopoulos et al., 2012). This traditional design with gearbox connecting generator with rotor is also denoted as conventional Danish concept and is considered as one of the two main standard designs. In this arrangement, gearbox converts mechanical rotational motion of rotor into faster revolutions per minute (rpm) used by generator, which in turn converts mechanical energy into electrical power by spinning magnets around the coil. Multistage gearboxes prove to be complex machines, the efficiency of gearboxes depending on number of gear stages and on power transmitted (Hau and Renouard, 2013). Of designs ranging from a single to three stage systems of planetary and parallel configurations, the most common to be found in larger turbines is one with planetary and two parallel shaft stages. While the main advantage of this traditional wind turbine design lies within the conversion of rotor torque into rpms used by generator, the main disadvantage is the large number of moving parts such as wheels and bearings. If applied offshore, faster wind speeds tend to aggravate the problem (Morris, 2011). In fact, wear of gearboxes renders the technology unreliable, main sources of failure stemming from incorrect dimensioning with respect to load spectra, what makes them most maintenance prone and one of the most expensive parts of a wind turbine (Hau and Renouard, 2013). While gearboxes do not suffer from largest failure rates, they have the longest downtime of all turbine parts (Polinder, 2011). In response to this, several efforts were undertaken to eliminate gearbox failures (NREL, 2007).

After several decades striving to increase reliability of gearboxes by prolonging their design lives and reducing their servicing schedule, it was proposed to eliminate them completely in order to decrease maintenance costs. This resulted in developing the first gearless generator system in 1992 by Enercon - the direct drive generator with copper windings. In this arrangement, the generator mounted in the nacelle is directly connected with the rotor shaft (Hau and Renouard, 2013). Enercon's electric excitation synchronous generator (EESG-DD) is much larger compared to high speed generator in the traditional gearbox design. In fact, more electrically excited pole pairs are required in order to generate electricity at low rotational speed, the larger radius of rotation increasing speed of the rotation of magnets around the coil. This however causes the generator to be heavier, what negatively affects weight of tower heads. In addition to this, electromagnets are fed with electricity from the generator itself what causes excitation losses. These issues were partially corrected for with replacement of electromagnets by permanent magnets within generator's rotor - the so called permanent field excitation generators (PMSG-DD). These do away with excitation losses and greater power density, increase efficiency and grid compatibility of generators and reduce size of the generator itself and thus eliminate the heavy nacelle (Hau and Renouard, 2013; Polinder et al., 2006). The design has quickly been adopted by manufacturers and is currently established as the second main standard. Its disadvantage lies within additional cost of a fully rated electronic converter necessary for grid connection (McMillan and Ault, 2010; Arabian-Hoseynabadi et al., 2010), as well as within the cost of rare earths materials used in permanent magnets (Hau and Renouard, 2013). Even though the latter has been decreasing over time, it becomes more relevant with larger dimensions of MW power range wind turbines.

Technology which reduces the use of permanent magnets in wind turbines is a compromise between the two standards. For example, the Multibird wind turbine by Areva contains a drive train machine with a single-stage gearbox combined with a medium speed permanent magnet generator (PMSG - SG).

This system combines the advantages of the two standards by decreasing the size, weight and cost and increasing the efficiency of the generator (Hau and Renouard, 2013; Polinder et al., 2006). A more complex design by Aerodyn is made up of Super Compact Drivetrain containing a two-stage gearbox with a permanent magnet generator (PMSG - MG) directly attached to it (Hau and Renouard, 2013). Finally, the High Temperature Superconductor (HTS) technology originates from ship propulsion and is currently under development by American Superconductor, General Electric and Suprapower.

Understanding the difference in these designs is important in the discussion of how rare earths are impacting the deployment of offshore wind turbines. An overview of these technologies can be found in Hau and Renouard (2013) and a discussion on their respective merits and disadvantages in Arabian-Hoseynabadi et al. (2010); Jensen and Abrahamsen (2011); McMillan and Ault (2010); Polinder et al. (2006); Polinder (2011). As can be seen from the information collected in Table 3, not all wind turbine technologies use rare earths in their generators. While no permanent magnets are used in either traditional geared and electrically excited gearless drivetrains, reportedly 650 kg/MW are used in low speed direct drive machines with permanent magnet excitation. Substantially smaller permanent magnets are used in hybrid drivetrains, with 160 kg/MW in medium speed single-stage and 80 kg/MW in high speed multi-stage gearbox machines. In terms of rare earth content, PMSG-DD machines with 250 kg of neodymium, dysprosium, praseodymium and terbium use up 10 times more rare earths per MW of power produced than hybrid designs (Vestas, 2013; Wittrup, 2011). Compared to this, YBCO coated conductors of HTS generators utilise minute quantities of yttrium, barium and copper per MW (Janssen et al., 2012). Figures reported in Table 3 are estimates. In fact, there is a lack of consensus on permanent magnet content in wind turbines, opinions on permanent magnet content within direct drive generators ranging from 500-625 kg/MW (Constantinides, Steve, 2010) through 600-800 kg/MW (Jensen et al., 2013), up to 1000 kg/MW reported by various consultancies. Magnet and rare earth contents reported in Table 3 are based on information by Jensen and Abrahamsen (2011); Lacal Arántegui et al. (2012). For what concerns the share of rare earths in permanent magnets, this amounts up to 35% according to patent information (Fujimura et al., 1997; Fujimori et al., 2010; Nobutoki et al., 2007). This is in line with rare earth contents indicated below.

Now that different drive train technologies have been examined along with the extent to which these rely on rare earth permanent magnets, it proves interesting to examine how widespread is the use of these technologies in reality. For this purpose, all offshore wind farm projects were screened globally. Data was collected from dedicated online databases and news portals on offshore wind (4C Offshore, 2014) (Pierrot, 2014; Recharge, 2013; Wind Power Offshore, 2013; Wind Power Monthly, 2013; Offshore Wind, 2013) and enriched with information on generator designs from manufacturers' websites. The results are presented in Figure 10, illustrating shares of various technologies within offshore wind market

**Table 3:** Generator Types in Wind Turbine Technologies and Their Respective Permanent Magnet and Rare Earths Contents.

| Wind Turbine | Gearbox | Generator | Permanent Magnet | Rare Earths |
|---|---|---|---|---|
| **Geared Drivetrain** | Single-Stage | Induction (IG) | - | - |
| | Multi-Stage | Wound Rotor Induction (WRIG) | - | - |
| | | Squirrel Cage (SCIG-MG) | - | - |
| | | Doubly Fed Induction (DFIG-MG) | - | - |
| **Direct Drive** | - | Electrical Excited Synchronous (EESG-DD) | - | - |
| | | Permanent Magnet Excited Synchronous (PMSG-DD) | 650 kg/MW | 250 kg/MW (Nd, Dy, Pr, Tb) |
| | | High Temperature Superconducting (HTS) | - | YBCO: 0.1 kg/MW (Y, La, Ce) |
| **Hybrid** | Single-Stage | Permanent Magnet Synchronous (PMSG-SG) | 160 kg/MW | 45 kg/MW (Nd, Dy, Pr, Tb) |
| | | High Temperature Superconducting (HTS) | - | YBCO: 0.02 kg/MW (Y, La, Ce) |
| | Multi-Stage | Permanent Magnet Synchronous (PMSG-MG) | 80 kg/MW | 25 kg/MW (Nd, Dy, Pr, Tb) |

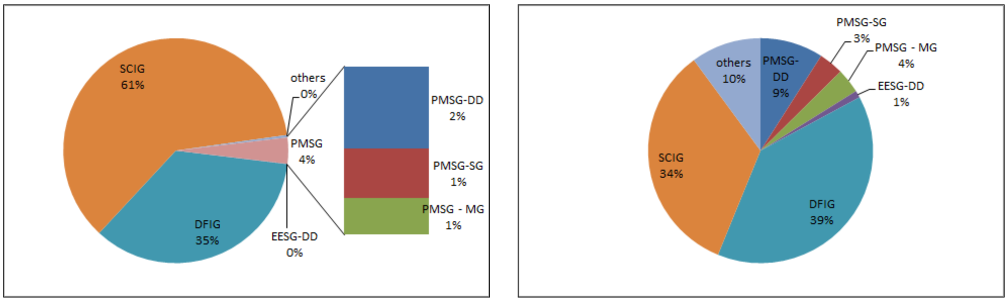
*Source:* Complied based on information from (Buchert, 2011; Hau and Renouard, 2013; Jensen and Abrahamsen, 2011; Lacal Arántegui et al., 2012; Polinder, 2011; Zhang et al., 2011).

taking into consideration all projects commissioned by end of April 2014.[6] In total, 99 offshore wind projects have been operating 2'463 turbines and producing 7.62 GW of offshore wind power globally. Following observations stand out: in terms of capacity generated as illustrated in Figure 10a, the most widely spread design is the conventional geared drive train with squirrel cage generator, which together with doubly-fed induction generator make up 96% of current offshore market. Permanent magnet driven technology lags significantly behind covering the remaining market share of 4%, with an equal split of 2% between direct drive and hybrid generator designs. Looking at the distribution of generator types across projects in Figure 10b, 16% of all commissioned projects make use of permanent market drivetrain technology. This can be explained by the fact that many of these turbines are currently at prototype stage and are being tested in low numbers at various test sites. Finally, average power range of generator types is illustrated in Figure 12a. While conventional geared drive train designs have similar average powers of 2.88 MW for SCIG and of 2.77 MW for DFIG, this is substantially higher for PMSG overall topologies with 3.45 MW. The average of 4.50 MW for EESG-DD is to be interpreted with caution since currently there is only one Enercon turbine deployed offshore worldwide. Having said this, one can conclude that PMSG drivetrains, though with currently lower market share, tend to be deployed within larger power range turbines. While the UK is the leader in total installed offshore capacity, followed by Denmark and Germany, by

[6]The analysis is carried out on the level of deployment phase of a farm rather than of wind farms themselves.

far the most permanent magnet driven machines are at present deployed offshore in China. All of these are of direct drive designs and are supplied by Chinese manufacturers Goldwind or XEMX.

**Figure 10:** Generators in Commissioned Global Offshore Wind Projects.



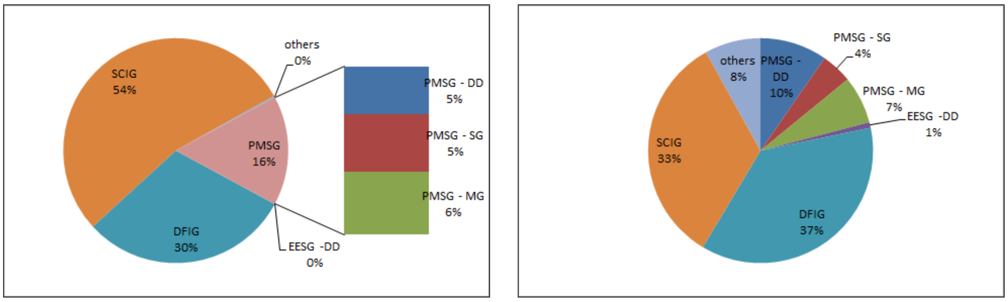

**(a)** Total Capacity (MW) **(b)** Number of Projects

Note: Based on fully commissioned global offshore wind projects by end of April 2014, test sites included (unless set up onshore). Additionally, partially generating projects with installed capacities announced were included. Some of the projects still operate old wind turbine technology - these were classified as "others". *Source:* Data collected from websites of respective wind turbine manufacturers, as well as from 4C Offshore, 2014 Offshore Wind (2013); Recharge (2013); Pierrot (2014); Wind Power Monthly (2013); Wind Power Offshore (2013).

In order to determine the growth of PMSG technology deployment in offshore wind, data on projects currently under construction was collected as well. Within this dataset, capacity generated increases by more than half to 12.72 GW and number of turbines increases to 3'871. Also, looking at Figure 11a share of PMSG turbines increases to 16% of total capacity, with shares of hybrid models increasing to 5% and 6% for single and multi-stage gearboxes respectively, while share of direct drive machines increases to 5%. Share of projects relying on permanent magnet driven technology increases to 21% - see Figure 11b. Figure 12b indicates that the average power range of permanent magnet excited machines increases slightly to 3.62 MW and the total capacity produced increases by 600% - from currently 284 MW to 2'000 MW of produced power once these projects turn fully operational. At the same time, increase in geared drivetrains remains below 50%. Market share of electrically excited generator technology remains unchanged. To summarize, there is acceleration in deploying permanent magnet drivetrains in the near future, at the expense of traditional geared technologies. This trend is predominantly driven by Germany which is planning to add 600 MW of power produced by PMSG turbines offshore, followed by China and the UK with 464 MW and 436 MW respectively, and Belgium with half as much additional power produced at full commissioning of projects. While Belgium and Germany will be installing only hybrid drives, half of added MW by PMSG machines in China and the UK will be produced by direct drive generator wind turbines.

This trend is further confirmed by an overview of the largest wind turbines with power range of up to 10 MW (Power Technology, 2014). Six out of 10 use per-

**Figure 11:** Generators in Commissioned Global Offshore Wind Projects and in Projects under Construction.

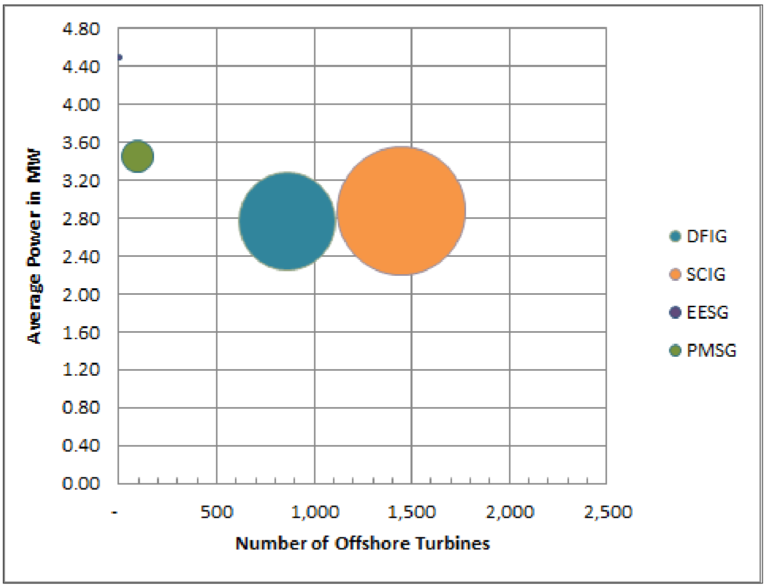



**(a)** Total Capacity (MW) **(b)** Number of Projects

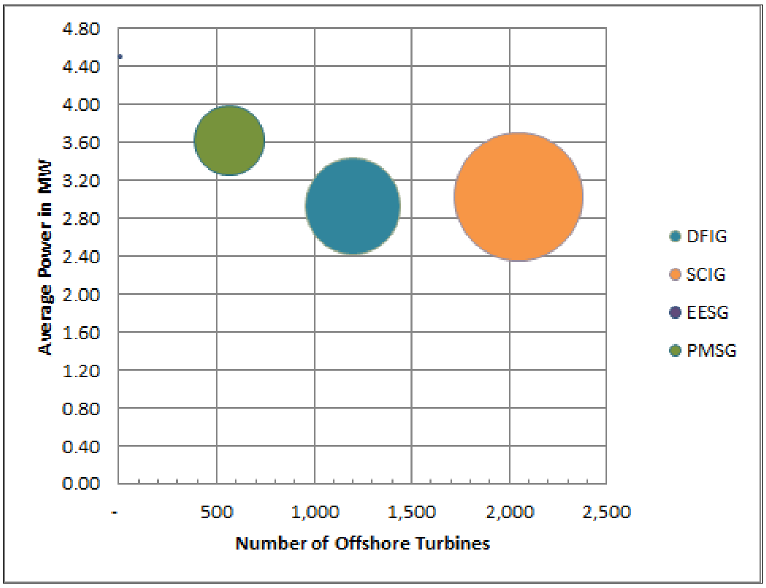
Note: Based on global offshore wind projects which were fully or partially commissioned or are under construction in 2014, test sites included (unless set up onshore). Projects under construction where turbine types were not publicly announced were omitted. Some of the projects still operate old wind turbine technology - these were classified as "others". *Source:* Data collected from websites of respective wind turbine manufacturers, as well as from 4C Offshore, 2014 Offshore Wind (2013); Recharge (2013); Pierrot (2014); Wind Power Monthly (2013); Wind Power Offshore (2013).

manent magnet driven synchronous generator, one is electrically excited direct drive, one uses HTS and the remaining two utilise conventional gearbox technology. For completeness, note that three out of the 6 machines are direct drive, while the other three have hybrid design. There has also been a tendency to increase size of wind turbines with the purpose of reducing costs and improving environmental profile of wind energy (Caduff et al., 2012). Looking at the evolution of power ratings, turbine sizes were increasing from 50 kW with rotor diameter of 15 m in the 1980s, through 10 MW with rotor diameters of 190 m and more to-date, with up to 20 MW turbines currently under development (Chandler, 2004; InnWind, 2013). Having said this, it is important to note that with increasing power range of a turbine, also the amount of rare earths increases. For example, the currently largest PMSG-DD wind turbine of 10 MW would contain 10 times more magnets than turbines with 1 MW power range. Assuming a rare earth content of 250 kg/MW as specified in Table 3, this implies an increase to approximately 2.5 tonnes in total. In reality, 108 tonnes of permanent magnets and 40 tonnes of rare earths were used for all currently commissioned offshore wind farm projects. Additionally, for all newly installed turbines in projects under construction, manufacturing of generators requires 430 tonnes of permanent magnets. With a rare earths content of approximately 150 tonnes, this implies an increase in demand by 380%. Nevertheless, in terms of consumption of individual rare earths, this only represents less than half a percent of respective neodymium and dysprosium supplies forecasted for 2014. For completeness, note that China, unlike the rest of the world, has been installing PMSG-DD technology onshore as well. This becomes obvious when looking at sales figures of some of the Chinese wind turbine manufacturers. For example, in 2013 Goldwind sold 2'912 MW of direct drive turbine technology, which is by far more than fore-

**Figure 12:** Average Power Ranges of Generators.




**(a)** Generators in Commissioned Global Offshore Wind Projects.




**(b)** Generators in Commissioned Global Offshore Wind Projects and in Projects under Construction.

*Source:* Data collected from websites of respective wind turbine manufacturers, as well as from 4C Offshore, 2014 Offshore Wind (2013); Recharge (2013); Pierrot (2014); Wind Power Monthly (2013); Wind Power Offshore (2013).

seen to be installed in global offshore projects in near term (Goldwind, 2014).[7] If considered in calculation, permanent magnets used in onshore wind turbines add to the consumption of rare earths, though not substantially.

It would have been interesting to offer a longer term perspective on developments in offshore turbine technology market. Unfortunately, for most of "consent authorised" projects wind turbine models have not been decided on yet. Same applies for those in "consent application submitted" and in "concept" stages. But considering total capacities foreseen to be installed within all consented projects, once fully commissioned they will produce between 29-31 GW wind power: 22.25 GW in Europe - with Germany, the UK and the Netherlands constituting over 70% - and 8.9 GW in the rest of the world - predominantly in China. In general, future expansion of offshore wind is tied to regulatory stability, as well as to existence of cable routes and high voltage transmission lines linking offshore wind farms to mainland grid (Hau and Renouard, 2013). Penetration of PMSG topologies in particular, will depend on availability risk and pricing volatility of rare earths on the one hand, and competition from alternative technologies on the other. There exist no estimates on market share of PMSG topologies offshore. For example, while Buchert (2011) expects that share of direct drive drivetrains will increase to 15-40% by 2020 for the entire wind market, Moss et al. (2011) assume a European penetration of 15% and 20% for wind turbines with permanent magnet technology in 2020 and 2030, respectively. At this stage it proves difficult to predict the future technology mix. Share of traditional geared machines, which despite of improvements are most maintenance prone, is expected to diminish overtime. While, it does not seem that either electromagnets or high temperature superconductors would increase their respective market shares in the short to medium term, once testing has been completed, these technologies might become a viable option due to decreased capex and opex, as well as to increased efficiency when applied within larger power ranges. As the only commercially available alternative to gearboxes at present, it is probable that PMSG technology is to catch momentum in short run. In fact, considering its technical advantages and the global trend towards wind turbines with larger diameters, and assuming the current tendency in deployment to be further strengthened with operator's need to decrease opex and to increase efficiency, as well as timely commercialisation of such turbine models by new entrants, it can be expected that PMSG technology will gain on market share substantially. However, for this technology to remain cost competitive it is important that supply of neodymium, dysprosium, and partially praseodymium and terbium remains undistorted both in terms of quantities and price volatilities.

In conclusion, considering the variety of drivetrain designs available on the market, further adoption of offshore wind energy per se is not impeded by potential supply shortage of rare earths. Contrary to this, the deployment of permanent

[7] While sold does not imply installed, this figure is a good indication of importance of direct drive technology onshore.

magnet technology in particular, might become prone to supply risk, depending on its total market share and level of hybridisation adopted. In fact, considering the significant price volatility of rare earths in recent years, even the relatively small quantities used in individual wind turbines might exercise a significant pressure on the final price of a wind turbine. This will be illustrated in Section 6.2.

## 4.2 Advanced Technology Vehicles

Besides reduction of greenhouse gases' emissions, another main line of argumentation in favour of advanced technology vehicles, is the reduction of importer countries' dependence on foreign oil. The question remains though, to what extent does the technology shift from internal combustion engine to advanced technology vehicles expose us to dependence on rare earths.

Electrically powered vehicles were invented in Scotland and the US beginning of the 19th century. The technology boomed in late 19th and early 20th century, these vehicles becoming top sellers in the US. However, cheap and abundant oil as well as invention of electric starter motor, lack of battery technology fulfilling performance requirements and relatively low price of the mass produced Ford-T model prevented electrically powered vehicles from keeping up the competition with conventional internal combustion engine vehicles (Constantinides, 2013; Kirsch, 2000; Ovshinsky et al., 1993; Trigg and Telleen, 2013). Nonetheless, they caught a second breath with oil crises and more stringent environmental regulations of transportation. Based on the level of their hybridisation, modern vehicles can be classified into internal combustion engine vehicles (ICEV), hybrid electric vehicles and all-electric vehicles (AEV). Their respective hybridisation factors are provided in Tie and Tan (2013). The latter two can be further broken down based on energy sources used into battery, fuel cell and solar energy models. While all the three types have in common the electric motor drives, they differ in configurations. Namely, fuel cell vehicles (FCV) are powered by hydrogen and oxygen converted by chemical reaction into electricity within fuel cell stacks, while photovoltaic cell vehicles (PCV) are powered by sunray which is converted into electrical energy within solar cells (Çağatay Bayindir et al., 2011; Hannan et al., 2014). These two technologies are still in early stages of development and are not part of the present analysis. For what concerns the battery technology, this differs based on the extent to which it is used to propel vehicles. An overview is provided in Table 4. Battery electric vehicles (BEV) are propelled entirely by battery packs, while full-hybrid vehicles (HEV) run on fuel alone, and plug-in hybrids (PHEV) use the combination of gasoline and battery. Both HEV and PHEV use battery as power storage units. In case of the former, the discharged battery is recharged by ICE or regenerative braking, while it is plugged in to charging stations in case of PHEV and BEV (Çağatay Bayindir et al., 2011; Tie and Tan, 2013) and (IEAHEV, 2013).

One thing all advanced technology vehicles have in common is the electric motor in their drivetrains. Essentially electric motor is the reverse of generator: while the latter transforms mechanical energy to electricity as discussed in case of wind turbines, the former converts electricity to mechanical energy in alternative vehicles. An overview of main motor design drives together with their specifications and comparison of performance is provided by Pellegrino et al. (2012). In short, the most common design is the permanent magnet motor with currently more than 80% of market share, as compared to the induction motor with market share of 11% only (Burwell et al., 2013). This is due to its superiority in terms of performance, efficiency and reliability - a comparison across alternative drivetrains can be found in Tashakori et al. (2010). Just like in wind turbines, magnets in electric motors contain neodymium, dysprosium and traces of praseodymium and terbium. It has been estimated that an electric motor of an electric powered vehicle contains some 0.6 kg of rare earths (Alonso et al., 2012b).

**Table 4:** Vehicle Technologies Classified by Hybridisation and Their Respective Rare Earths Contents.

<table>
<tr><th>Hybridisation</th><th>Energy Models</th><th>Propulsion (Rare Earths)</th><th>Powered by</th><th>Battery (Rare Earths)</th><th>Other (Rare Earths)</th></tr>
<tr><td>Internal Combustion Engine Vehicle (ICEV)</td><td>ICE Vehicle</td><td>Gasoline or Diesel Engine (-)</td><td>Fuel</td><td>-</td><td rowspan="6">0.22-0.44 kg:<br>Nd, Ce, Pr, Dy, La</td></tr>
<tr><td rowspan="2">Hybrid Electric Vehicle*</td><td>Full-Hybrid Electric Vehicle (HEV)</td><td rowspan="2">Gasoline Engine and Electric Motor (0.6 kg: Nd, Dy, Pr, Tb)</td><td>Fuel Alone</td><td>NiMH (3.5 kg: La, Ce, Nd, Pr);<br>Li-ion, LiPo, PbA (-)</td></tr>
<tr><td>Plug-in Hybrid Electric Vehicle (PHEV)</td><td>Fuel & Battery</td><td>Li-ion, LFP (-)</td></tr>
<tr><td rowspan="3">All-electric Vehicle (AEV)</td><td>Battery Electric Vehicle (BEV)</td><td rowspan="3">Electric Motor Alone (0.6 kg: Nd, Dy, Pr, Tb)</td><td>Battery</td><td>Li-ion, LFP, LiPo, PbA (-)</td></tr>
<tr><td>Fuel Cell Vehicle (FCV)</td><td>Hydrogen</td><td>-</td></tr>
<tr><td>Photovoltaic Cell Vehicle (PCV)</td><td>Sunray</td><td>-</td></tr>
</table>

*There are six types of hybrid electric vehicle drivetrain architectures: mild-HEV and full-HEV, while the latter can be further split among parallel full-HEV, series full-HEV, series-parallel full-HEV and complex full-HEV, as well as PHEV. These differ in use of propulsion power and in configurations.
*Sources:* Complied based on information published on websites of car manufacturers and from Alonso et al. (2012b); Çağatay Bayindir et al. (2011); China Auto Web (2014); Hannan et al. (2014); Hybrid Autos (2014); Hybrid Cars (2014); Kopera (2004); Plug-In Cars (2014); Tie and Tan (2013) and DOE, 2014; IEAHEV, 2013.

The case of batteries is somewhat different in that several battery technologies co-exist on the market. The function of batteries in advanced technology vehicles is to store chemical energy and to convert it into electrical energy used to power vehicles. While in case of HEV, battery stores energy generated from regenerative breaking, BEV and PHEV are charged externally. The extent of power produced depends on the chemical composition of the cell, among others.

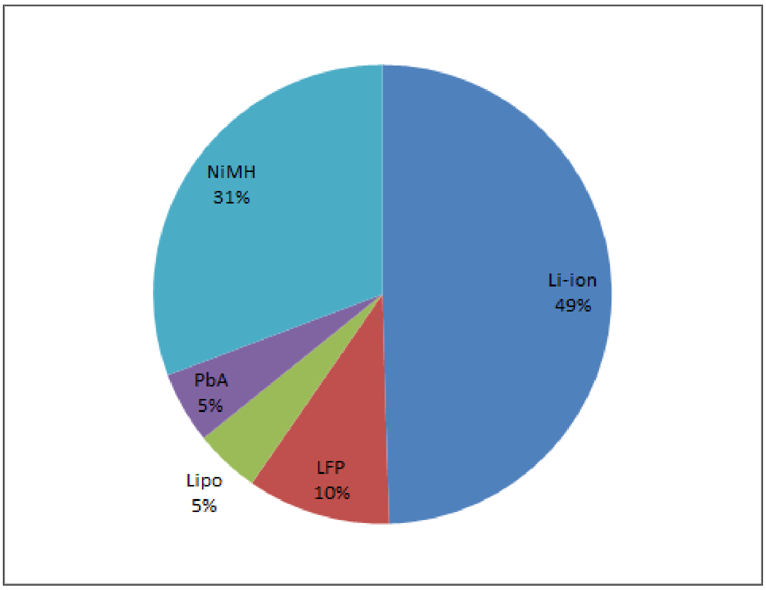
An overview of secondary battery systems is reported in Van den Bossche et al. (2006); Catenacci et al. (2013); Kopera (2004); Råde and Andersson (2001); Rydh and Svärd (2003); Tie and Tan (2013). Battery technologies currently used in respective vehicle energy models are summarised within the fifth column of Table 4. Two most widespread technologies - nickel metal-hydride (NiMH) and lithium-ion (Li-ion) - are discussed in detail, while the other ones are only touched upon shortly since these are either outdated - nickel-cadmium (Ni-Cd) and lead acid (PbA) - or still in stage of development - zinc-air (Zn-air), lithium-sulphur (Li-S) and lithium-iron phosphate (LFP) - or have currently very low market share due to their unproven viability - Zebra and lithium- metal-polymer (LiPo).

The NiMH battery is made up of a positive nickel hydroxide electrode and a negative electrode of hydrogen absorbed in metal alloy. The most commonly used metal hydride is a multi-element alloy of the type MN(Ni,Co,Al,Mn)_5. Such batteries contain up to 10% mischmetal (MN), made up primarily of lanthanum and to some lesser extent of cerium, neodymium and praseodymium, as well as of metallic impurities (Constantinides, 2013; Kopera, 2004; Lichtenberg et al., 1997; Ovshinsky et al., 1993; Shukla et al., 2001). Various aspects of NiMH battery technology have been continuously improving over the past 25 years, what contributed to its widespread commercial use, mainly within electrically powered vehicles. Indeed, when compared to Ni-Cd and PbA technologies, main advantages are its long life, safety, use of non-toxic components and energy density. Nonetheless, major costs of NiMH batteries are tied to commodities such as rare earths and nickel. In fact, their large use of rare earths - 3.5 kg as estimated by Alonso et al. (2012b) - was one of the reasons why other types of batteries started to catch up. In this light, with development of Li-ion battery the use of rare earths has been eliminated. Its positive electrode involves one of the three families: lithium cobalt, nickel or manganese oxide, and has graphite for its negative electrode (Broussely et al., 1997; Rydh and Svärd, 2003). In case of LFP, the cathode consists of LiFePO_4 and aluminium foil (Zackrisson et al., 2010), while in case of LiPo, it is made up of polymer materials. Besides the fact that this technology does not contain rare earths, it is also considered superior in terms of twice as high power and energy densities and its lower weight, implying a greater storage in smaller volume when compared to NiMH batteries (Constantinides, 2013; Kopera, 2004). This has however been achieved at the expense of almost twice as high cost and shorter cycle life. In general, battery characteristics translate into vehicle's overall performance (Ovshinsky et al., 1993). For those using Li-ion technology this implies lighter vehicles with better performance but also smaller range driven without recharging, as well as additional fire safety considerations due to chemical properties of lithium (Baker and Krisher, 2013; The Economist, 2014; Martín, 2013; Wojdyla, 2011). Consequently, further applied research is required to improve on these (Catenacci et al., 2013). For completeness, the availability of lithium production which is concentrated in South America also needs to be taken into consideration.

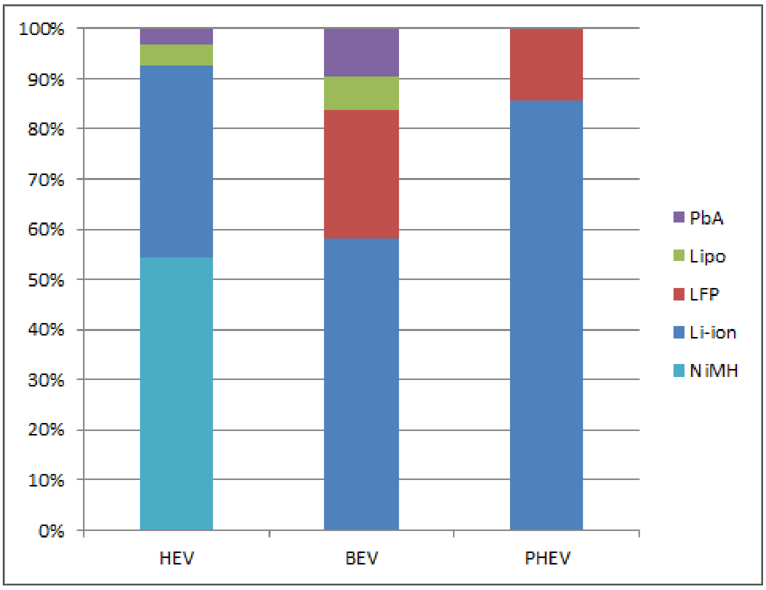
Now that an overview of various designs of batteries has been provided, it proves interesting to examine to what extent manufacturers adopt individual designs within their vehicles. For this purpose, global data on advanced technology vehicle models in production by end of 2014 was collected. Only passenger cars were taken into account. Buses, heavy duty vehicles, motorcycles and three-wheelers are not within the scope of this analysis. Also, vehicles in prototype or pre-production stages and those not mass produced were excluded, while discontinued models were kept. This dataset was enriched by information on battery usage as indicated by respective manufacturer websites and dedicated online portals. The results are summarised in Figure 13a. The most diffused in terms of share of vehicle models is the lithium technology, led by Li-ion with 49% of total share of vehicle models, followed by LFP and LiPo - both emerging technologies with low shares of 10% and 5%, respectively. NiMH batteries are employed within nearly a third of currently available advanced technology vehicle models, what makes them the second most deployed battery technology. However, when looking at the breakdown of uses across specific vehicle energy models as illustrated in Figure 13b, it becomes obvious that the latter are only used within HEV. The reason behind are limitations in specific power and energy densities, as well as lack of scalability with respect to size. In fact, while HEV are propelled by both ICE and electric motor, in BEV and to some extent in PHEV it is the battery which powers the electric drivetrain and hence higher performance of the former is required. This makes NiMH batteries less suitable to be deployed in the latter two energy models (Axsen et al., 2008; Bitsche and Gutmann, 2004). Finally, share of PbA technology is relatively small at 5% and is mostly only used within discontinued models.

In terms of rare earths quantities used, Bryce (2010); SAE International (2010) claim Toyota Prius to be the most rare earths intensive consumer product ever made with its 11 kg of rare earths content. However, other sources are more moderate with their estimates ranging from 2.17 kg to 2.45 kg of rare earths in Prius II batteries alone (Bauer et al., 2011; Schüler et al., 2011). Finally, according to estimates by Alonso et al. (2012b), a hypothetical mid-size HEV with a nickel metal hydride battery, contains 3.5 kg and 0.6 kg of rare earths within its battery and electric motor respectively, and another up to 0.44 kg scattered across over 700 vehicle parts. The latter quantity is contained in all conventional ICEV - for example neodymium and dysprosium within small magnets contained in sunroof and automatic door locks, or cerium in catalytic converter (Alonso et al., 2012b). In fact, two thirds of the quantity is estimated to be made up of neodymium, 18% of cerium, 7% of praseodymium and 6% of dysprosium, the share of other rare earths being below 1% each. Note that this quantity decreases to half when considering rare earths content in basic vehicles in developing countries. As negligible as these quantities sound across single vehicles, for the total of 87.25 million vehicles produced globally in 2013 (OICA, 2014), 29'700 tonnes of rare earths elements were used based on the above assumptions. This quantity when converted into REO content using the conversion ratio of 1:0.85 as suggested by Goonan (2011), constitutes as much

**Figure 13:** Battery Technologies Deployed in Advanced Technology Vehicles.




**(a)** Batteries in Advanced Technology Vehicle Models




**(b)** Batteries across Vehicle Energy Models

Note: Based on mass produced electric passenger cars in production by 2014. Buses, heavy duty vehicles, motorcycles and three-wheelers not considered. Includes also recently discontinued models. Excludes those in concept and pre-production stages. *Source:* Compiled based on data collected from websites of car manufacturers and from China Auto Web (2014); Hybrid Autos (2014); Hybrid Cars (2014); Plug-In Cars (2014) and DOE, 2014.

as 31% of global rare earths supply for 2013. In terms of individual rare earths, this implies that approximately 70% and 120% of forecasted global neodymium and dysprosium supplies for 2014 are used for designing these vehicle features alone. When considering tighter supply estimated for 2016 (Kingsnorth, 2013c), the respective consumptions would increase to 80% and 210%.

In order to determine the quantities of rare earths used in electrically powered vehicles, it is important to first establish the actual global share of separate energy models as well as share of battery technologies deployed within these. Unfortunately, it turns out difficult to determine the exact quantities, since global stock or sales figures broken down to car maker/model levels are not publicly available. Hence, an estimation was carried out based on information gathered from various sources, such as EV Obsession (2013); evsroll.com (2013); Green Car Congress (2014); Hybrid Cars (2013); Mock (2013); Sehgal (2013); Schreffler (2013); Stoddard (2013); Trigg and Telleen (2013); World Nuclear Association (2014) and JADA, 2013, as well as from car manufacturers' websites. For 2013, estimates on global vehicles sales are as follows: 93'924 PHEV, 111'718 BEV and about 1'300'000 HEV. While several different estimates exist, all point to the general trend of HEV dominating the market with a global share of approximately 86%, while respective shares of PHEV and BEV are approximately 6% and 8%. Based on data collected on battery technologies in Figure 13 and on sales figures it was possible to determine major producers of HEV and their battery usage. Toyota seems to be dominating hybrid vehicles manufacturing with almost 2/3 of the market share, followed by Honda, Lexus, Nissan and Ford whose models jointly constitute another quarter of global sales. On the level of batteries deployed, all of Toyota HEV models (with the exception of Prius V), as well as all Lexus hybrids and some of Honda models (Insight, CR-Z and Freed) rely on NiMH batteries. On the contrary, Nissan Serena, Ford Fusion and C-Max, as well as Honda Accord, Civic and Fit use alternative battery technologies. Besides these, Hyundai Sonata, Kia Optima and Chevrolet Malibu have a minor share but none of them uses rare earths in their batteries. It is thus possible to conclude that NiMH batteries currently have an approximate market share of 75% of all HEV. This implies that in addition to the 662 tonnes of rare earths used across various parts, electric motors and batteries in electrically powered vehicles require 723 tons and 3'413 tons, respectively. This represents a 5% share of global rare earths supply in 2013. In terms of particular rare earths, electrically powered vehicles consume 4% of neodymium, 14% of dysprosium and 5% of lanthanum considering respective supplies forecasted for 2014. In view of tighter supplies in 2016, the share of dysprosium usage increases to 24% (Kingsnorth, 2013c). Finally, considering the growing deployment of electrically powered vehicles projected to reach global sales of 6.1 million by 2023 as estimated by Fourin Consultants (as cited in Schreffler, 2013), these alone would require 18% of current annual rare earth's production. This is an approximation and only holds when assuming that global production stays the same, as well as market share of NiMH batteries and rare earths permanent magnet motors remains unchanged, and that no minimisation takes place. In general though, due to the uncertainty in deployment trends of energy models and their charging infrastructures, it is difficult to estimate how much additional demand would be created by electrically powered vehicles in the future. On the one hand, while shares of all three energy models are forecasted to increase, those of PHEV and BEV are expected to grow faster than that of HEV powertrain. In fact, Navigant Research forecasts a global compound annual growth rate of some 12% for HEV and of almost a third for both PHEV and BEV by 2020 (Hurst and John, 2013). This also depends on incentives and regulations by governments, as well as on fuel prices. Finally price decreases envisaged for Li-ion battery packs and potential increasing prices of NiMH batteries due to volatilities in rare earths, might induce manufacturers to substitute latter by former. Nevertheless, as suggested by several studies (Andersson and Råde, 2001; Catenacci et al., 2013; Moss et al., 2011), in order to avoid technology lock-in, variety in battery technologies should be supported due to the uncertainties in the material shortages. This implies that despite the expected paradigm shift to Li-ion technology, market share of NiMH is to remain substantial in the future as well.

To conclude with, it remains to be seen which of the battery technologies will dominate the advanced technology vehicles market in the future. Also in terms of electric motors, possible future development of alternative rare earths free architectures might replace rare earths permanent magnets. Nonetheless, automotive market and its electrification is substantially dependent on availability of rare earths. Therefore a potential supply shortage would disrupt the further development of the market altogether. To what extent this threat is real, depends on availability of material substitutes to be used within permanent magnets, as well as on recycling as an alternative source of rare earths. These are to be discussed in the upcoming section 5.

# 5 Curbing Rare Earths Dependence

The aim of this section is to discuss the mitigation strategies pursued on the upstream side of the supply chain, with the view of curbing the dependence on rare earths. According to the material life cycle (Graedel et al., 2011), the choice of product design is important in that it determines the material and product life cycle, which in turn drive the demand for materials used. In this light, the following two subsections investigate alternative designs in wind turbine and electrically powered vehicle technologies, as well as rare earth material substitutes. Next, end-of-life stage is discussed in terms of efficiency of recycling as an alternative source to primary materials. Finally, stockpiling as a short term strategy to supply shortage is looked at. Strategies followed by the downstream side of the supply chain have already been discussed in Section 3.2.3: opening mines outside China, raw materials diplomacy with exporting countries, and strategic alliances between producers.

## 5.1 Material Substitutes

From the quanto-mechanics standpoint, rare earths are unique due to the configuration of their atom shells which allows them to have unique magnetic interactions with other elements. Also, there exist no perfect substitute elements which would achieve same levels of magnetism. Mature magnet technologies are ferrite magnets - based on strontium or barium ferrite - and alloy magnets - AlNiCo and SmCo as previously discussed. When compared to NdFeB technology, these are considered less costly in terms of price volatilities and potential supply disruption, but at the same time inferior in terms of their lower magnetization, magnetocrystalline anisotropy and thus also lower coercivity (Skomski and Sellmyer, 2009). It is precisely the high coercivity that makes rare earth high energy density magnets essential for direct drive wind turbines and electric traction motors of advanced technology vehicles. In line with this, some of the research streams concentrate on improving the performance of existing non-rare earths based permanent magnets on the one hand, and the coercivity of permanent magnets with smaller quantities of neodymium and dysprosium on the other. At the same time, minimisation is taking place, i.e. development of nanocomposite magnetic material, whereby Nd- and Fe-based nanoparticles are mixed together to reach superior magnetic properties. Finally, replacement by cheaper and more abundant materials is being investigated on. A summary of major projects related to permanent magnets is provided in Table 5.

In terms of initiatives by countries, the US DoE Advanced Research Projects Agency-Energy (ARPA-E) provides funding for technologies that eliminate or minimize use of rare earths, especially through its Rare Earth Alternatives in Critical Technologies (REACT) program. In Japan, related R&D projects are implemented by Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organisation (NEDO) on the one hand, and Ministry of Education, Culture, Sports, Science and Technology (MEXT) and National Institute for Materials Science (NIMS) on the other. The EU instead, is lacking concentrated capabilities in magnet industry. It currently runs a collaborative project with view of facilitating networking, mapping European substitution initiatives, proposing a roadmap and making respective policy recommendations on substitution of critical raw materials (CRM Innonet, 2014). Besides this, a European Rare Earths Competency Network (ERECON) has been established with the view of analysing, among others, European projects aiming at reducing and substituting rare earths in major applications (EC, 2014b).

In general, most of the research initiatives listed in Table 5 are in initial stages. Since these entail basic research one cannot expect new technologies to result from these. In conclusion, though very important, research on rare earths substitution pursues long term objectives and is very unlikely to deliver results in the short to medium term.

**Table 5:** Current Projects on Material Substitution of Rare Earths.

| Aim | Research Organisation | Project Description | Contribution |
|---|---|---|---|
| **Improvement of Performance** | METI/NEDO | Enhance coercivity while reducing dysprosium usage within permanent magnets in high temperature environments. | Reduces amount of dysprosium used by 30% in 5 years. |
| | Hitachi Metals America | Apply dysprosium vapour deposition diffusion technology to NEOMAX sintered magnets. | Reduces dysprosium while maintaining high performance at lower production cost. |
| | Electron Energy Corporation | Apply friction consolidation extrusion to powders. | Produces magnets with larger energy density with reduced rare earths content. |
| | United Technologies Research Center | Develop high-efficiency electric motor using additive manufacturing technique. | Reduces use of rare earths while process and design. |
| | Ames National Laboratory | Improve performance metrics of non-rare earth based permanent magnets. | Provides alternative mature magnet technologies using non-rare earth materials. |
| | MEXT/NIMS | Develop highly coercive magnetic powder and metallic nanoparticles. | Increases coercivity of magnet powder while eliminating use of dysprosium and reducing use of neodymium. |

Continued on next page

**Table 5 – continued from previous page**

| Aim | Research Organisation | Project Description | Contribution |
|---|---|---|---|
| **Miniaturisation** | GE Global Research | Research on nanostructured magnet materials of NdFeB. | Decreases requirement of rare earths and leads to more energy-efficient and power-dense magnets. |
| | Argonne National Laboratory | Research on exchange-spring magnets with hard magnetic shell and a soft magnetic core. | Increases performance and lowers cost using existing materials. |
| | University of Delaware | Minimise rare earths content by mixing existing magnet materials with more abundant ones, e.g. iron. | Provides magnets with less rare earth content and twice the energy density of current magnets. |
| **Replacement** | METI/NEDO | Develop iron-nitrogen compounds as alternative rare earth materials. | Provides magnets with superior magnetic properties using readily available raw materials. |
| | Ames National Laboratory | Develop cerium-transition metal (Ce-TM) magnets. | Provides superior magnet technology to any non-rare earth magnet, using cerium which is more abundant. |
| | University of Minnesota | Research on alternative magnet material made up of iron and nitrogen inputs. | Uses low cost and abundant raw materials only. |
| | Darmouth College | Swap rare earths for manganese-aluminium alloys. | Guarantees superior properties and lower cost of magnets. |
| | Northeastern University | Replace rare earths by iron-nickel crystal structures. | Manipulates market structures at atomic level to create superior magnetic properties as found in meteorites. |

Continued on next page

**Table 5 – continued from previous page**

| Aim | Research Organisation | Project Description | Contribution |
|---|---|---|---|
| **Replacement** | University of Alabama | Development of iron- and manganese-based nanostructured magnets. | Improves performance using low-cost and more abundant materials. |
| | Pacific Northwest National Laboratory | Develop manganese-based nanocomposite magnet. | Substantially higher power at higher temperatures reduces the need for a cooling system which in turn reduces price of wind turbines and electric vehicles. |
| | Virginia Commonwealth University | Replace rare earths with low-cost and abundant carbon-based nanoparticles. | Provides rare earth free alternative to high performance magnets. |
| | Case Western Reserve University | Develop highly magnetic iron-nitride alloy. | Reduces overall price of the motor by replacing rare earths with abundant and inexpensive iron-nitride powder. |

*Sources:* Complied based on information from (ARPA-E, 2009, 2010, 2012a,b, 2014d,b; Chaturvedi et al., 2014; University of Delaware, 2010; The Daily Fusion, 2013; Gehm, 2013; Harris et al., 2010; Kawamoto, 2008; Kozawa, 2011; McCallum, 2012; McQuade, 2013; University of Minnesota, 2012; Northeastern University, 2012; Wenning, 2012) (NIMS, 2010a; NIMS, 2010b; NIMS, 2011).

## 5.2 Technology Substitutes

The increasing price volatilities of rare earths and their tight supply have spurred research for new technologies which have less rare earths content, or which eliminated their use completely. Substitution on the level of technologies is far more progressed than innovation on the level of materials.

### 5.2.1 Alternative Wind Turbine Designs

In case of wind turbines, an alternative to permanent magnet drivetrains discussed was the gearbox technology. Adding a gearbox to the machine not only decreases size of the generator, it also reduces quantity of permanent magnets needed, eventually eliminates them completely. In Section 4.1, single or multiple stage gearbox combined with permanent magnet has been discussed. It has however also been pointed out that due to its large amount of moving parts, the operational expenses of wind turbines increase. On the other hand, there have been constant improvements in gearboxes leading to increased reliability of drive trains (NREL, 2007) (Reliawind, 2011).

In terms of larger offshore wind turbines, the electrically induced wind turbine might have been a viable alternative. The downside of this technology is that it uses current from electrical grid. While Enercon - the major producer of this technology - currently only targets onshore wind parks and is not expected to penetrate the offshore market, some of the competitors have been developing this technology further (Dodd, 2013; Patton, 2012). The future trend towards direct drive generators is further underpinned by the EU project on developing a 20 MW wind turbine (INNWIND). While the predecessor of this project (UPWIND) considered conventional direct drivetrain optimisation, the new project is to focus on superconductive and magnetic pseudo direct drive generator (PDD) (InnWind, 2013). This latter concept integrates a low ratio magnetic gear with a permanent magnet generator, thanks to which costly maintenance and reduced efficiency of mechanical gearbox on the one hand, and substantial size and cost of conventional direct drive generators on the other, are eliminated (InnWind, 2014; Magnomatics, 2014).

On the contrary, HTS machines, generating rotor field by superconducting coils, are intended to reduce generator weight and volume as well as the dependence on rare earths. This however depends on the conductor technology adopted. Currently, the AMSC generators use YBCO conductors (yttrium-barium-copper oxide), while General Electric makes use of niobium-tin superconductors (NbSn) and Suprapower of magnesium diboride (MgB_2) (Magnusson et al., 2013). Hence, instead of using neodymium and dysprosium, this design relies on yttrium, lanthanum and cerium - the latter two being the most abundant oxides in terms of supply (Buchert, 2011). Also the content of rare earths is largely reduced as compared to permanent magnet. For illustration, a HTS generator in a 5 MW wind turbine requires up to 3.8 kg of YBCO superconducting layer, while a PMSG-DD generator in a wind turbine of same dimension makes use of 2.3 tonnes of NdFeB permanent magnet (Henriksen, 2011). Whether HTS machines diffuse to outweigh other offshore technologies remains to be seen. AMSC claims that thanks to its power density advantage, the HTS technology will become the leader at 10 MW and higher power ranges (Cleantech Magazine, 2011). However until the point of their commercial deployment, they need to be tested, their reliability proven and their costs reduced (Magnusson et al., 2013).

Overall, it remains to be seen which wind turbine technology will dominate the market going forward. One thing is clear though: in order to make wind energy competitive, producers need to decrease its costs. This can be achieved by increasing reliability and manufacturing larger offshore turbines. Should these be exposed to supply risk of some of the components, it is likely that producers will shift away to cheaper and more secure alternatives. To which exactly, will depend on the state of technologies available.

### 5.2.2 Alternatives to Batteries and Electric Drives in Vehicles

For what concerns the automotive industry, alternative technologies for batteries in HEV have already been discussed in Section 4.2. Currently, there seems to be a paradigm shift ongoing from NiMH to lithium technology. The rate at which this shift occurs will depend on the extent of supply risk and price volatility of rare earths on the one hand, as well as on price and reliability of the rare earths-free battery alternatives on the other. As an example, Ford has been switching away from NiMH battery in its earlier Escape model to Li-ion battery in its Fusion and C-MAX models. While other technologies are emerging, Li-ion is expected to dominate the market in the future, with construction of Tesla's gigafactory expected to further significantly decrease the manufacturing cost of batteries (Forbes, 2014).

In terms of electric motors, potential replacement of permanent magnets used in traction is yet in the elementary phase. Currently only few vehicles rely on induction electric motors (Tesla), whereby the magnetic field which turns the rotor shaft is created using electrical current (Tesla Motor, 2014). It is the latter which makes the induction motors to be less efficient as compared to the permanent magnet motors which rely on the magnetic fields created around their respective magnets. Besides developing its own technology for induction motor to be used in hybrids, Toyota Motor also currently uses Tesla's induction motor within the RAV4 EV model (Ohnsman, 2011). Similarly, Renault is using an externally excited synchronous motor in some of its models as delivered by Continental (Continental Corporation, 2011; Vignaud and Fennel, 2012). Other car manufacturers are developing electric motors with reduced amounts of dysprosium, such as Nissan within Nissan Leaf and GM within Chevrolet Volt (Renault Nissan, 2012; Redall and Gordon, 2012; Syrett, 2012). Finally, Hitachi has been developing a prototype of a motor using amorphous metal for iron cores and ferrite magnets as rotors (Hitachi Ltd, 2012), while Hybrid Electric Vehicle Technologies (HEVT) has patented switched reluctance motor which eliminates use of rare earths by ferromagnetic instead of permanent magnet rotor (Environment News Service, 2012). This technology however is claimed to need more optimisation before being marketed. Also, several other projects are on their way, such as the three financed by ARPA-E: Baldor Electric Company developing rare earth free traction motor design with improved cooling system (ARPA-E, 2014a); QM Power developing electric motor with use of iron-based magnets and new motor control technique (ARPA-E, 2014c); and University of Texas developing an electric motor with double stator design which is completely rare earths free (ARPA-E, 2014e).

However, as discussed previously, also regular ICEV contain some quantities of rare earths. Consequently, even if batteries and magnets in advanced technology vehicles could be produced rare earths free, a substantial level of dependence on rare earths in automotive industry would remain. While this remains a serious issue in the coming years, it is expected that in the long run these can also be replaced by other materials resulting from basic research initiatives as discussed above.

## 5.3 Secondary Market

In his 2011 analysis of rare earths life cycles, Du and Graedel (2011) note that one of the 5 points within material flows cycles where losses of rare earths occur is waste management. Hence, improving this stage of life cycle via efficient recycling creates secondary market for rare earths, which in turn decreases dependence of rare earths-importing countries on Chinese supplies. This would furthermore lower environmental degradation from mining and also address the balance problem (Binnemans et al., 2013). However, while commercial recycling for base metals was developed long ago - lead being the most recycled metal with rate of 80% - no large scale recycling of rare earths currently exists. In particular, it has been estimated that recycled content (RC) of lanthanum, cerium, praseodymium, neodymium, gadolinium and dysprosium is in the range of 1-10% and inferior to 1% for the rest of elements (Graedel et al., 2011).[8] The global end-of-life recycling rates (EOL-RR) are also less than 1% for all rare earth elements, due to inefficiencies in collection and processing of discarded products. Instead, no data is available for old scrap ratios (OSR). This can be explained by long in-use lifetimes due to which wind turbines are only available for recycling with a lag of 20 years. Such low levels of recycling imply that substantial quantities that could be reused are lost. This is further confirmed by Goonan (2011)

[8] RC is 0% for yttrium, while no estimates are available for scandium.

who illustrates distribution of rare earths from end uses in consumer products to various modes of disposition. Close to no recovery of rare earths occurs for catalysts and metallurgical alloys and to some small extent for coloured glass and ceramics. While technology is available, at present separation of rare earths proves costly. However, considering that stocks of rare earths exceed annual extraction in 2007 four-fold, recycling definitely has a potential to offset part of the primary materials mining (Du and Graedel, 2011). In this light, substantial R&D has been directed to the area of chemical processing and re-use of material recovered.

For what concerns magnetic materials, as opposed to SmCo magnets, reprocessing NdFeB magnets is complicated in that corrosion of material requires refining. Also, strong magnetic fields and nickel plating which protects magnets from humid environments make the recycling more complex. Finally, considering the high content of iron which is disposed of as waste (2/3 as compared to 1/3 of rare earths content), recycling of NdFeB magnets is economically not justified (Binnemans et al., 2013; Goodier, 2005). Recycling routes, their respective advantages and disadvantages as well as current research on recovery of rare earths are described in Binnemans et al. (2013); Schüler et al. (2011). Pre-consumer recycling concerns magnet production scrap which can amount to as much as 30% of the alloy at the beginning of the manufacturing process and should be carried out by magnet manufacturing companies. Post-consumer recycling is mostly targeting NdFeB material present in electronic goods recovered from "urban mines", such as HDD, cell phones and air conditioners, and is becoming an established practice in Japan (Baba et al., 2013; Hitachi Ltd, 2010; Tabuchi, 2010). Re-use of magnets in current form and shape is deemed especially suitable for large magnets in wind turbines and advanced technology vehicles, though it is rarely made use of due to their long service lives. The authors also estimate the global recycling potential for 2020 to lie between 3300 and 6600 tonnes of rare earths for magnets, assuming global collection rate of 30-60%, recycling efficiency of 55% and an average lifetime for magnets in wind turbines of 15 years.

In case of NiMH batteries, these are made up of 8-10% of rare earths mischmetal, the rest being constituted by nickel, cobalt, manganese and aluminium (Müller and Friedrich, 2006). While until recently rare earths from batteries were lost to the steel industry, nowadays hydrometallurgical and pyrometallurgical methods are employed to recover these, as described within Müller and Friedrich (2006); Binnemans et al. (2013); Schüler et al. (2011). In case of NiMH batteries, Binnemans et al. (2013) estimate a global recycling potential of 1000 to 1750 tonnes by 2020, assuming the global collection rate to lie between 40 and 70%, with recycling efficiency of 50%, with lifetime for batteries of 10 years. Toyota was the first producer to recover rare earths by recycling NiMH batteries from end-of-life HEV (Toyota, 2013). In 2013, Honda announced that it would be reusing raw materials from recycled batteries (and various other used parts) to build new ones (Honda, 2013). In Europe, Umicore claims to be the first to have built a recycling facility to recycle NiMH, Li-ion and Li-polymer battery technologies in 2011 (Umicore, 2014). In the US, Retriev Technologies is the major recycler of all types of batteries (Retriev Technologies, 2014). Since recycling of vehicle batteries is a developing industry, there is no data available for it yet.

To conclude with, some of the main constraints to recycling as discussed above could be solved by appropriate policy responses. For example, in Europe the following legal enforcement of waste collection, recycling of batteries and recovery of vehicles and their components was enacted: Directive 2013/56/EC on Batteries, Directive 2012/19/EU on Waste Electrical & Electronic Equipment and Directive 2000/53/EC on End of Life Vehicles (EC, 2014a). Such policy measures, if efficiently implemented might help creating a secondary market for rare earths within Europe and thus contribute to decreased dependence on supply of primary material from China. Besides decreasing private costs, these policies could also decrease social costs to mining by lowering environmental degradation, as discussed in Section 7.

### 5.4 Stockpiling

As opposed to the above strategies, stockpiling is a short term measure which serves as a buffer against interruptions in trade. This is especially true in the period of crisis as defined by Nordhaus (1974), when storage acts like an alternative source of supply. This however only pays out if the price of rare earths and their cost of storing do not exceed the marginal cost of developing reserve capacity.

The EU has evaluated feasibility of economic stockpiling as a correction measure in the short to medium term (EC and RPA, 2012). It also considered the form of stockpiled material, claiming that while stockpiling of concentrates would give end-users the possibility to tailor make their products, the EU does not posses processing and refining capacity to cope with less processed rare earths at the moment. Finally, due to high costs of up to 940 million Euros required to set up a stockpile on the EU level, it was suggested to keep stockpiling on private level and on voluntary bases. The US instead intends to build up national defence stockpile (NDS) of rare earths to support defence production and essential civilian needs in the context of congressionally mandated 4 year conflict scenario (DOD, 2013). They however recommend a mix of mitigation strategies, stockpiling being the last of these due to the relative high cost of federal inventories when compared to other measures.

Several countries have such stockpiles in place already. Japan has established stockpiling in 1983 to cope with short-term supply interruptions of 9 rare metals and has recently started to investigate the possibility of a rare earths stockpile (DEFRA, 2012; JOGMEC, 2012; METI, 2011) (Kawamoto, 2008; Maeda, 2010). Besides the national stockpile, companies also keep their private reserves of rare earths (Topf, 2013b). Similarly, South Korea has established a stockpile for strategically important elements, rare earths among others, to cover 60 days of domestic demand, the level of reserves reaching 1'500 tonnes by 2014 (DEFRA, 2012) (Japan Metal Bulletin, 2010; Park, 2011). This is to cover both economic and strategic purposes. Also China started to build up strategic reserves in 2011, aiming to purchase 100'000 tonnes of rare earths for national storage. The estimated value of the purchase is almost USD 1 billion, targeting mainly HREE and is aimed to protect rare earth resources and to establish a secure and stable supply system (Areddy, 2011) (MIIT, 2012; MOFCOM, 2012g; MOFCOM, 2012m; MLR, 2011). Nonetheless, the recent reserve accumulation by China is also foreseen to act as a stabilisation mechanism in times of falling prices (Currie, 2012; Topf, 2013a; Xinhua, 2012).

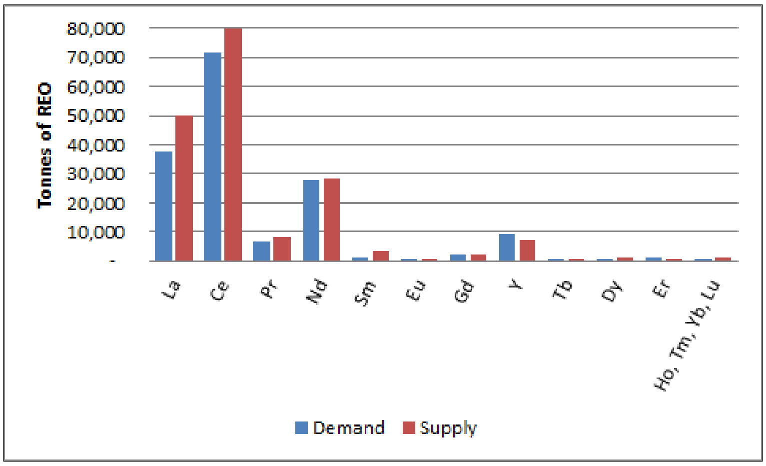
In conclusion, while stockpiling strategy could significantly mitigate supply shortages and price spikes in periods of disruption, it could by the same token adversely affect prices and quantities of raw materials in periods of acquisition (EC and RPA, 2012). Besides issues with administrative burden and efficiency with public stockpile, as well as speculation and financial risk accompanying private stockpile, this strategy is targeting short term disruptions and hence does not address the potentially long term tight supply issue. Moreover, should manufacturers substitute away from rare earths, the stockpile might become quickly obsolete (EC and RPA, 2012). Therefore, a combination of strategies discussed should be pursued in order to curb supply dependence on imported rare earths. This ultimately translates into building up the whole supply chain outside China.

# 6 Factors Influencing Prices of Rare Earths

From the above discussion it becomes clear that the major issue of rare earths is the growing imbalance between increased demand and tighter supply. Figure 14 depicts demand and supply estimates for 2016. Of the five critical metals, yttrium and terbium appear to be short of supply, while the forecasted demand of neodymium, dysprosium and europium is only slightly inferior to the respective supply figures. However, with a further increase of demand for rare earth magnets from low carbon technologies, high-tech and medical applications, the former three will also turn into under-supplied. The more so, since China might further tighten the supply of HREE. In this light, Kingsnorth (2013c) forecasts that the non-Chinese HREE supply could cover as few as 10% of the global needs in 2016.

This section examines demand and supply in combination with the Chinese industrial policies, in order to offer a complete picture on the driving forces behind rare earths' prices. Both demand and supply are largely inelastic. Since rare earths are mined mostly as by-products, their mining decisions often depend on those of main products. However, with the opening of Mountain Pass and Mount

**Figure 14:** Global Demand and Supply Forecast for Individual Rare Earths, +/- 20% (in tonnes), 2016.




*Source:* Adapted from Kingsnorth (2013c). Data are a courtesy of Professor Kingsnorth.

Weld for primary mining of rare earths, supply of LREE is expected to become more price elastic. Demand in turn is inelastic due to the lack of substitutes for rare earths with same or superior properties. This implies that tightening of supply by China would drive prices up and trigger higher production costs for technology applications which use rare earths as inputs. While prices alone are not the only factor inducing innovation, they serve as an indicator of scarcity in that they embed developments on the market. Hence, it proves important to understand the historical price development of rare earths.

## 6.1 Rare Earths Price Trends

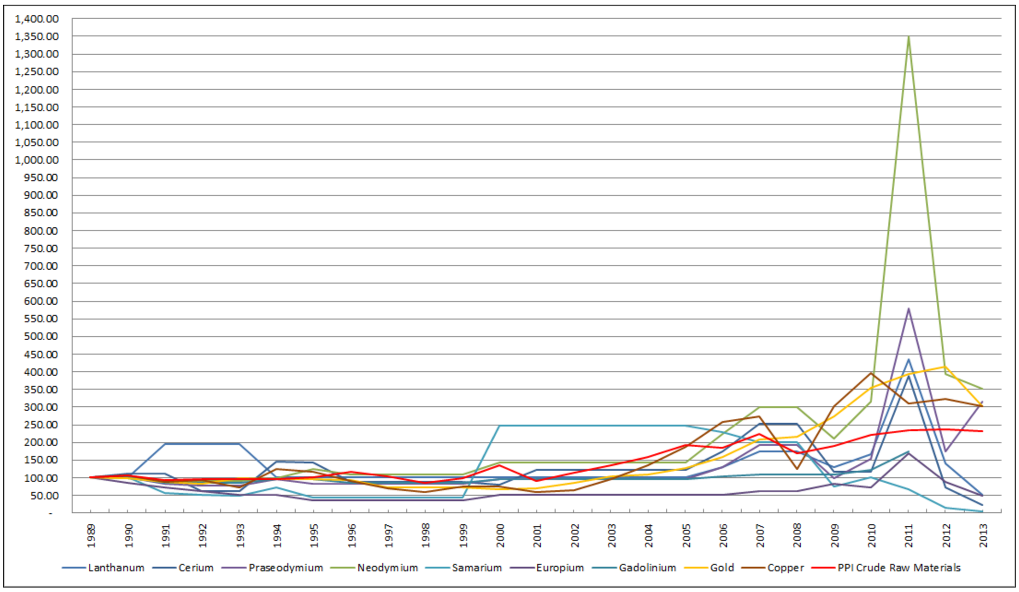
Figures 15a and 15b report historical price developments for the 2 groups of rare earth oxides, respectively. Nominal pricing data was collected from various sources and indexed to 100 in 1989 in order to allow for comparison of changes over the period examined (1989-2013). Note that prices vary with quantity and quality of oxides, as well as across producing companies. Due to the fact that rare earths are not exchange traded, no official prices exists. Year-end prices are recorded as reported by various suppliers or users based on long term contracts (BGR, 2014; USGS, 2013). Daily time series instead, are calculated mid prices by Datastream, 2014. Moreover, pricing data is not available historically for uniform purities, what caused some price jumps in historical trends for Samarium, Terbium and Dysprosium between 1999 and 2000. Specific oxide purities taken into consideration are declared within the Figure. Scandium oxide was excluded due to the lack of sufficient historical pricing data available. Promethium was excluded due to its minor use. For comparison, indexed prices for gold and copper as well as the Producer Price Index for Crude Materials for Further Processing

(PPI Crude Raw Materials) as constructed by FRED, 2014 are plotted.

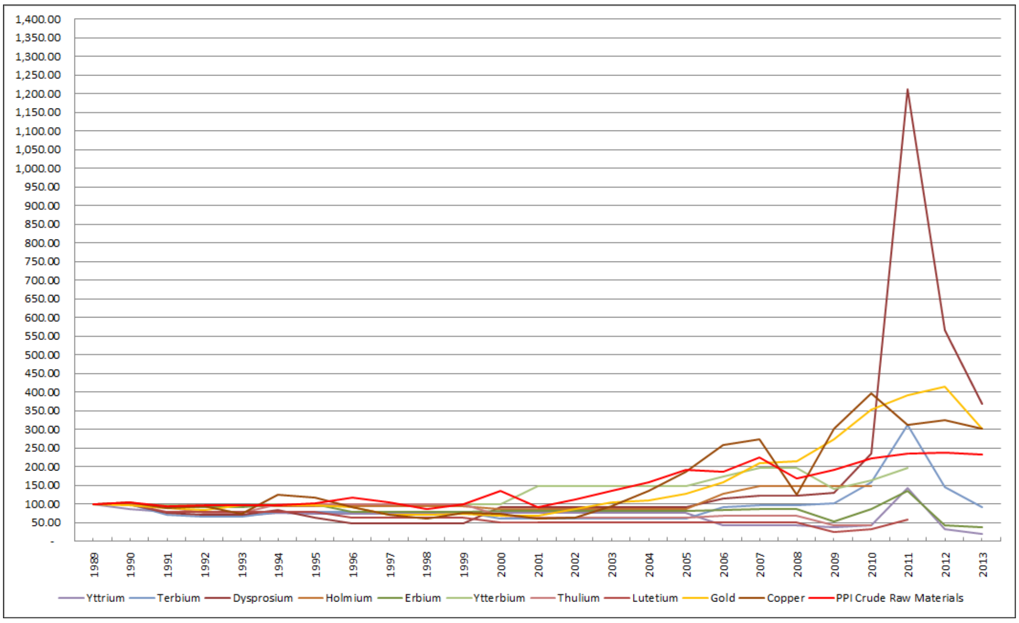
Looking at Figure 15 it becomes obvious that rare earth oxide prices were mixed but fairly stable throughout the 1990s and the first five years of the 21st century. Though majority have higher price changes than those of copper and gold, they remain below the PPI Crude Raw Materials. Overall, prices for HREE tended to be smoother in terms of spikes and also more correlated. In general, they were also substantially higher than those of the LREE. Prices of lanthanum and cerium increased in early 1990s due to the demand from automotive industry for NiMH batteries and petroleum fluid cracking catalysts, and catalytic converters and ultraviolet absorbing glass, respectively (USGS, 2013). Price for samarium was on decrease due to the industry substituting away from SmCo to NdFeB permanent magnets. Permanent magnets constituted the largest increase over all alloys and metal uses. In line with this, price for neodymium was increasing throughout the period (USGS, 2013). Dysprosium, terbium and praseodymium, also used in production of these magnets, were slightly decreasing due to the growing supply from China. Besides pushing down prices, competitive pricing from Chinese producers also triggered a continuous decrease in the rest of the world's production of rare earths from 1991 onwards. With the shut down of Molycorp and Russian mining operations in 2002 and 2003 , China gained a monopoly and by 2005 it produced some 95% of global rare earths. In 2005 the export VAT rebate was abolished by Chinese Government. After 2005, prices and their variations were on increase for both HREE and LREE. This trend was driven by increasing demand which originated predominantly from permanent magnets and rechargeable batteries within automotive and electronics industries, as well as from fibre optics and medical applications (USGS, 2013). It started to increase substantially from 2006 onwards, with 20% increase within a single year only - a significant part of it coming from China. Besides this, China also introduced production and export quotas to cap the quantities produced and exported. As illustrated by Figure 6, the latter have been decreasing since until they reached the lowest levels in 2011. In 2007 China adopted export tariffs to further limit the export of rare earths (Tse, 2011). These currently range from 15% to 25% (Metal-Pages, 2009) and lead to price discrimination by pricing domestic and foreign firms differently. Table 6 provides a comparison between domestic Chinese prices and Chinese prices FOB for the critical REO. As can be seen the wedge between them was increasing from 2007 onwards, with FOB prices being at times twice as high as domestic prices, even before transport and storage costs are included. Though the latter have been increasing over times as well, the gap has not been matched yet.

In 2008 prices remained stable, hampered by economic downturn and a stagnant market for most of rare earths oxides as well as for permanent magnets. The latter decreased further in 2009 from 66'000 tonnes in the previous year to 58'000 tonnes (USGS, 2013). On the supply side, some of the Chinese producers started to halt their production. It was further tightened by the decision to limit new mining permits, and further centralised by establishing the Inner

**Figure 15:** Nominal Rare Earths Prices, Year-end Quoted in USD/kg, Index 1989 = 100.




**(a)** Light Rare Earths Prices, Index 1989 = 100.




**(b)** Heavy Rare Earths Prices, Index 1989 = 100.

Note: Year-end prices for respective oxides reported in different purities historically: 1989-1999: Dy, Nd 95%; Pr, Er, Sm 96%; Yb 99%, Ce 99.5%; Ho, Tb, Tm 99.9%; Eu, Gd, La, Lu, Y 99.99%; 2000-2009: Dy 99%, Sm, Tb 99.99%, the rest remains same; in 2010 and 2011 changes with respect to preceding year: Dy 96% and Sm 99.9%, and Dy 99.5%, respectively; 2012-2013: La, Y 99.999% and the rest 99.9%. *Source:* Own calculations based on data compiled from (BGR, 2014; Datastream, 2014; FRED, 2014; USGS, 2013).

**Table 6:** Price Comparison of Selected Rare Earth Oxides, Average Yearly Prices Quoted in USD/kg, on FOB China and China Domestic basis.

| | **Y Oxide 99.999%** | | **Tb Oxide 99.9%** | | **Nd Oxide 99%** | | **Eu Oxide 99%** | | **Dy Oxide 99%** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **FOB*** | **Domestic†** | **FOB** | **Domestic** | **FOB** | **Domestic** | **FOB** | **Domestic** | **FOB** | **Domestic** |
| 2005 | N/A | 5.28 | 311.19 | 300.99 | 7.34 | 7.38 | 278.08 | 267.55 | 41.38 | 41.43 |
| 2006 | N/A | 4.72 | 463.94 | 452.35 | 15.26 | 14.81 | 243.85 | 236.28 | 71.54 | 69.20 |
| 2007 | N/A | 6.39 | 582.57 | 517.61 | 29.85 | 26.25 | 314.54 | 279.45 | 88.20 | 78.24 |
| 2008 | N/A | 9.41 | 663.65 | 508.54 | 26.28 | 21.02 | 471.98 | 370.20 | 112.92 | 88.20 |
| 2009 | N/A | 6.28 | 361.09 | 253.82 | 14.83 | 12.29 | 475.06 | 362.99 | 107.55 | 85.25 |
| 2010 | 58.31 | 6.84 | 554.18 | 393.54 | 49.71 | 30.19 | 549.98 | 418.65 | 232.07 | 172.40 |
| 2011 | 141.82 | 42.48 | 2310.27 | 1674.42 | 248.39 | 136.23 | 2876.77 | 2137.80 | 1487.27 | 1070.21 |
| 2012 | 118.44 | 26.98 | 2037.78 | 964.69 | 124.23 | 77.03 | 2613.35 | 1240.29 | 1205.57 | 660.22 |
| 2013 | 25.74 | 12.34 | 925.86 | 602.10 | 72.09 | 51.80 | 1105.96 | 747.26 | 556.67 | 313.24 |
| Q1/2014 | 20.96 | 10.07 | 788.73 | 554.18 | 69.81 | 51.07 | 925.91 | 727.72 | 465.36 | 294.02 |

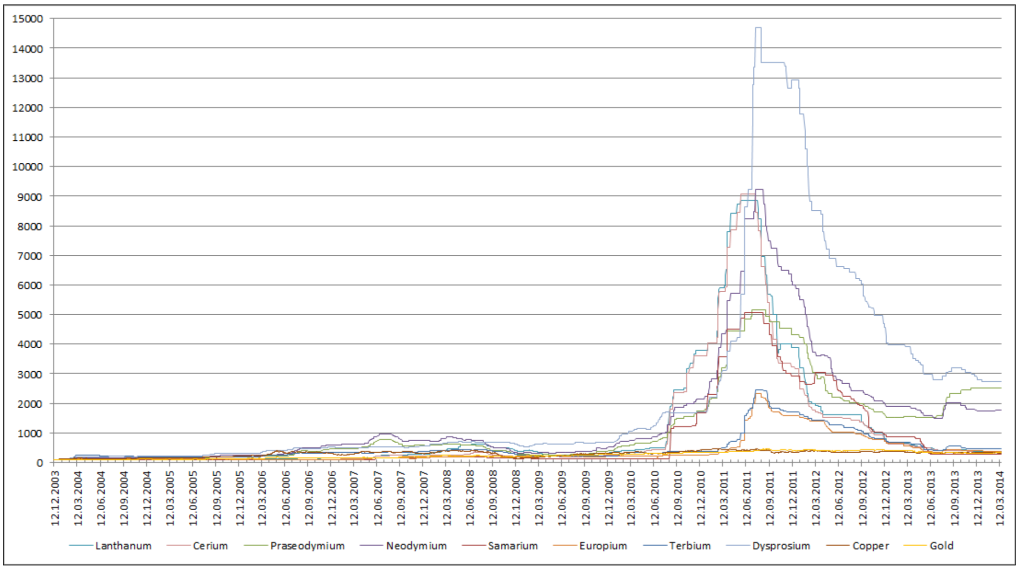
*FOB China (Freight on Board), †China Domestic
*Source:* Own calculations based on data compiled from (Thomson Reuters Datastream Database, 2014).

Mongolia Baotou Steel Rare Earth Trading Company (USGS, 2013). Finally, in 2011 China started to crack down illegal mines and increased the resource tax imposed on bastnäsite and monazite minerals 10-fold (Yuan, 2011). The same year it started the stockpiling program which was to exercise further pressure on demand of rare earths.

All these measures, combined with an increasing demand for rare earths, adversely affected prices which were increasing exponentially through 2010 and peaked in summer 2011. By far the largest increase since 1989 occurred for neodymium (1250%) and dysprosium (1112%), followed by praseodymium, lanthanum, cerium and terbium with respective increases of roughly 480%, 330%, 290% and 210%. Hence, all four of the oxides currently used as inputs in permanent magnets, as well as lanthanum used for production of NiMH batteries have experienced exponential price increases. Contrary to this, the price of samarium used for in the mean time niche product of SmCo permanent magnets, experienced a decrease by 30% since 1989. Similarly, the price of lutetium used in small quantities in x-ray phosphors decreased by roughly 40%. For the rest of rare earths examined, price increases were below 100% since 1989. Overall, following the definition of Nordhaus (1974), one can conclude that due to the sharp increases in prices and to quantitative restrictions which held back substantial supply from the market, rare earths market was in crisis. For comparison, within the same period gold and copper prices were increasing by roughly 290% and 210%, while the PPI Crude Raw Materials increase by 140% between 1989 and 2011.

For a better overview of price developments, daily historical prices are reported in Figure 16. Note that the data represents daily averages calculated by Thomson Reuters Datastream Database (2014) which are rebased to 100 in 2003. Here it can be seen that price hikes started in July-August 2010 and reached their peaks in June-July 2011 when the speculative bubble burst. The variation in prices measured as quarterly annualised volatilities is reported within Table 7. There was a substantial volatility in Q3/2011 for each of the examined REO which was further increasing in the first half of 2012 for the five critical REO. The uncertainty about China tightening the supply even more lead to speculation. Companies hoarding rare earths in view of higher profits and then disposing of them triggered further price fluctuations.

**Figure 16:** Historical Prices for Selected Rare Earths Oxides, Daily, Index 12/12/2003 = 100, Average Quoted in USD/kg, on FOB China Basis.




*Source:* Own calculations based on compiled data from (Thomson Reuters Datastream Database, 2014).

**Table 7:** Annualised Quarterly Volatilities for Selected Rare Earth Oxides, Quarterly Prices Quoted in USD/kg, on FOB China Basis.

| | Q3 2010 | Q4 2010 | Q1 2011 | Q2 2011 | Q3 2011 | Q4 2011 | Q1 2012 | Q2 2012 |
|---|---|---|---|---|---|---|---|---|
| Lanthanum | 16.37% | **374.47%** | **366.10%** | **343.28%** | **348.71%** | 143.07% | 140.42% | 59.82% |
| Cerium | 20.36% | **439.84%** | **425.33%** | **410.26%** | **412.68%** | 139.05% | 135.20% | 65.63% |
| Praseodymium | 46.15% | 61.51% | 59.72% | 88.99% | 94.00% | **108.49%** | **120.27%** | 43.22% |
| Neodymium | 37.13% | 63.97% | 64.58% | 97.58% | 84.79% | **122.07%** | **138.34%** | 73.88% |
| Samarium | 1.47% | **865.67%** | **840.27%** | **808.42%** | **803.10%** | 122.45% | 117.11% | 45.00% |
| Europium | 7.62% | 5.85% | 3.60% | 77.71% | **285.42%** | **296.18%** | **303.59%** | **322.21%** |
| Terbium | 48.30% | 44.48% | 45.35% | 84.52% | **191.66%** | **204.88%** | **211.99%** | **222.02%** |
| Dysprosium | 44.82% | 48.99% | 45.72% | 76.68% | **199.73%** | **199.38%** | **218.60%** | **242.57%** |

*Source:* Own calculations based on data compiled from (Thomson Reuters Datastream Database, 2014).

Prices were on decrease till end of first half of 2013. On the one hand, this can be attributed to the increased non-Chinese supply of primarily LREE coming from Lynas which started mining in 2007 and processing in its Malaysia plant by end of 2011, and from Molycorp which resumed mining late 2010 and processing operations a year later. Coupled with this, export quotas have increased by some 3% from 2011 to 2012 and remained unchanged in 2013. On the other hand, the global demand for rare earths decreased due to the economic downturn. This is obvious from Figure 6, where export quotas remain unfilled for 2011 and 2012. Also, compared to 1989, prices in 2013 increased by 267% for dysprosium, 252% for neodymium and 215% for praseodymium. These increases by far outperform price developments of both gold and copper as well as of the PPI Crude Raw Materials with respective growths of 201%, 203% and 133%. However, most of the other rare earths prices have decreased compared to the 1989 levels, for example lanthanum by 48% and cerium by 78%. In general it is expected that price of LREE would further decrease due to additional supply from Lynas and Molycorp, but at the same time prices for the critical REO to remain strong in the short to medium term due to recovery of demand from major importing countries and to increased demand from new technologies.

From the above it is safe to conclude that while price increases in the period of 2002-2008 were driven by increased demand from countries' economic growth, from 2005 onwards additional non-market forces in form of Chinese industrial policies were distorting the rare earths market. Most significantly, it was the decreased production and export quotas which were feeding expectations of further supply shortages. Speculation has driven up prices in excess of fundamentals, especially in the period of crisis. While increased volatilities indicate risk, at the same time they also signal opportunity to make profits. These were triggered by lack of transparency due to missing spot and forward markets. In fact, in the past trades used to be carried out based on long term contracts and prices set by producers. Once prices started to become volatile, these were fixed to shorter periods. Now, China has set up a trading platform and national pricing system to exercise larger control over prices. Baotou Rare Earth Products Exchange started trading end of March 2014 (Bloomberg News, 2014) and should bring in more transparency into pricing by regulating supply and demand and setting volatility under control. The question remains though, what are the implications of such volatilities on producers of wind turbine and electrically powered vehicle technologies.

## 6.2 Impact on Low Carbon Technologies' Producers

Though China has been dominating the rare earths market since mid-1990s and export and production quotas were in place already in early 2000s, the rare earths problematic has only become a prominent topic in recent years. One of the reasons for this are the small quantities of rare earths used in single technologies, as well as the largely inelastic demand. Moreover, since rare earth prices are rather low relative to the total cost of the final product, changes in prices did not have substantial impact on producer costs. However, price hikes like those in 2010-2011 brought significant uncertainty, which ultimately put pressure on manufacturers and called innovation of rare earths intensive technologies in question.

In this light, several experts confirm that further development of direct drives, despite them being the superior technology on open sea, is threatened by pricing and sourcing volatility of materials used as inputs in this technology (Bills and Sison, 2013; Böhmeke, 2013; Sörensen, 2013). In fact, manufacturing costs of a wind turbine are influenced primarily by the wind turbine itself, by the production environment where it is manufactured, by its production status achieved, as well as by the cost of raw material used (Hau and Renouard, 2013). While steel has the largest share of up to 85% of turbine's total weight, the importance of rare earths used for permanent magnets should not be neglected either. For illustration, assuming a PMSG-DD with rated power of 2 MW, rotor diameter 82 m and hub height 80 m, and following the components cost breakdown as specified by Hau and Renouard (2013), 80 USD/kg of required quantity of permanent magnet constitutes 23% of generator costs and 6% of total component costs. Assuming a variation of prices of permanent magnet up to 420 USD/kg during the rare earths crisis in 2011 (Polinder, 2011), this increases the share of permanent magnet costs to almost 2/3 of the cost of generator and a quarter of cost of all components. This in turn increases the cost per kW by 50% relative to competing DFIG gearbox technology with same parameters (as compared to only 7% when calculated with 80 USD/kg). Certainly, lower costs for maintenance and repair in case of PMSG-DD design contribute to better economics in the long run and balance higher production costs to some extent. However, uncertainty about high and volatile prices and threat of supply disruption of rare earths is inducing producers to adjust the designs of their drivetrains. In fact, high investment costs might turn rare earths-intensive machines very expensive and counterproductive in pushing down the cost of energy. Offshore wind energy must become cheaper to compete with onshore wind and with other renewable energies.

For what concerns raw material costs in advance technology vehicles, according to the component cost comparison carried out by Burwell et al. (2013), the cost of a 50 kW permanent magnet electric motor is by 30% - 200% higher than that of a 50 kW copper rotor induction motor, depending on the pricing of rare earth magnets. From manufacturer's point of view, this implies that switching to the latter technology would decrease total vehicle costs (even when considering the need for increased battery size) and eliminate the dependence on rare earths. In terms of batteries, these constitute the most expensive part of electric vehicles - ranging from a third to over a half of HEV's component cost. Of the battery costs, almost 60% are material costs related to cell packs (Bitsche and Gutmann, 2004). For comparison, Li-ion batteries, despite their higher production costs than NiMH batteries, are cheaper in terms of materials used (Toyota, 2010). The cost of rare earths used within a NiMH battery, when converted into rare earths mischmetal composed of 63.0 wt.% La, 17.4 wt.% Ce, 10.7 wt.% Pr, 2.2 wt.% Nd and 6.7% others (Lee et al., 2000), using the daily prices for rare earth metals FOB China as provided by Datastream, 2014, increased substantially from 21 USD on 30/12/2005 to 121 USD on 18/03/2014 - an increase by almost 500% overtime. Considering metal prices as of end of June 2011 when rare earths crises peaked, the cost of total rare earth content was 707 USD - a 3300%

increase when compared to 2005.[9] Nonetheless, during the time of higher prices producers presumably use up their private stocks so as to mitigate temporary price hikes.

To conclude with, besides the uncertainty of availability of supply, increasing prices of rare earths are also critical to their usage in both wind turbines and advanced technology vehicles. In fact, this price volatility causes the attention of manufacturers to shift away from technologies containing rare earths and ultimately renders innovation in these economically non-viable. In face of increasing demand for these, it might follow that manufacturers, and thus all their innovation activities, relocate to China with view of sourcing cheaper inputs at stable supply. It remains to be seen whether some of the industrial policies will be abolished following the recent resolution on the WTO dispute.

# 7 Social Costs of Rare Earths

Besides private costs of rare earths in terms of price volatility and availability uncertainty, there is also a social cost to mining rare earth minerals containing radioactive thorium and uranium. This manifests itself in form of externalities to environment and health. In fact, while China has been supplying almost the entire world with rare earths during the past 20 years, the costs to environmental degradation and health of local communities have been born entirely domestically. In his famous quote, Wen Jiabao acknowledges that rare earths were under-priced: “In the beginning of the 1980s, we sold rare earths at the price of salt. But they deserve the price of gold. We are just starting to protect our natural interests” (Hayes-Labruto et al., 2013). Having said this, it would seem justifiable for importing countries to pay a surplus on their imports in order to compensate for negative externalities caused by pollution. This section discusses the social costs to the extensive use of primary production of rare earths.

## 7.1 The “Dirty” Clean Energy

According to the Chinese Society of Rare Earths and Materials Department of the Ministry of Industry and Information Technology (as cited in Hurst, 2010), up to 12’000 cubic meters of waste gas, 75 cubic meters of acidic waste water, as well as one tonne of radioactive waste residue and 2’000 tonnes of mine tailings containing thorium are emitted for each tonne of rare earths produced.

[9] Note that the cost or rare earths within NiMH changes in function of the composition of mischmetal. For example, Shukla et al. (2001) assumes a cerium-rich mischmetal with the following composition: 25 wt.% La, 50 wt.% Ce, 7 wt.% Pr, 18 wt.% Nd. Based on this the total cost of rare earths would amount to 159 USD and 918 USD for 30/12/2005 and 30/06/2011, respectively.

With 2013 Chinese production levels, these amount to 100'000 tonnes of radioactive waste and 200 million tonnes of tailing per year. Discharged into river without any treatment, these poison the water used for irrigation of farm lands and have catastrophic effects on lives of both local residents, fauna and flora. The severity Baotou production facility dumping waste to the Yellow river was reported by several independent Chinese information sources as well as by foreign newspapers (Bradsher, 2013; Guardian, 2012; Hui-juan, 2011; NTDTV, 2013b,a,c). China itself has acknowledged that rare earths mining deteriorates its environment through processing of rare earths (MIIT, 2012) and in the broad sense of environmental protection, the Government has been enacting laws since 1980s on environmental protection, water pollution, land reclamation, pollutant discharge standards, as well as laws on prevention and control of radioactive pollution (MIIT, 2012) (National People's Congress, 2011). The National 12th Five-Year Plan for Environmental Protection also aims at reducing the discharge of major pollutants by 40% (MEP, 2012). However, while environmental policies are picking up, these are not expected to reach the stringency of policies in developed countries. In the particular case of rare earths, examining the criteria rare earths producers must fulfil in order to have production quotas allocated to them (MOFCOM, 2012a) hints on China's genuine concern over environmental pollution. Admittedly though, these measures provide an incentive rather than an imperative to adhere to environmental standards (Liu and Maughan, 2012).

Other examples of precautionary action taken in light of environmental degradation caused by extraction and processing of minerals containing radioactive elements exist in developed countries. France in its la Rochelle rare earths processing plant, decided to switch the feed materials to a thorium-free rare-earth chloride due to concerns about radioactive thorium as a by-product of monazite (Hedrick, 1994). Furthermore, Molycorp in the US was shut down in 2002, after a series of waste water leakages from to the Mojave desert, containing heavy metals and radioactive material (Nystrom, 2003). Lynas instead, mines rare earth ores in Mount Weld mines in Australia, however outsources the processing of concentrates to Lynas Advanced Materials Plant (LAMP) in Kuatan, Malaysia. Here, wastes from the process are also disposed of, supposedly due to Malaysia's lower environmental standards. After all this would not be the first case of pollution export by developed countries relocating industrial production to a developing country. An analogy to this case is the Asia Rare Earth (ARE), the main shareholder of which (Mitsubishi Chemicals) despite of its established know-how in handling of radioactive materials has relocated the rare earths processing industry in 1979 from Japan, a country with stringent environmental regulation to Bukit Merah, Malaysia. While products were shipped back to Japan, the radioactive waste remained in Malaysia. It was decided by the Government that thorium was supposed to be stored as a potential nuclear fuel for the future, though the factory was operating without a proper waste disposal system and a permanent dump site in early years, and was seen using a dubious process of rare earths extraction and neglecting all safety standards (Consumers Association of Penang, 1993).

Despite this evidence, the rest of the world tends to devalue the environmental motivations of China in setting export and production quotas. Certainly, China's intention to promote industrial upgrading by using rare earths to manufacture technologically advanced products is undeniable. Nonetheless, there is no reason to question the justifiability of its environmental claims. Also, keeping in mind the environmental implications of mining and processing rare earths, there is quite some irony in using 'dirty' rare earths in 'clean' technologies. All in all, unless sustainable model of extraction and process is introduced which would reflect efficient and environmentally friendly approach to mining, rare earths do not live up to their denomination of 'green elements'. Even switching to underwater extraction of deposits at seabed of Pacific Ocean, concerns prevail that rare earths mining might destroy the respective ecosystem (Arte, 2013). Finally, the race for new mining sites to come online in shortest delays due to the pressing demand of rare earths might come at the expense of upholding environmental standards, especially in developing countries.

## 7.2 Health Issues

Documentation on rare earth mining-caused illnesses is rather scarce globally. At present there is exists only one account, namely the one of Malaysian Bukit Merah and its inhabitants documented by Consumers Association of Penang (1993). This book collects testimonies of inhabitants on both children and adults falling sick, on death cases due to leukaemia and brain cancer, as well as on cases of newborns with congenital defects and on mothers suffering from higher miscarriage rate. The health situation has also been documented scientifically by Bertell (1993), who compared the monocyte depression across populations of children exposed to bone-seeking radionuclides. Children from Bukit Merah constituted one of the samples exposed to thorium hydroxide and lead sulphate waste from ARE and were compared a sample of children from Carey Island - exposed to palm oil, pesticides and herbicides effluences, but no radioactive gases. From the two testing periods in 1987 and 1988 the study concludes a shift towards lower monocyte counts for children with longer exposure, with more than half of the children tested in the second period having counts of below the normal range. Children from Carey Island instead, though having a similar socio-economic and lower nutritional status, demonstrated superior health. This study confirmed that the increased levels of lead in Bukit Merah children's blood was to be attributed to ARE plant, lead being a marker of thorium hydroxide presence in blood. Indeed, ARE was extracting rare earth from monazite, which is known to contain radionuclides in uranium and thorium decay series, as well as lead. These are being released from ores when crushed and ground and decay into radioactive radon airborne in dust. Furthermore, after rare earth chloride is separated from monazite, thorium hydroxide cake or sludge is left behind. These in turn produce alpha radiation, which when exposed to, cause cancer (Bertell, 1993) (IAEA, 2011). It is a well known fact that radiation lowers the white blood cells in the bone marrow and thus destroys the immune system which in turns lowers the resistance to disease. Taking into consideration the Malaysian statistics on leukaemia in 1986, with 3 cases diagnosed in 6 months time, the Bukit Meran incidence was some 180 times higher than Malaysia wide incidence.

For what concerns China, in its report on rare earth industry (MIIT, 2012) the Government acknowledges damage to peoples' safety and health. Unfortunately, there are no official health statistics from Baotou, the world capital of rare earths production, accessible to underpin the extent of this damage. However, according to the Chinese Cancer Map revealed by the journalist Deng Fei and translated in O'Donnell (2013), Baotou is one of the "cancer villages" with a cancer death ratio of more than 70% of all deaths in 2006. This high cancer rate is claimed to be caused by bad water quality due to the presence of heavy metals and radioactive materials. The contamination of the soil in the vicinity of treatment, storage and disposal areas as well as the doses of airborne radionuclides on workers exposed to mining and beneficiation facilities in this region are summarised in IAEA, 2011. In this respect, it is not surprising that China is one of the countries hardest hit by cancer, with 21% of newly diagnosed cancer cases of global total, with the risk of getting cancer before reaching age of 75 being 17%, according to the World Cancer Report (as cited in Jing, 2014) and the IARC GlobalCan (as cited in Cancer Index, 2013). Another 6 out of 8 provinces with rare earths processing appear on this map as well: Shandong, Sichuan, Jiangxi, Guangdong, Hunan and Yunnan. Ultimately, the Chinese Government has acknowledged the existence of cancer villages, the long term harm to environment and human health arising from poisonous chemical products emitted, among others, by non-ferrous metal smelting and processing which include rare earths (Briefing, 2013).

# 8 Conclusions: Separating Myth from Reality

The aim of this paper was to shed clarity on the far reaching consequences of rare earths demand-supply imbalances on innovation of low carbon technologies. It provided a thorough overview of market forces in place, investigating the main drivers of demand and supply, as well as the industrial policies distorting the rare earths market. Furthermore, the paper discussed private and social costs to using rare earths in low carbon technologies and reviewed mitigation strategies which could help reducing rare earths dependence for the future.

On the supply side, the existence of a supply risk was confirmed. Rather than from physical scarcity, this arises from institutional inefficiency within the market. China is currently the largest global producer with a market share of 89% and also possesses single largest reserves of rare earths. However, as opposed to the common belief, concentration per se is not the main driver of supply disruption. Instead, it is China's abuse of market power as a means of political instrument to achieve its economic targets. In fact, China has been holding a monopoly on rare earths during the past 20 years, but only recently it started to significantly tighten their supply. In line with its resource nationalism, China introduced several industrial policies to satisfy own needs of rare earths for manufacturing higher valued added products. Restrictions such as introduction of production and export quotas, as well as banning of foreign companies from engaging in the supply chain within China, are holding back rare earths supply from the global market. While both export and production quotas have been continuously decreasing, the former remained largely unfilled in 2011 and 2012. Though the situation is expected to reverse in the short term, it is the decrease in production quotas which ultimately tightens both international and Chinese supply. Moreover, not the cumulative quotas, but the limitation these impose on the production and export of more scarce HREE, are the main threat to disruption. Coupled with other measures of intentional supply disruptions, such as the national pricing system and double pricing practices, these protectionist policies favour China's national interests of industrial upgrading and substantially distort the market.

The rest of the world responded to these threats by diversification of supply. From long term perspective, opening new mines will assure new supply of rare earths. However, due to various political, economic, financial and environmental obstacles, most of the mines are expected to start producing with a delay of up to 10 years, if at all. However, while overall reserves of rare earths seem to be distributed evenly across the globe, 80% of continental HREE deposits are concentrated in ionic clays of China. This implies that even if non-Chinese rare earths projects brought LREE supply back to balance, HREE will remain critical going forward. In this respect, mining from Pacific Ocean seabed might become an alternative in the long term, though at the same time a source of geopolitical tensions in East Asia. Short term strategies for diversifying supply are raw materials diplomacy on country level and strategic alliances across supply chain on company level. Though these might solve potential short term supply shortages of LREE, no immediate alternatives to mitigate HREE supply disruptions exist outside China. In such cases, stockpiling might serve as a backup resource in times of crisis. Finally, establishing recycling, as a secondary source of rare earths might deliver results in medium term.

The demand for rare earths is driven primarily by permanent magnets used in low carbon technologies, in consumer electronics as well as in medical applications. This paper has examined the role of rare earths in the specific context of offshore wind turbines and advanced technology vehicles. The results disprove the widespread allegation that availability risk of rare earths impedes deployment of offshore wind per se. Contrary to this, the deployment of permanent magnet technology in particular - the superior technology on the open sea due to its reliability and efficiency - might become prone to supply risk, depending on its future market share and level of hybridisation adopted. This topology is characterised by its high rare earths intensity. However, while its share of total capacity produced is currently growing at a rate of 600% - outpacing by far the growth of traditional geared drives - its share of annual global supply of neodymium and dysprosium in particular, is negligible. Despite the inelastic demand for rare earths, it is foreseeable that in case of substantial pricing or sourcing volatility, manufacturers might switch to alternative technologies in order to keep offshore wind energy competitive. The more so, since currently there exist no substitutes for rare earths within permanent magnets. While various R&D initiatives have been undertaken in the direction of minimisation through nanocomposite magnets, and of replacement by cheaper and more abundant materials, this research is not expected to yield commercially deployable results any time soon.

The automotive market and its electrification instead, are substantially dependent on availability of rare earths. A typical electrically powered vehicle requires up to 4.1 kg of rare earths for its electric traction drive, and in function of the energy model, also for the battery. Besides these, every energy model, including the conventional ICEV, contains up to 0.44 kg of rare earths scattered across various parts. Despite the seemingly small quantities, the latter alone would require approximately 70% and 120% of neodymium and dysprosium supply forecasted for 2014, while respective shares would increase to 80% and 210% considering tighter supply estimated for 2016. While, the current share of electrically powered vehicles in total rare earths demand is substantially smaller, this is expected to increase in the future with their growing deployment. Therefore a potential supply shortage would disrupt the further development of the market altogether. While there is a substantial uncertainty in deployment trends of energy models and of their charging infrastructures, price decreases envisaged for Li-ion battery packs and potential price volatilities and availability risk of rare earths might speed up the paradigm shift towards the former.

In summary, uncertainty about volatile prices and threat of supply shortages induce manufacturers to shift away from technologies containing rare earths, and ultimately render innovation in the latter economically non-viable. In the face of increasing demand for these, it might follow that manufacturers, and thus all their innovation activities, relocate to China with view of sourcing cheaper inputs at stable supply. Keeping in mind the slow pace of increase of primary supply outside China and the low efficiency of recycling, it becomes imperative for policy makers to design policies in order to avoid getting the world "trapped" in the rare earths dependence. In this light, more concerted action in research should be directed towards R&D on material substitution within permanent magnets, on increasing efficiency in use of the latter and on developing sustainable mining and processing techniques - especially for handling toxic wastes safely. The latter also proves important with regards to high social costs of mining in form of externalities to environment and people's health. Finally, technical skills and manufacturing capabilities in rare earths processing need to be re-built in order to close the gap between China and the Western countries and to put the latter back on the map of global players.

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# A Appendix

**Table 8:** Data on Chinese Rare Earths Production and Exports, and Respective Quotas, in tonnes, 2003-2013.

| Year | Production | Production Quota | Exports | Exports Quota |
|---|---|---|---|---|
| 2003 | 92’000 | NA | 73’522 | 47’059 |
| 2004 | 98’000 | NA | 69’713 | 52’941 |
| 2005 | 119’000 | NA | 65’207 | 65’580 |
| 2006 | 133’000 | 86’620 | 66’410 | 61’070 |
| 2007 | 120’000 | 87’020 | 54’353 | 59’643 |
| 2008 | 125’000 | 87’620 | 54’986 | 49’990 |
| 2009 | 129’000 | 82’320 | 43’918 | 48’155 |
| 2010 | 120’000 | 89’200 | 39’813 | 30’258 |
| 2011 | 105’000 | 93’800 | 16’861 | 30’184 |
| 2012 | 100’000 | 93’800 | 16’265 | 30’996 |
| 2013 | 100’000 | 93’800 | NA | 30’999 |

Note: Production quotas for 2003-2005 are unknown. For 2012 there was no production quota announced, therefore assumed unchanged. Data according to MLR (aligned with MIIT from 2010 onwards) reported annually, set for HREE and LREE separately. Exports are estimates and do not contain illegal mined quantities. Export data not published yet. Export quota figures before 2005 recalculated into REO, since officially published in gross weight. They are summed across semi-annual allocations to both Chinese companies and foreign joint ventures. Since 2012 MOFCOM reports allocations for HREE and LREE separately. *Source:* Based on data collected from UN Statistics Division, 2013; MOFCOM, 2014; USGS, 2013; USGS, 2014 Tse (2011).

**Table 9:** Advanced Rare Earth Projects Outside China, by company.

| **Company Name** | **Project Name** | **Country** |
|---|---|---|
| Alkane Resources | Dubbo Zirconia Project | Australia |
| Arafura Resources | Nolans | Australia |
| Avalon Rare Metals | Nechalacho Upper | Canada |
| Avalon Rare Metals | Nechalacho Basal | Canada |
| Commerce Resources | Ashram Main | Canada |
| Commerce Resources | Ashram MHREO | Canada |
| Frontier Rare Earths | Zandkopsdrift | South Africa |
| Great Western Minerals Group | Hoidas Lake | Canada |
| Great Western Minerals Group | Steenkampskraal | South Africa |
| Greenland Minerals and Energy | Kvanefjeld | Greenland |
| Greenland Minerals and Energy | Sørensen | Greenland |
| Greenland Minerals and Energy | Zone 3 | Greenland |
| Hudson Resources | Sarfartoq | Greenland |
| Lynas Corporation | Mount Weld CLD | Australia |
| Lynas Corporation | Mount Weld Duncan | Australia |
| Lynas Corporation | Kangankunde | Malawi |
| Matamec Explorations | Kipawa | Canada |
| Molycorp | Mountain Pass | USA |
| Navigator Resources | Cummins Range | Australia |
| Pele Mountain Resources | Eco Ridge | Canada |
| Quest Rare Minerals | Strange Lake Granite | Canada |
| Quest Rare Minerals | Strange Lake Enriched | Canada |
| Rare Element Resources | Bear Lodge | USA |
| Stans Energy | Kutessay II | Kyrgyzstan |
| Tasman Metals | Norra Kärr | Sweden |
| Tasman Metals | Olserum | Sweden |
| Ucore Rare Metals | Bokan | USA |

*Source:* Adapted from Hatch (2014, 2011b).

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