Peak Neodymium
- Material Constraints for Future
Wind Power Development

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Abstract:
Developing renewable alternatives for energy production is one of the main methods for climate change mitigation and sustainable development. As the key component in permanent magnets, neodymium is considered as one of the most critical elements in the rare earth family in the development of modern society. It plays a significant role in increasing efficiency and reducing weight in many applications like hard disc drives, audio equipment, direct- driven gearless and conventional wind turbine design, as well as electric vehicles designs with NiMH batteries. The emerging problem of neodymium production is the peak neodymium issue, which implies a potential risk of supply in the future due to the unsustainable production pathway. Now, China is producing more than 90% of the rare earth elements with an around 40% reserves and is facing severe problems of environmental pollution, smuggling, and increasing domestic demand. This paper makes efforts to see if the risk of supply would constrain future wind power development with a special focus on the China’s dominance in production and policies.

By fitting historic production data with three curve models (logistic, Gompertz, and Richards) and designing future demand based on IEA’s scenarios, the projections of future supply and demand trends of neodymium was obtained. This paper shows that though neodymium-based wind turbine construction might not be the cause for neodymium shortage, it would be confronted with material constraints in the future. Thus, more consideration should be taken in the investment of wind turbines with permanent magnet. Also, a mineral strategy, which integrates technological innovation, joint effort from different stakeholders, and better resource management, is required for a sustainable production of neodymium in the long run.

Keywords: Sustainable Development, Peak Neodymium, Renewable Energy, Material Constraint, Wind Power, China Policies

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Summary:
The element neodymium is one of the most important component in our modern society, since it increases efficiency and reduces weight at the same time in applications like hard disc drives, audio equipment, direct-driven gearless and conventional wind turbine design, as well as electric vehicles designs with NiMH batteries. But the production of neodymium might have risk of supply in the future because of current unsustainable production pathway, which leads to a peak neodymium issue. Now, China is dominant in global production market due to insufficient environmental regulations, lower cost of production, illegal extraction, and smuggling. This paper tries to examine the risk that peak neodymium might become a constraint for future wind power development, with a special focus on the China’s dominance in production and policies.

Future supply and demand trends are predicted by curve modelling in this paper. The results show that the investment in future wind turbine construction should avoid using neodymium due to the potential risk of supply caused by growth of all kind of applications. Meanwhile, a mineral strategy that integrates technological innovation, joint effort from different stakeholders, and better resource management, is required for a sustaining future production of neodymium.

Keywords: Sustainable Development, Peak Neodymium, Renewable Energy, Material Constraint, Wind Power, China Policies

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Abbreviations

CCS = Carbon Capture and Storage
ECEs = Energy Critical Elements
GHG = Greenhouse Gas
Nd = Neodymium
REE = Rare Earth Element
REM = Rare Earth Metal
REO = Rare Earth Oxide
HREE = Heavy Rare Earth Elements
LREE = Light Rare Earth Elements
URR = Ultimately Recoverable Resources

PMs = Permanent Magnets
PMGs = Permanent Magnet Generators
PMSG = Permanent Magnet Synchronous Generator
DFIG = Doubly-fed Induction Generators
WRIG = Wound Rotor Induction Generators
WRSG = Wound Rotor Synchronous Generator
PMSSG = Permanent Magnet Synchronous Generator
HAWT = Horizontal Axis Wind Turbines
VAWT = Vertical Axis Wind Turbines

EVs = Electric Vehicles
HEVs = Hybrid Electric Vehicles
NiMH Battery = Nickel Metal Hybrid Battery
PHEVs = Plug-in Hybrid Electric Vehicles
PV = Photovoltaic

11th FYP = 11th Five Year Plan (2006-2010)
12th FYP = 12th Five Year Plan (2011-2015)

CIM = Canadian Institute of Mining, Metallurgy and Petroleum
CRIRSCO = Committee for Mineral Reserves International Reporting Standards
LCA = Life Cycle Assessment
UNFC = United Nations Framework Classification

ABS = Australian Bureau of Statistics
APS = American Physical Society
BGS = British Geological Survey
CIS = Commonwealth of Independent States
DOE = U.S. Department of Energy
EPA = The U.S. Environmental Protection Agency
GENI = Global Energy Institute
GWEC = Global World Energy Council
IEA = International Energy Agency
IUPAC = International Union of Pure and Applied Chemistry
JORC = Joint Ore Reserve Committee
MRS = Materials Research Society
MLR = Ministry of Land and Resources (of the People's Republic of China)
POST = The Parliamentary Office of Science and Technology
SAMREC = South African Mineral Committee
USGS = U.S. Geological Survey
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1. Introduction
Fossil fuel, once regarded as abundant and low cost, has been the main engine for global development in the industrial history. But today, we are confronted with an unprecedented energy crisis, with pollutions of all kinds, with climate change caused by atmospheric greenhouse gas (GHG) accumulation, and so forth. There is an emergent demand for investing in the renewable energy sector, which is expected to supplement traditional energy sources or even sufficiently contribute to energy supplies. However, increasing number of research results and public concerns fall on the dark side of renewable energy development. For example, damage to the local or larger ecosystem due to construction of hydropower plant, and the “food versus fuel” debate that results from biofuel production in some developing countries in order to meet the energy demand in developed ones. This thesis is focusing on another emerging problem led by renewable energy development. Since it is less commonly known that in the trend of developing renewable energy, the actual power plants are resource-consuming, including a great amount of energy and raw materials construction. Apart from normal materials like concrete and steel, a lot of more valuable and rare elements are more frequently required to improve production performance. In this paper, the research is narrowed down to a specific case— the rare earth element (REE) exploitation in the process of expanding wind power plant construction. By shedding light on the application of one of the rare earth elements, neodymium (Nd), in both wind to electrical energy conversion and in other areas, this thesis aims at simulating future neodymium supply and demand trends based on historic and empirical data. In this way, further analysis and discussion of peak neodymium issue can be carried out according to the prognosis outcome.

As the demand of renewable energy continues to grow rapidly along with the expansion of portable electronic devices market, people start to look into the mineral related issues, not only regarding the negative effects to environment and human health caused by element extraction, but also more and more concerning about the REEs depletion, which is also referred to as the “peak mineral” issue. It is getting acknowledged that clean technologies could lead to material scarcity when rising demand for wind power and electric vehicles utilization could strain supplies of certain rare earth metals (Chandler, 2012). In 2011, the American Physical Society (APS) and Materials Research Society (MRS) released a report named Energy Critical Elements: Securing Materials for Emerging Technologies, aiming at fostering energy independence of U.S. by securing future supplies of REEs and other energy critical elements for emerging sustainable energy sources and new technologies in various fields. In this report, it brings about the definition of Energy Critical Elements (ECEs) as chemical and isotopic species that are crucial in energy capturing, transmission, storage as well as conservation processes, in the same time, application of these elements might probably face the risk of supply disruption in the near future (APS and MRS, 2011).

This paper takes a deeper exploration of neodymium, one of the most crucial elements in REE category, which is also included as one of the most critical types in ECEs (DOE, 2011). As a finite resource, neodymium plays a major role in high-strength permanent magnets (PMs) on the base of the Nd$_2$Fe$_{14}$B alloy. Permanent magnets show great performance in electronic industry in applications like electric motors, computer hard drives, and powerful electricity generators, which is catching the attention from the aspect of wind turbine manufacture and efficiency improvement (Encyclopædia Britannica Online, 2013). The problem is whether future supply of Nd can sustain or not in the pressure of its growing demand. With most of its reserve located in China (APS and MRS, 2011), where neodymium utilization and its market is heading to when inevitably affected by political and economic influences; these issues are worth studying since all the countries are seeking way to secure their energy supply and to develop clean technology in this renewable era.

1.1 Aim of the Study
By fitting historic production and utilization statistics to different curve models, the aim of this study is to predict the supply and demand trend of neodymium based on the currently available public data. Both descriptive and predictive curves will be generated. This thesis mainly focuses on making long-term (100 years) prognosis, followed by interpretation of the outcome and discussion for future application. But short-term (5 years) and medium-term (15 years) analysis would also be touched upon in order to discuss near future prediction based on economic factors. In this way, it tries to show different projections within different timeframes. Since curve-fitting models are beneficial for long-term outlooks with general trends, the farther future projections help provide an interpretation of future prediction of mineral supply in the condition of “what if” the geological factor is the main constraint (Rensburg, 1975; Milici, 1997; Höök et al., 2011).

Thus, obtaining approximate peak year of neodymium production, general future supply as well as demand trends both in a global case and exclusively from China’s aspect is one of the main goals of this study. Combined with future energy and element resource strategy from various sources, the resulting curves are
helpful in terms of strategic decision-making and control. Since in the end, peak element would turn out to be resource strategy and energy security issues due to its unevenly distribution, political interference and immature resource management. Furthermore, possible scenarios and solutions will also be provided according to literature review and analysis.

Meanwhile, with a special focus on China, this paper aims at gaining a more profound understanding of the current situation of neodymium production and the impacts caused by relevant policy. Also, it makes effort to reveal both challenges and chances imposed on the REE industry in China due to the pressure from not only the global market, but also inside China in terms of consequential environmental and social concerns.

1.2 Delimitation and Uncertainty of the Study
Shortcomings and uncertainty occur when it comes to data collection process. Throughout the research, sufficient data for rare earth production, especially in terms of neodymium production, reserve estimations, and data regarding to production in China, are not available in most of the public database. It is difficult to obtain or even locate reliable source. There is almost not any independent data for neodymium production; in this case neodymium related data is gathered by factoring down the ones of rare earth oxides based on former study archives or relevant researches (Schüler et al., 2011; Goonan, 2011; Vikström, 2011).

The main data source in this study includes annual or analytical reports of international or national organizations, research agencies, and so on. For example, most of the data are assembled from IEA (International Energy Agency), USGS (U.S. Geological Survey), BGS (British Geological Survey), and MLR (Ministry of Land and Resources of the People's Republic of China), while others are collected from research results from secondary data or from related scholar work.

Another limitation of this study is that the prognosis of future trends are mainly based on the “what if” assumption, which means taking geological constraints as a main concern but leaving out some other factors like economic interference, political influence, technological development, and so on, due to the limitation of used curve models. Thus, supplemental analysis would be carried out and furthered study would be mentioned in the end of the paper.

Moreover, it is worth mentioning that no accurate forecast method exists. What this study is able to achieve is capturing plausible general long-term trends in different scenarios. Even if one of the trajectories did fit in the future situation, the real production would still be expected to fluctuate around the projection outcome. Similarly, in the scenarios regarding shorter-term future neodymium demand, there is no guarantee for the validity of the chosen historic growth rate or the estimated market trend concerning wind turbine and electric vehicle due to significant unforeseen future circumstances. This research would attempt to make proper estimations and assessments with best available information to mitigate the uncertainty.
2. Background

This section covers the background knowledge of wind power utilization technology as well as basic information of rare earth elements (REEs) with a special focus on the element neodymium. The concept of peak mineral is also introduced in order to lay the foundation for a better discussion of the links between neodymium supply risks and future wind turbines development.

2.1 Rapid development of wind power utilization

As one of the most commonly found renewable energy sources, wind power has made significant contribution in human activities for more than 5,000 years (Pozner, 2012). Initially, people started to make use of wind for sailing, then for water pumping in irrigation or in grain grinding processes. Simple windmills emerged in ancient agriculture activities when the first documented one was invented in Persia in late ninth century (Musgrove, 2010). Later on, wind power captured by wind turbines is transformed from wind kinetic energy to electricity. In the early 1900s, household started investing in small wind turbines started due to growing demand for household electricity-powered appliances when the first wind turbine for battery charging was installed in 1887-1888 (Wizelius, 2006, p. 103). Scaling up of wind power plants emerged in the early 1920s, mainly in European countries. Then the Soviet Union and US joined the competition in the 1930s; Asian countries like China, Japan, India, and South Korea also began to seek for their wind energy potential since early 1980s (Gillis, 2008).

From the beginning of wind to electricity conversion, the size of wind turbines has been growing with improved techniques and better materials in various applications. Wind turbines of 20-35 kW size range were first built between 1891-1918 in Denmark, and now the commercial wind turbines have reached 6 MW, with models up to 10 MW under design (Manwell et al., 2010, p. 19). There also emerge models that are armed with larger rotors (more than 125m in diameter) and higher towers (more than 100m). Apart from conventional onshore wind farms, offshore wind power projects are emerging with a rapid pace. From the construction of first offshore wind farm with around 5000kW capacity in 1991, to a 1000 MW one under development in England in the year of 2000, offshore wind utilization is taking up a bigger market with its advantages (Burton et al., 2011, p.2). Offshore locations impose less pressure on land demand, and wind speed could be 0.5-1m/s higher as the wind turbines go farther away from the coastline (WEC, 2010). When the size keeps growing, the cost of wind power plant has fallen substantially with higher productivity and lower manufacture cost. Nowadays the typical cost for electricity generation is around US$ 2,000 per kW installed capacity and can be reduced to US$ 1,000/kW (Wizelius, 2006) according to market price of materials, compared to US$ 3000 per kW in 1980s (WEC, 2010). Commercial wind turbines have a technical lifetime ranges from 20 to 25 years when the economic lifetime is expected to be shorter due to higher maintenance cost that increases with age (Wizelius, 2006).

There are various ways of wind turbine classifications for different applications and there is no fixed standard for some of the classification. Wind turbines can be classified based on size, location, function, design concepts and so forth. For example, there are micro, farm, medium, MW, and multi- MW-size turbines in terms of size difference (Wizelius, 2006, p. 24). Also, wind turbines can be categorized into Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) by the position of the rotating shaft (Wizelius, 2006, p. 73). But in practice vertical ones are less commonly installed in commercial scale and their contribution is minor when compared to horizontal ones. Furthermore, it is commonly seen these days to use classification as onshore, offshore and near shore turbines according to the location of the wind power plants (WindSector, 2011). However, the classification that will be addressed here in this article is defined by generator design, which includes more conventional ones paired with the gearboxes and gearless turbines with direct drive generator (Wizelius, 2006, p. 107). The direct drive generators are able to reduce a great amount of weight (up to 50% less) and operating costs, and this reduction mainly comes from the application of permanent magnets that replace traditional electromagnets (copper coils) (Fairley, 2010).

2.1.1 Basic Working Principles of Wind Turbines

A commonly used horizontal-axis wind turbine consists of several main components as blades, a nacelle, low-speed and high-speed shafts, a gearbox, and an electricity generator (EWEA, 2012), as shown in Fig 1 below. Blades that stretch out from the supporter are used for kinetic energy collection in the air. According to one publication (the Various Wind Turbine Technologies) of Global Energy Institute (GENI), blades are manufactured with airfoil shapes (with the top half is curved-shaped and the rest is flat) (Shen, 2012). Fig 2 demonstrates the blade design and turbine aerodynamics in detailed. The curved part that is thicker of a blade slows down the laminar wind. In consequence, the wind speeds up to catch up with the relative ones. The increased speed generates a lower pressure area right above the blades while the pressure remains comparatively
higher below it. Lifted by the difference of pressure, blades start to rotate. This phenomenon refers to lift effect. In the same time, a drag effect results from the friction along the blade is observed. Drag effect changes the moving direction of the blades that is led by lift one. Both of them contribute to the turbine rotation around the rotor (Shen, 2012). Then the rotation of the blades is passed to a shaft attached to a large gear that has the same speed as the rotor and then to a smaller gear with higher speed. This process is able to turn the slow movements of turbine rotor into fast-rotation. The shafts with higher speed are connected to coils that drive the electric generator in the nacelle to accomplish electricity production by creating an alternating electromagnetic field (Jacobson and Delucchi, 2011).

There are several factors that determine the efficiency of wind turbines. According to GENI's report (2012), the radius (also called “swept area”) of the blades influences the energy collection. The following equation 1 demonstrates the power of an air mass that flows at speed V through an area A in a straightforward manner (Ackermann, 2005, p.33). As shown in the formula, the larger area they cover, the more energy can be collected. Besides the blade radius, other factors like wind speed and air density also determines how much electricity can produce. Higher wind speed and heavier air contribute to better performance of wind power plants. Normally, a wind speed between 4-25 m/s is needed. But more than 25m/s would probably damage the turbines as well, although turbines are equipped with brakes that stop the blades when wind speed achieves certain limit. Meanwhile, air density is a function of altitude, temperature, and pressure. Higher air density leads to more effective rotors. Thus, high altitude areas which show lower air pressure and lighter density are not recommended for wind power collection, while one of the reasons that drives fast development of offshore wind
power plants is the high density of air near sea level (EWEA, 2012). Thus, wind turbines with larger rotor diameters, higher towers, and offshore construction are attracting more interest.

\[ P = \frac{1}{2} \rho A V^3 \]  

(1)

Where \( P \) (watts) denotes power output in kilowatts, \( \rho \) stands for air density (kg/m\(^3\)), \( A \) and \( V \) represent rotor swept area (m\(^2\)) and wind speed in m/s, respectively.

Moreover, a mechanism, anemometer and a wind vane are installed on horizontal- axis wind turbines. They help measure or sense the speed and direction of the wind and adjust the turbine in order to maintain facing the wind direction, since horizontal- axis wind power plants only capture wind that comes at the perpendicular angle (Shen, 2012). But no yaw mechanism is needed for vertical- axis wind turbines since they are able to catch wind from all directions. Vertical- axis wind power plants generates less energy and less noise, which makes them better for smaller scale or household installation.

### 2.1.2 Fast- growing demand for Wind Energy

Having been more dependent on oil price in the past, wind power utilization is nowadays driven by energy security as well as global warming issues. Both increasing energy efficiency and expanding renewable energy sources are essential in the process. Since the energy demand for economic activities and global development continues to grow rapidly regardless of the limited resources we possess, seeking for renewable energy has became focus of energy policy (Li, 2010). As stated in IEA’s report, the goal of limiting climate warming to 2°C is increasingly difficult and costly, and now the deployment of energy- efficient technologies can only buy us a bit of time for the implementation of real solution, the cut of greenhouse- gas emissions. Without carbon capture and storage (CCS) technology being widely deployed, renewable, carbon- neutral, or zero emission energy supply might be the only way out. Since it is suggested that less than one-third of fossil fuels can be consumed in order to limit the increase of global temperature within a 2°C range before 2050, which is also interprets into IEA’s 450 ppm GHG scenario (IEA, 2012).

Researchers all over the world are making great efforts to look for new reliable and practical energy sources that can supplement or even replace the fossil fuel we are using currently. Large amount of investment is getting into the research fields and the market. Nowadays, hydropower, wind energy and photovoltaic of solar power (PV) techniques are regarded as comparatively mature and commercial viable, while bioenergy, new generations of solar panels, wave power and tidal energy are still in development phase. In the meantime, hydroelectricity is raising concerns about negative impacts on surrounded the ecosystem and its potential remains largely restricted by hydrogeological condition (Smil, 2005, p. 246- 258). Thus wind power and PV are seen as viable energy sources and undergoing a rapid expansion, though both of these alternatives are faced with challenges of deployment, including intermittency, variability in source, material and resource demand, and certain concerns of environmental impacts. By comparison, wind power utilization is still advantageous due to its comparatively matured technology development as well as lower cost for investment when solar power being currently most costly renewable electricity source (Brown and Whitney, 2011).

Wind turbines that generate electricity out of wind are emerging at a high speed as a renewable energy technology. Generally speaking, wind energy is regarded as environmentally friendly, but in fact it is not an emission- free technology. Indirect emissions like the production of different parts of a wind power plant, such as blades, the nacelle, the tower etc., the exploitation of the material, and the equipment transportation to construction sites are present as long as the energy sources come from fossil fuel. However, the reported CO\(_2\) intensity of wind turbines is highly dependent on LCA methodology and data collection. According to a review of LCA on wind energy systems, CO\(_2\) intensities can vary from 7.9 to 123.7 g/kWh in published studies (Davidsson et al., 2012). Though given the arbitrary results that can be obtained by different life cycle analysis, wind power utilization is still advantageous in terms of emission when compared to other energy production pathways. The wind-based production has lower carbon footprint at 20-38g CO\(_2\)/kWh for on-shore turbines and 9-13g CO\(_2\)/kWh for off- shore techniques. Meanwhile, the carbon footprint for coal based generation is 786-990g CO\(_2\)/kWh, 488g CO\(_2\)/kWh for natural gas, and 26g CO\(_2\)/kWh for nuclear power. Moreover, some renewable production systems like geothermal power have 15-53g CO\(_2\)/kWh, when 88g CO\(_2\)/kWh is calculated for solar based production systems (Allen, 2011). In another similar study that uses average German energy mix, technology efficiency and lifetime, wind turbines emit 0.01-0.016 g SO\(_2\), 0.014-0.022g NO\(_X\), and 10-17 g CO\(_2\) for each kWh electricity produced at the average wind speed level of 6.5m/s, when 0.63-1.37 g of SO\(_2\), 0.63-1.56g NO\(_X\), and 830-920g CO\(_2\) would be emitted by coal- fire based electricity generation (Ackermann, 2005, p. 20).
In 2011, investment for developing clean energy mainly focused on the support of utility-scale projects, reached $260 billion. Among the assets, wind farms, solar parks and biofuel plants constructions are main actors (GWEC, 2012). In the same year, renewable energy took up nearly 50% of global electric capacity growth, which was estimated to be 208 GW. In this case, wind power shared almost 40% alone. And solar photovoltaic (PV) came as the second by accounting for around 30% of added production, followed by hydro- power with almost 25% (REN21, 2012). In U.S., wind power took up 13% of total renewable energy production, which shared 9% of total primary energy consumption in 2011 (U.S. Energy Information Administration, 2012). And in 2012, the total installed wind energy capacity achieved 100GW in EU (EWIA, 2012), which is equivalent to the electricity generated from 62 coal plants or from 32 nuclear power plants or from 52 gas power plants and is capable of supporting 57 million households’ electricity consumption.

A continuous growth has been witnessed over the wind energy utilization history, especially in last couple of years. The global cumulative installation of wind turbines reached 282 GW at the end of 2012 (GWEC, 2013). Figure 3 and Figure 4 illustrate the global installed capacity from wind.

As one of the countries with rich wind resources, China grew rapidly in wind energy utilization even though its wind industry only emerged in the late 20th century. It grew from only 340 MW in total cumulative installed wind capacity in 2000, to 44.7 GW in 2010 with an annual installed wind capacity of 18.9 GW. In the same year, China surpassed the United States to become the largest wind market in the world. China’s annual growth rate for cumulative installed wind capacity was over 100% between 2006 and 2009. According to the latest report, the cumulative installed capacity reached 75.32 GW by the end of 2012 (CWEA, 2013). In order to promote and regulate the development of wind industry, the Chinese government has issued a series of polices including providing subsidy and support, formulating mandatory targets of wind power quotas, establishing mandatory institution for grid connection, and localizing wind power equipment, during the 11th Five-Year-Plan (FYP) (Kang et al., 2012). During the 12th Five-Year Plan period, the new installed renewable energy capacity is expected to reach 160 GW, including 70 GW of wind power by the end of 2015 (European- China Clean Energy Centre, 2012). Such political determination is one of the underlying forces driving its rapid development.
2.2 Nd demand
This section introduces the basic definitions related to rare earth elements (REEs) and facts about rare earth industry. Three different parts that shed lights on the applications of neodymium in various fields (especially in the wind energy sector), the current production status, as well as the potential supply risks of neodymium (peak neodymium) would be presented in detail respectively.

2.2.1 General introduction to REEs
Rare earth elements are named because of their relatively low concentration for economically viable extraction rather than their scarcity (POST, 2011). The rare earth elements (REEs) are defined by the International Union of Pure and Applied Chemistry (IUPAC) and are referred to 15 elements with atomic number 57-71 in the group of lanthanides, plus scandium (Sc), and yttrium (Y), as similar chemical properties can be found in them (Neil G. Connelly et al., 2008). Among all the REEs, La, Ce, Pr, and Nd are regarded as light rare earth elements (LREE) that take up around 75% of total REEs production, while Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Ku, and Y are categorized as heavy rare earth elements (HREE) (Chen, 2011). According to Chen (2011), REEs are widely and unevenly distributed in around 34 countries all over the world, with about 110 million tons of reserves (U.S. Geological Survey, 2012). 95-97% of world supply comes from China alone and the rest from countries like Russia, Brazil, and Vietnam (POST, 2011). However, the domination of REM production from China does not reflect the global distribution of rare earth reserves. Currently, China is responsible for 97% of production with 120kt per year of REM (Humphries, 2010), but according to the report Situation and Policies of China’s Rare Earth Industry released by the Chinese Information Office of the State Council (2012), China only possesses 18.59 Mt of reserves, an equivalence of around 23% of the estimated total world reserve.

The main end-uses of REEs are glass manufacturing, catalysts, magnetic products, batteries, rare-earth phosphors, and so forth (Goonan, 2011). Permanent magnets (PMs) contain REEs like neodymium (Nd), samarium (Sm), praseodymium (Pr), terbium (Tb), and dysprosium (Dy) are the largest and fast expanding area of rare earth utilization (Schüler et al., 2011).

The element neodymium (Nd) is a soft, bright, silvery white metal with atomic number of 60 in the lanthanide series of the periodic table. Neodymium is strongly paramagnetic and was discovered by Austrian chemist Carl Auer von Welsbach in 1885. Neodymium has seven naturally occurring isotopes, among which the most abundant one (27.13%) is $^{142}$Nd (Encyclopaedia Britannica Online, 2013). Neodymium can be found in ores like the monazite and bastnäsite, and is also a product of nuclear fusion. Among Nd-containing ores, bastnäsite contains 12-19% neodymium carbonates by weight, when monazite has 17-18% neodymium phosphates in composition (U.S. Geological Survey, 2012). But monazite is less commonly mined compared to bastnäsite because it contains thorium, which shows high radiation levels (Humphries, 2010). Currently the main production of Nd is in the countries China, the United States, Brazil, India, Sri Lanka, and Australia.

As one of the rare earth elements, Nd forms intermetallic compounds like Nd$_2$Fe$_14$B or NdFeB with the transition metal Fe. Many of REEs based compounds tend to show strong anisotropy and have Curie temperatures that are above room temperature. These characters make them into ideal materials for permanent magnet. SmCo$_5$, Sm$_2$Co$_17$, and Nd$_2$Fe$_14$B or NdFeB are three main families of permanent magnet materials due to their better performance than earlier materials when measured by the maximum energy product (Cullity and Graham, 2008, p. 489). NdFeB magnets can reach energy products of 400 kJ/m$^3$ or more and remain as materials of choice for size minimization, such as in portable devices (Cullity and Graham, 2008, p. 491). This powerful neodymium, iron and boron (also referred to as NIB) alloy was first introduced in 1983 and is now widely used in portable devices (mobile phones, speakers, microphones, hard disks, etc.), fuel pumps, functional glasses, catalysts, motors, and also in wind turbines (Emsley, 2011, p. 338-339).

In the report of Critical Materials Strategy released by U.S. Department of Energy in 2011, neodymium remains in the category of critical material with high importance to clean energy and relatively high supply risk in the future, both in short and medium term analysis (DOE, 2011). Figures 5 and 6 point out the criticality of selected elements by three category levels with different time span analysis. In the chart, materials with higher criticality locate in the upper quadrant with higher scores of importance to clean energy as well as supply risk in designed time scope. Similarly, elements that have lower scores are characterized as near-critical or not critical (DOE, 2011).
At present, China dominates the neodymium production market, while USA, Brazil, India, Australia, and some other countries possess great amounts of unexploited deposits (Emsley, 2011, p. 338). China took the lead in REO production market in 1980s, mainly resulting from its lower production cost, looser environmental standards, and larger market of illegal extraction and smuggling activities. The overall historic production data and distribution areas are presented in Fig 7.

2.2.2 Nd demand in wind based energy industry

Wind turbine constructions require a great variety of materials, ranging from steel, concrete, different types of reinforced plastic, and various metals. Among these materials, steel and concrete are mainly for tower and nacelle building, reinforced plastic is used for blades, metals like copper and aluminium are needed for nacelle, and rare earth elements are made into permanent magnets for some generators (Jacobson and Delucchi, 2011). According to Jacobson and Delucchi (2011), there is no severe environmental or economic limitation to the expansion of wind power utilization in terms of material demand for bulk construction, since it mainly consumes concrete, which is made of gravel, sand and limestone. By recycling and reusing of concrete and steel (containing iron ore) can maintain the availability of bulk material sufficiently. Nevertheless, the property of concrete production in terms of energy intensity should not be neglected, since concrete and cement industry emits large amount of GHS as well as consumes non-renewable resources.

However, the biggest challenge in material requirement falls on the rare earth elements that are installed in permanent magnets for electricity generators (Lifton, 2009). Among all the components, the generator installed inside the nacelle is a crucial part in electricity production process. The principle of electricity generation is based on the electromagnetic induction phenomenon, which was discovered by Michael Faraday in 1831 (Ulaby, 2006). Moving at right angles to a magnetic field, a conductor is able to produce or induce a voltage, this is how electricity is generated. In wind energy engineering, there are two main categories of generators (Lynn, 2011, p.119). The first one is a synchronous generator, with which electricity is produced by separate excitation in a wound rotor synchronous generator (WRSG) or by permanent magnet in a permanent magnet synchronous generator (PMSG); the second type is an asynchronous generator, sometimes referred to as induction generators.
that rotate with a speed difference (slip). The asynchronous generators include squirrel-cage and wound-rotor induction generators (WRIGs), and doubly-fed induction generators (DFIG) (Lynn, 2011, P.128). The fundamental distinctions between synchronous and asynchronous operations can be illustrated in an imaginative analogy of “a very long bike” (Ackermann, 2005), where the cyclists act as either generators or loads in the grid system, while the balance of the bike is equivalent to the equilibrium of the grid. Ackermann (2005) gives further description and explanation in his book Wind Power in Power System.

Permanent magnet synchronous generator (PMSGs) mentioned above plays an increasingly significant role in recent wind power industry development. One of the main aims of improvement is to find a drivetrain that achieves high efficiencies, increases availability, and with grid-tie that avoids grid-side disturbances. Permanent magnets are applicable in direct-drive, medium speed, as well as high-speed designs, both for onshore and offshore applications (Saban, 2011). Double-fed induction generators (DFIGs) have dominated wind power industry with their performance by using two sets of electrically excited windings to generate magnetic fields instead of using permanent magnets (Hatch, 2009). But permanent magnet generators (PMGs) emerged rapidly into the market since 2005 with its significant advantages due to the demand of improvements in both wind power plant reliability and availability (Hatch, 2009). The permanent magnet generators are armed with higher part-load efficiency (up to 5% of annual energy yield), wider speed range, no rotor winding, which brings about rotor losses and thermal stress. Meanwhile, permanent magnet generators have lower weight for the same speed design and smaller envelope that requires smaller, lighter and cheaper nacelle. Furthermore, this type of generator reduces maintenance and service needs, which means less non-producing time offline (Saban, 2011). Currently the direct driven design has a 14% of market share (Schüler et al., 2011).

Nowadays the best permanent magnet is neodymium-iron-boron (Nd₂Fe₁₄B) based magnets, which also contain certain amount of praseodymium, and smaller quantity of dysprosium and terbium (Schüler et al., 2011). According to the study carried out by Schüler’s team (2011), neodymium based magnets has the advantage of high energy product that can reach 400 kJ/m³ or more (Cullity and Graham, 2008, p. 491), being about 2.5 times higher than samarium cobalt magnets and 7-12 times stronger than aluminium iron magnets. Meanwhile, additional rare earth metals such as dysprosium and terbium (Goonan, 2011) are added to the magnets in order to overcome the corrosion problems as well as limitation of operation temperature (Müller et al., 2001).

Consequently, the growing popularity of permanent magnet generator leads to increasing demand of Nd. Based on Emsley’s (2011) statement, wind turbines armed with permanent magnets require 0.7-1 ton of neodymium alloy for every megawatt (MW) of capacity. And a single Scanwind 3500 DL wind turbine with a 3.5 MW capacity, produced by a Finnish company called The Switch, needs more than 2 tons (equal to approximately 0.6t/MW produced) of neodymium-based (Nd-Fe-B) permanent magnet material for manufacturing (Hatch, 2009). In order to achieve enough wind power based electricity supply for global from Wind, Water and Sunlight (WWS) system, an increase by a factor of more than 5 in annual neodymium world production would be needed, which is quite impossible to be realized for a long time even with new extraction along with recycling measures (Jacobson and Delucchi, 2011). Additionally, more constrains from political power and incentives resulting from environmental concerns will limit the expansion of supply in the future (Lifton, 2009). The U.S Department of Energy (DOE, 2011) conducted a criticality assessment of rare-earth metals and pointed out supply challenges for dysprosium, neodymium, terbium, and yttrium in terms of clean energy technologies. Rare- earths permanent magnets benefits larger turbines and slower turbine speeds with direct-driven arrangement. Both of these designs are regarded as main trends of wind power development.

Meanwhile, the conventional wind power plant can also cause growth in demand of neodymium apart from the direct-driven ones. Since permanent magnets are also capable of reducing weight and cost of conventional wind turbine construction. An example of neodymium usage is that it is able to reduce an amount of weight of 10 tons of steel in the V112–3.0 MW tower (Davidsson et al., 2012). Different from direct-driven gearless wind turbines in which the neodymium in the form of permanent magnet is irreplaceable, conventional turbines require much less neodymium or even can be free from it. But more and more conventional designs are implementing permanent magnets to increase the efficiency and reduce the weight. Thus, neodymium utilization in conventional wind turbines should not be neglected.

In fact, the criticality of neodymium along with other rare earth metals used in wind turbines manufacture is less mentioned in current discussion or assessment of wind power plant constructions. More generally discussed issues are environmental and social impacts caused by wind power plant construction. These impacts mainly include sound propagation (Pedersen and Halmstad, 2003), health disturbance (Colby et al., 2009), threats to wildlife (Kuvlesky et al., 2007), increasing demand in land, and so forth (Wizelius, 2006, p.127-205).
2.2.3 Nd demand in other sectors

Apart from wind turbines, the strong Nd based magnets enables miniaturized design of applications like small speakers, and hard disc drives. Electric motors in hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are also the main interests of permanent magnets usage (Schüler et al., 2011). Furthermore, magnetic lifting and separation are widely applied in industrious field, while magnetic cooling are under research and development process, which might possibly add up to the future expanding demand for neodymium (Müller et al., 2001). Neodymium also plays a significant role in NiMH batteries production when it comes to electric and hybrid vehicles design. Overall, applications of electric motors for vehicles, wind turbines utilization, and hard disks would be the main factors that significantly determine the future permanent magnets demand (Schüler et al., 2011).

Nowadays, magnet-related applications are responsible for a share of around 20% in the global total volume of rare earth applications, while the share of value is about 37% (Schüler et al., 2011). An analysis of global in-use stocks (by application) of rare earths in 2007 demonstrates that the total Nd in-use stocks were 137, 000 tons, which shared approximately 31% of global total REE stocks. In the same year alone, 14,800 tons of Nd flew into use. The whole in-use stock of Nd resides largely in computer applications with an amount of 40,000 tons (29%), audio systems with 31,000 tons (22.6%), wind turbines manufactures with 18,000 tons (13%), and automobile related application also took up 13% with 18,000 tons of material (Du and Graedel, 2011). Similarly, in 2008, the total production of rare earth oxide reached 129,000 tons, and the neodymium oxide production accounts for 23,900 tons, taking up 18.5% of the total production. Among neodymium applications, about 76% was used for magnets, an equivalence to 18,200 tons. The rest was used for metallurgy apart from batteries (8%), battery alloys (5%), ceramics (3.5%), glass additives (1.5%), automobile catalytic converters (1%), and other applications (4.7%) (Goonan, 2011). As following, figure 8 demonstrates global REO end use status and possible substitutes options (UKERC, 2013), while figure 9 presents a closer look of neodymium application in 2010, based on the data provided by Peiró et al. (2013).

![Fig 8. Global REO end uses and substitutes, image source: UKERC (2013).](image1)

![Fig 9. Neodymium application by percentage in 2010, data source: Peiró et al., 2013.](image2)
The significance of REEs is caused by their critical functionality as well as their indispensability in various application areas and key technologies that support both sustainable mobility and energy supply in the global context. The challenges of REEs availability are mainly caused by monopolist, co-mining, environmental and social concerns (Alonso et al., 2012).

2.3 Peak Nd
In order to investigate the peak neodymium issue, it is necessary to bring up the theoretical background of this subject. In the following part, the concepts of mineral related topics as well as the historic background of peak mineral would be clarified.

2.3.1 Defining Resource and Reserve
The future application of minerals depends heavily on various factors. Their production status and values are influenced by economic factor, technological developments, population growth, living standards, political power, social attitudes, and so forth. Although in the case of some more abundant resources, the concept of reserves or resources might be less important, it serves as a useful qualitative leading indicator when we talk about the future production of exhaustible or finite resources. An inventory of resources is not only very useful for future production forecasting, but also is a prerequisite to the formulation of resource management policies. Thus, it is worth making effort to explore future production of certain minerals with an acknowledgement of availability being a major constraint (Rensburg, 1975).

The definition and usage of terminology regarding mineral estimation varies from region to region. There emerges great confusion about different definition of concepts and inconsistency in the usage. It is of great significance to clarify various definitions and standardize the usage in order to prevent confusion as well as inconvenience. Acute and sufficient mineral estimation also plays a crucial role in the description and forecasting process in this paper. Thus, the following part makes effort to provide definition of important glossaries based on the database and regions chosen for study, though given the fact that current international standards for mineral resource and reserve reporting system are still under development.

The most commonly implemented codes worldwide are JORC (Joint Ore Reserve Committee) in Australasia, SAMREC (South African Mineral Committee) code in South Africa, CIM (Canadian Institute of Mining, Metallurgy and Petroleum) guidelines (NI43-101) in Canada, CRIRSCO (Committee for Mineral Reserves International Reporting Standards) that models its member countries’ existed standards, USGS (U.S. Geological Survey) system, and UNFC (United Nations Framework Classification) for energy and minerals (USGS, 2013; CRIRSCO, 2008). Detailed introduction of USGS standard can be found in report Principles of a Resource/Reserve Classification for Minerals (USGS, 1981).

Mineral resources and mineral reserves are the two main categories in mineral estimation based on the evaluation of deposit’s technical and economic perspectives. And these two categories are furthered classified depending on the geological knowledge and confidence of the mineral. Later on, more subcategories are defined as inferred, indicated, or measured resources; and probable or proved reserves (Vaughan and Felderhof, 2002). Different frameworks for mineral classification are applied in different researches and evaluations. Most of the acknowledged frameworks follow similar terms in classification scheme although differ in details. Figure 10 below demonstrates the “CRIRSCO style” classification system in correspondence to definition of resource and reserve classification respectively.

![Fig 10. An illustration of ‘CRIRSCO style’ classification system (Weatherstone, 2008).](image-url)
There is general acknowledgment of terminology in mineral reporting, despite different words and ways of interpretation in terms of description and mathematical calculations in different standards. As stated by Vaughan and Felderhof (2002), mineral resources are concentrations or occurrences of minerals that have reasonable prospects of potential and value for eventual economic extraction. In the resource category, the part that can be assumed but not verified in terms of grade and content, according to its geological evidence, is defined as inferred mineral resource. An indicated mineral resource is armed with higher level of confidence results from exploration, sampling, and information collected from locations. When upgraded with certainty, these resources can be further categorized into measured mineral resources that are capable of supporting production planning. On the other hand, mineral reserves (also referred as “ore reserves” in JORC code) are mineable part of the measured or indicated mineral resource in an economical term. In the range of mineral reserve, probable mineral reserves are the economically extractable part of indicated mineral resource and in some cases, of measured mineral resources, while proved mineral reserves have higher level of confidence and are the economically mineable part of measured mineral resources.

It is worth noticing that the status of reserves and resources keep changing since new deposits are discovered and old ones are extracted continuously. Such dynamic behaviour is caused by the interaction between discoveries and depletions. On one hand, new technologies and increasing efforts (both time and investment) of developing new reserves. On the other hand, growing demand from the market and end-use would lead to decline of available volume and rise of mining costs, since the more economic viable deposits becomes depleted. Especially for reserves, its fluctuation depends much on available extraction techniques, process methods, market demand, political interference, and social factors. Though reserves represent the extractable part of resource concentration, they could become uninteresting for extraction activities when the price or market demand decreases.

2.3.2 Peak mineral

Peak mineral issues arise due to the continuous growing demand for metallic and nonmetallic minerals. The driven force mainly comes form the rapid rise of global population, urbanization and industrialization. The peak mineral is one of the most crucial topics of the sustainable development. As pointed out in the book Limits to Growth (Meadows et al., 2004), which explores how exponential growth in modern society interacts with our exhaustible resources, the demand of finite resources (like oil, metal, fresh water) are growing in an exponential manner due to the growth of population, living standard, industrialized level, and economy; and this overshooting of demand would lead to similar growth of pollution and emission in return. Similarly, Richard Heinberg, one of the world’s foremost Peak Oil educators, points out that we will be confronted with an end to growth and a commencement of decline of population, arable land, fresh water availability, uranium production, climate stability, wild fish harvests, annual extraction of some metals and minerals, and so forth (Heinberg, 2010).

As we talk about peak mineral, the production of terrestrial ores must also follow up in order to provide sufficient supply for the service to this development. Thus, accurate estimation and evaluation of resource availability, production rates, future trends and the associated impacts from different aspects is needed for a better management of finite mineral resources (Bleischwitz and Bringezu, 2008). As one of the focus of resource depletion problems, peak mineral shares similar properties with peak oil issue, which sheds light on peak and ultimate decline of worldwide oil market. The research of peak oil contributes better understanding of the resource utilization situation as well as for proper response to the fluctuation of price and supply.

A rapid exhaustion of oil resources had already caught people’s attention before Hubbert, an oil geologist, developed the first formal mathematical techniques for generating extrapolations of production trends for finite resources and presented the peak of oil production in his paper (Hubbert, 1956). He predicted 1970 as the approximate year of peak oil production in USA by applying a bell-shape curve in projections for unconstrained production of finite resources. Now this concept is generally known as “Peak Oil” or sometimes as “Hubbert’s Peak” (Deffeyes, 2009). Hubbert is one of the most fundamental researchers in the field of sustainability of natural resources production. His laid the foundation for future production study of exhaustible natural resources (fossil fuel in particular) by establishing prediction approach on the base of the historical data and the ultimately recoverable reserves (URR) (Almeida and Silva, 2009). Apart from the upper limit of production rate, Hubbert’s analysis also indicates that the production would become more difficult and eventually unfeasibly expensive in the context of growing population and demand, in which situation the alternative energy sources (nuclear power as he suggested) would be favoured. Thus, a transition from conventional oil supply to new energy system should be planned in advance in order to secure the energy services (Hubbert, 1956).
As an extension of his model, Hubbert’s methodology was later implemented in different finite resources research, such as coal, natural gas, uranium, and other minerals. 57 minerals were examined by modelling and the result shows that bell-shaped curves can be applied in mineral study (Bardi and Pagani, 2007). “Peak minerals” was raised because terrestrial mineral deposits are considered as non-renewable and their stocks as exhaustible, while their production has increasingly influence on our society. Similar to peak oil, the thing that really matters in mineral economy is not how much the resource exists but the feasibility and speed of extraction.

As by definition, the peak production of a mineral occurs when the production from the ores can no longer sustained to meet the demand (Prior et al., 2012). Prior points out that there already has been evidence that indicates peak mineral issue in Australia. Declines in ore grades, increasing inputs such as energy costs and investment for mining, growing pollution results from mineral extraction, as well as accumulating social pressure are driving the industry towards more sustainable ways of production and management. According to Fig 11, the curves are capable of visualizing the peak production and future supply trend (Prior et al., 2012).

The extraction costs are relatively low in the beginning phase. But after those easily accessed and easily processed ores were extracted, the market would witness an increase of production costs as well as a decline of ore grades (Mason et al., 2011). It is unlikely that mineral resources will be depleted completely, but the increase of costs caused by lower concentration of resource and drop of quality in remaining reserve would outweigh the factors of technological improvement and new reserves. Consequently, a rapid production decrease would occur (Bardi, 2005). Meanwhile, the peak of mineral is also interlinked with impacts of sustainability, technology, economic, and other constraints (Mudd and Ward, 2008).

Forecasting future production trends of peak minerals and mineral depletion has significant implication for society and the discussion of its processes and consequences is on going. The projections of future production focus on studying when a certain resource would become unfeasibly extracted and how it might happen, either in an economical or in a physical term. At the same time, it is acknowledged that they are designed to capture geological constrains but inevitably leaving out variants like social and environmental impacts of changing production capacities as well as processing methods (Prior et al., 2012). This is because geological abundance is one of the constraints to production. It also often refers to the ultimately recoverable resources (URR) as the limiting factor of finite resource production. Therefore, these models are based on the assumption of free market without concerning dynamic processes led by political, economic and social factors in the system (Höök et al., 2011). Moreover, a great proportion of modelling activity that fits historical production data to Hubbert’s curves fails to engage with his original objective, which makes effort to assess the way to a transition from oil to alternative energy supplies (Mason et al., 2011). Hubbert’s peak oil assessment lays the foundation for better understanding of broader economic and social impacts. A more holistic framework is developed in the paper “Availability, addiction and alternatives: three criteria for assessing the impact of peak minerals on society” (Mason et al., 2011). This framework takes not only the availability of a resource (including geological characteristics and geographical distribution) into account, but also considers the society’s dependence on the resource (its centrality and criticality to economic, social and environmental systems) as well as the technological perspective (its recoverability and substitutability).

Since there is limited work that has been done to explain the validity of applying peak modelling in mineral study, a call for more efforts in peak mineral research. One of the main differences between peak oil and peak minerals discussion is that recycling of minerals can be done in industrial life cycles (though at present lithium and REEs are seldom recycled because of their chemical properties and high associated costs), while oil consumption are non-renewable. Available data can also be hard to obtained due to various standards of reserves and resources classification. Thus, the estimation of mineral reserve and resource is comparatively
uncertain when compared to oil (May et al., 2012). Along with difficulties lie in the consideration of social and economic constrains, it is more realistic to predict the peak as a range of timeframe instead of making an exact prediction of peak year. However, it is of great importance to consider assumptions regarding the modelling process, production conditions, and estimation of resource properties (quantity and quality).
3. Methodology
This section demonstrates the main methodology applied in this study.

3.1 Quantitative Data Collection
Quantitative data analysis makes effort to search for patterns in the data by various established techniques and then to draw conclusions (Oates, 2006). Data or evidence can be assembled from various sources. This paper is document based study, including literature review and data collection from both found documents and researcher- generated documents.

The main source of data comes from annual reports of international or national organizations, such as IEA, USGS, and Ministry of Land and Resources of the People's Republic of China, while some of analyses are modified research results from secondary data and former study archives of related subjects.

In terms of annual worldwide production data for analysis, the literature contains the USGS (U.S. Geological Survey) database that records a wide range REO data in different aspects. Annual REO production statistics from 1900 to 2011 were assembled from Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140, in the category of rare earth (2012). Production of REO in specific regions and countries from 1995 to 2013 are gathered from sources in the same data series and from annual statistical review of mineral production report, the Minerals Year Book (USGS). Annual neodymium production data are generated from production of REO based on the neodymium oxide ratio of 18.5% as indicted in Goonan’s paper (2011). In the same time, U.S. Geological Survey also points out that, in bastnäsite, 12-19% neodymium carbonates can be found by weight, when monazite contains 17-18% neodymium phosphates (2012). Thus, a percentage of 18.5% is chosen to be a plausible generalization for the world, since detailed figures of neodymium oxide concentrations per deposit are seldom available.

Meanwhile, the overall climate initiatives for future clean technology plan as well as development plan for wind power plants are collected from IEA’s World Energy Outlook (2011), China’s 12th-Five Year Plan (FYP), other material flow analysis regarding REO demand, and so on.

3.2 Time Series Analysis
Up till now, the growth curves have been well established and are widely applied in energy related studies, including resource analysis, demand modelling, fuel substitution, and technology development in energy systems (Ang and Ng, 1992). There are a great variety of available growth curve models. Fitting statistic data to proper models, research can be carried out by generating both descriptive and predictive curves.

According to Chatfield’s introduction in his book Time Series Forecasting (2002), a time series is defined as a collection of sequentially measured observations through time. This measurement can be done either continuously over time or discretely at time points. The key characteristic of discrete time series is that the data are collected at equal interval of time. The analysis of equally spaced time series accounts for the majority of time- series applications.

There are four main objectives of time series based analysis, which is based on the data consist of one or more time series. By building time series models, such analysis aim at producing descriptions of data, modelling (either with univariate or multivariate) data generating process, forecasting, and controlling according to the projection of future situation. Among these objectives, they are interlinked and at most of the time description and modelling of the data are prerequisites to forecasting and control procedures. Practically, time series forecasting is commonly used in applications like planning (economic, production and capacity), sales forecasting, inventory control, financial management, evaluation of models or alternative economic strategies, and so on (Chatfield, 2002, p. 2).

As stated by Australian Bureau of Statistics (ABS), a classical time series analysis tries to decompose the variations in an observed time series into seasonal or other cyclic variations, the trend, and irregular fluctuations (ABS, 2008). The seasonal variation arises for series when similar patterns, systematic behaviours, or calendar related movements are observed at particular times when other cyclic variations are not restricted to annual period. The irregular fluctuations, on the other hand, are often referred to random, unsystematic, or short- term correlation variations. Apart from these variations, the trend reflects underlying upward growth or downward decline patterns over successive time periods (ABS, 2008). Thus, it is also defined as the long- term change in the mean level with no presence of calendar related variation and irregular effects (Chatfield, 2002, p. 13- 14).
Time series analysis is suitable for forecasting activities along with other techniques and tools to help extract statistics and characteristics for target studies (Höök et al., 2011) as well as give aid to better understand the system by studying its underlying physical properties (Bardi, 2005). Hubbert first introduced his peak oil theory based on the projection of oil production with the help of a logistic curve model in 1949. The peak occurred in the year of 1971, only one year later than Hubbert’s prediction (Deffeyes, 2009). Later on, mineral production was observed to have similar behaviour as oil one. Compared to the symmetric bell-shaped curves, Bardi (2005) pointed out that the curves of mineral production could also be asymmetric by introducing factors like the search strategy or technological improvements.

In this study, time series is used for descriptive neodymium production over history and future supply prognosis when projected demand for neodymium will also be projected. In terms of supply, both predictive annual and cumulative (s-shaped or sigmoid curve) production trends will be generated by fitting historic production data of REO into three models (logistic, Gompertz and Richards), which have been applied to peak oil analysis and other exhaustible resources with limited reserves and continuous extraction. Later on, an attempt to estimate future potential demand scenarios for neodymium will be made. This projection will cover both revolutionary and evolutionary demands that are furthered, divided into four scenarios based on historic growth and World Energy Outlook report (IEA, 2011). With both supply and demand prognosis, this paper could carry out preliminary comparison and obtain discussion base for peak Nd issue.
4. Modelling
This sector introduces main methods and tools that are utilized in this study.

4.1 Growth Curve Fitting
Fitting historical data, such as non-seasonal data that displays a trend, to a proper curve in order to further describe and forecast the changes by giving changes to variables is commonly used in statistic analysis, for better strategic decision making. In this section, the discussion will focus on the introduction of fundamental curve models in energy system studies.

There are three basic types of growth curves: unbounded, bounded, and bell-shaped curves (Höök et al., 2011). According to Höök (2011), the unbounded curves will grow towards infinity in the long term, while the bounded growth models are subjected to limiting factors that bring about an upper limit to its value. The bell-shaped curves illustrate the derivatives of sigmoid functions, which can be used to indicate annual equivalents in a time series. In this case, bounded growth curves and bell-shaped curves are more realistic in finite resource or renewable energy studies in the long run.

At the same time, choosing proper curve models is not enough. It is also important to use certain techniques in order to fit the historical data into the model scientifically. For example, the least square method and other regression techniques are easy to carry out in modern statistical and data processing software. In the analysis, some points that might affect the accuracy of outcome should be addressed. The analysts should avoid generating models with a lack of physical meanings or unreliable behaviour for projection caused by overestimating the importance of fitting or overlooking underlying data. Also, the term called “over fitting” is witnessed in analysis due to the applications of excessively complex models. Such curves do not perform well in extrapolation tasks, since they describe noise instead of the real trend or exaggerate unimportant fluctuations in the data (Anderson and Conder, 2011; Höök et al., 2011). Statistic methods like cross validation, statistical regularization, or common sense can help prevent the problems of over fitting. The crucial requirement for analysts is to be cautious about the data and their intrinsic properties.

It is also pointed out that several factors should be taken into consideration since they might limit the confidence in model extrapolation process. They are the validity of the assumption, an appropriate model for the data, feasible curve-fitting methods, obtainable model parameters, and the sufficient reflection of future behaviour from present factual situation (John, 1998).

The general information of three chosen models applied in this paper is included along with specific settings in Table 1 as follows, where URR represents ultimately recoverable resources; t0 is the peak year; and M denotes a variable parameter in Richards model.

4.2 Future Demand Scenarios
In order to find out future availability of neodymium, it is beneficial to examine the difference between supply and demand. Thus, this study makes effort to evaluate future potential neodymium demand scenarios. Comparison between projected supply and demand trends will be made.

Four scenarios are designed in these estimations. Scenario A projects future demand based on the historical growth of REO, which will be transformed into Nd demand by multiplying the Nd content percentage in REO reserves. Scenario B, C, D are set as revolutionary demand according to three scenarios till 2035 in IEA’s World Energy Outlook (2011). Scenario B is corresponding to IEA’s New Policies Scenario, which summarizes the newly announced policies from different countries after promising to tackle emerging concerns about energy security, climate change, environmental pollution, and other challenges related to energy issues (IEA, 2011). Scenario C aims at interpreting IEA’s Blue Map scenario (450 ppm GHG target with carbon capture storage techniques). Meanwhile, Scenario D reflects the Delayed CCS 450 Case presented in the report. This prediction is designed due to the possible delay in the commercial viability of CCS according current global GHG technique development and deployment forecast. Thus, alternatives of low-carbon energy technologies,
reduction in energy demand, and/or sufficient increase in efficiency would be necessary to reach 450 ppm of GHG target. All of B, C, and D scenarios consist of two parts of demand (evolutionary and revolutionary), which is denoted as $D_e$ and $D_r$ respectively.

In calculation of historic growth rate ($g_h$) and revolutionary demand growth of neodymium ($D_r$), the Equation 2 and Equation 3 are implemented (Alonso et al., 2012).

$$g_h = \left(\frac{D_r}{D_0}\right)^{\frac{1}{\Delta T}} - 1$$

$$D_r = \sum D_w + \sum D_{(EV+PHEV)}$$

The following Table 2 shows the basic properties and setting of scenario models used in the prediction of future neodymium demand. Since it lacks sufficient data regarding individual neodymium when it comes to specific industrious sector as well as future market share, certain estimation and assumptions are made during the analysing process, which will be explained in detail later.

<table>
<thead>
<tr>
<th>Demand Scenario</th>
<th>Assumption</th>
<th>Demand Evolutionary growth</th>
<th>Revolutionary growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Uniform historical growth rates</td>
<td>$D_e$</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>IEA New policies scenario</td>
<td>$D_e + D_r$</td>
<td>$D_{w} + D_{(EV+PHEV)}$</td>
</tr>
<tr>
<td>C</td>
<td>IEA 450 ppm scenario</td>
<td>$D_e + D_r$</td>
<td>$D_{w} + D_{(EV+PHEV)}$</td>
</tr>
<tr>
<td>D</td>
<td>IEA Delayed CCS 450 scenario</td>
<td>$D_e + D_r$</td>
<td>$D_{w} + D_{(EV+PHEV)}$</td>
</tr>
</tbody>
</table>

($D_e =$ demand for neodymium with uniform historical growth rates; $D_r =$ revolutionary demand apart from application in wind and electric vehicles; $D_r =$ revolutionary demand in terms of growth in permanent magnets and battery utilization in wind turbines, EV, and PHEV; $g_h =$ historical growth rate; $D_0 =$ demand of base year; $D_{w} =$ neodymium demand for permanent magnets and batteries.)

When it comes to figuring out the approximate amount of neodymium needed in IEA scenarios, demand from wind turbine production ($D_w$) and from electric vehicle applications ($D_{(EV+PHEV)}$) are calculated by using following equation 4 and 5.

$$D_w = D_{\text{turbine}} \times A_w \times P$$

$$D_{\text{EV+PHEV}} = D_{\text{EV}} \times A_{\text{EV}} \times P_{\text{EV}} + D_{\text{PHEV}} \times A_{\text{PHEV}} \times P_{\text{PHEV}}$$

Among all the parameters, $D_{\text{turbine}}$ denotes neodymium demand for each single wind turbine that has direct driven gearless design when $D_{\text{EV}}$ and $D_{\text{PHEV}}$ means the ones required for certain vehicles; $A$ represents annual additions of particular application (here refers to wind turbines, electric vehicles, and plug-in hybrid electric vehicles respectively); $P$ is defined as the percentage of neodymium- required application in total market. A few assumptions are made in the projection due to lack of information and data.

4.3 Excel Spread Sheet Solver

In order to fit an optimal curve or model to data series and further to extrapolate the model, standard curve fitting functions are chosen in this paper. Then it presents an enhanced functional solution by employing the Solver add-in function, which is included in Microsoft’s Excel spread sheet package. The Excel Solver uses the Generalized Reduced Gradient (GRG) Algorithm, SIMPLEX linear programming and evolutionary algorithms methods as constrained optimizer (Microsoft, 2013). And GRG- mode is applied in this fitting. The Solver function in Spread Sheet Add-ins is capable of generating the optimum value of a “Target cell” (or objective function) by adjusting the values of variables designated as values in “Change cells” (or decision variables). The user sets all of these values based on the specification of the given problem. It is also necessary to input the Target and (or) Change cells within certain specified constraints. Consequently, solving a problem by using Solver needs not knowledge of the Target cell, the Change cells, as well as the Constraints for both or one of them. After defining the cells and specifying the search conditions and solution parameters, the user will obtain a solution to a particular problem. The Generalized Reduced Gradient Algorithm method applied in the form of Solver is widely acknowledged for its simplicity and convenience. Besides, it is able to fit various models in a whole range. Being capable of investigating several different models for a data series in the same time, the Solver gives aid to the model selection process by comparing the sum of squared errors of tested models (John, 1998).
In this paper, the Target cell is set as the sum of least square of generated annual production from selected models and actual collected data. By modifying values of peak year \((t_0)\) and growth, the Solver optimize the fit of the curves when minimizing the total least square value. Moreover, a constraint of maximum depletion rate is added in order to simulate the depletion behaviour in reality and to optimize the mathematical fits by assuming that there would be no future production that depletes recoverable resources faster than the most extreme cases found in history. Since it is not possible or reasonable for an over speed depletion based on the empirical experience and technology development. The depletion rate of remaining reserves is implemented in the projection and is defined in the following equation 6.

\[
Depletion\ rate = \frac{Annual\ production}{URR - Cumulative\ Production}
\]

The maximum value of depletion rate is set at 5% based on former study and similar production peak predictions (Höök and Aleklett, 2010; Vikström, 2011).
5. Results

5.1 Nd Reserve and Resource

5.1.1 Estimated Nd Availability and Distribution (Reserves and Regions)

According to U.S. Geological Survey’ annual report of rare earths status (USGS, 2013), the world total estimated reserve of rare earths oxide is around 110 Mt. This figure will be used in this paper for future production modelling. Though only a limited amount of reserve estimates of REOs is available in public database, there is not much variance in terms of global total reserves. Compared to the figure of USGS estimation, BGS (2011) states 113.8 Mt for world REO reserves.

Among all the deposits of rare earth economic resources, bastnäsite in China and the US take up the largest percentage, when monazite deposits comes as the second largest segment, though its extraction is restricted due to its radioactivity. With the shutting down of the once largest mining site- Mountain Pass, California in the mid-twentieth century, China has dominated the mining and refinement of rare earth with more then 97% of production these years, but with only 36% of total world reserves (Information Office of the State Council, 2012). The remaining monopoly of China mainly results from the elaborative separation and refining processes in production, since it is highly labour intensive along with consequential safety and environmental impacts (CSIS, 2010). It is also typical that REO production depends heavily on large deposits that determine economic viability (BGS, 2011). For example, a proportion of 43.5 out of 52 Mt of REO reserves in China are located in its Bayan Obo deposit (Schüler et al., 2011). The overall demonstration of reserve and main distribution countries of rare earth oxide is showed in Fig 12. Only some larger production countries are explicitly illustrated, countries and regions with smaller reserve amount or inaccurate data, such as Malaysia, Sri Lanka, Canada, South Africa, Zaire, Commonwealth of Independent States (CIS), are included in the category of other countries.

It is worth noting that estimation of world reserve varies from published study to study due to the fact that different research groups or organizations tend to include different amount of deposits from various regions. Also, a lack of available data in some regions or period of time is one of the main reasons for inaccurate figures as well as the difference between reports (BGS, 2011). It is also common that many reports only present aggregated figures without specific numbers in detail. Meanwhile, a wide range of estimated results could also be generated based on the same data with different analytical methods.

Meanwhile, it is acknowledged that the amount of reserves is not necessarily fixed, or can be changed when the definition of reserve is modified or updated, as mentioned in earlier section. Continuous discoveries, improving extraction technology and/or increasing economic input for more former unviable deposits lead to increase of estimated reserves. As Fig 12 shows, world total reserve of REO went through a rapid growth from 2010 regardless of growing extraction and in-stock utilization of these elements.
### 5.1.2 Describing Historical Production

By examining the historic production data in different countries, a graph (Figure 15) that shows REO production in countries was generated. It indicates that China entered the production phase after 1980, and started to gain its domination in the market when the USA decreased its production in Mountain Pass. Now it is called the China era in terms of rare earth oxides production.

With a closer look at the production data from 1994 to 2012, Chinese production had kept rocketing until around year 2010 due to Chinese policy of reduce export quota. China imposed restriction on rare earth oxide production as well as on export in order to preserve its future supply and conserve the degrading environment since 2007. The amount of produced rare earth oxide dropped from the peak of 129kt in 2009 to 95kt in 2012 (USGS, 2013). According to the statement of Ministry of Land and Resources (2012), the REO production quota for 2013 is 46.9kt, which is about half of the amount in year 2012, mainly due to environmental and sustainable concern regarding the finite REO resource and environmental hazardous extraction process (Wu et al., 2012).
5.2 Forecasting Future Production

5.2.1 Worldwide Production Projection

The general estimates of neodymium oxide content in REO is about 18.5% as discussed in previous chapters and the neodymium content in compound Nd₂O₃ is 85.74% by using standardized atomic masses. With these figures, this study estimates the approximate total reserve of neodymium oxide is around 20 Mt, and neodymium reserves to be 17 Mt. There are also other similar projections that include a more optimistic estimation based on 35 Mt reserve amount, more information can be found in related work (Vikström, 2011).

With the URR amount set at 17.5 Mt, three chosen models yield overall future neodymium supply trends (as shown in Fig 16). In order to gain a better perspective of long-term analysis, the model sets a time span of 100 years after the latest data of year 2011 gathered from sources. The logistic curve demonstrates a more obvious and higher peak, where year 2077 turns out to be the peak year of production with around 230kt worldwide. With the same URR base, the Gompertz curve peaks at the year of 2099 with production volume of 94kt, while Richards model indicates the peak occurs in 2089 with 130kt production. Unlike the other two models, the logistic curve shows a narrower shape and declines more rapidly after the peak.

The main reason for different outcomes of the projection comes from the depletion rate. Though a maximum depletion rate is set at 5% in the process, the logistic model has a comparatively higher depletion rate, since it shows a symmetric property that allows the curve to peaks when half of the URR is extracted. Meanwhile, the other two models illustrate a more gentle depletion behaviour. This difference in depletion rate can also be found in the maximum annual production amount as mentioned above, where logistic model reached around double volume of peak production. From the graph, it is obvious that both Gompertz and Richards models still maintain quite stable production till 2110. On the contrary, the logistic curve would go through a dramatic change of production volume from 230kt in 2077 to approximately 120kt in 2110.

However, the logistic model is a very well established model used in various fields from population growth to market diffusion, some of the examples are predictions of U.S. peak oil crisis, outlook for electricity demand (in New Zealand), and nuclear power plant installation limit (Höök et al., 2011). It reflects real world exploitation of exhaustible resources with supply-demand interactions, natural capacity limit for utilization, or social acceptance of certain contradictory development projects, in a reasonable manner. On the other hand, the Gompertz and the Richards projections can represent a more sustainable development strategy for finite resources exploitation with lower depletion rates. The difference of strategy can be determined by economic factors, political interference, and/or pressures lead by social concerns. More detailed interpretation and discussion are included in later chapters.
5.2.2 Future Production in China

Trajectories of future supply trends of China are generated with the same methodology and methods as demonstrated in Fig 18. Since it is a projection restricted in China, a corresponding REO reserve of 55 Mt is chosen. The neodymium oxide and neodymium reserves are 10.17 Mt and 8.75 Mt respectively. In terms of time span, the projection starts from year 2013 with a yield of 100 years. But the historic data is only available from the year 1982. The result of future production trends shows different characteristics when compared to the global prediction. The peaks of all three selected models are much closer. The logistic model peaks in year 2061 with 139.1 kt; the one of Gompertz occurs with 79.9 kt in 2062; and Richards model shows the maximum production in year 2059 with a volume of 103.5 kt. But similarly, logistic still goes through a steeper drop after the peak, while the other two are armed with comparatively smooth declines.
Nevertheless, there lies even greater uncertainty in China’s case, since the government is carrying out a series of policies that aims at reducing extraction quota, limiting exportation, as well as banning illegal extraction, in order to preserve its rare earth resource. In consequence, more constrains would be imposed on production while the market price would rocket and thus encourages the supply in return. As shown in the figure 18, a rapid drop of production appeared after 2009.

But without any doubt, neodymium production in China is confronted with big challenges if the extraction continues as it is in the future. Peak of neodymium production would show up around 2060, which is about 30 years earlier compared to the global one.
A comparison of peak year and peak production corresponding to different models between global and China perspective is presented in Table 3.

<table>
<thead>
<tr>
<th>Area</th>
<th>Model</th>
<th>Peak Year</th>
<th>Peak Production (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worldwide</td>
<td>Logistic</td>
<td>2077</td>
<td>229.9</td>
</tr>
<tr>
<td></td>
<td>Gompertz</td>
<td>2099</td>
<td>94.3</td>
</tr>
<tr>
<td></td>
<td>Richards</td>
<td>2089</td>
<td>130.1</td>
</tr>
<tr>
<td>China</td>
<td>Logistic</td>
<td>2061</td>
<td>139.1</td>
</tr>
<tr>
<td></td>
<td>Gompertz</td>
<td>2062</td>
<td>79.9</td>
</tr>
<tr>
<td></td>
<td>Richards</td>
<td>2059</td>
<td>103.5</td>
</tr>
</tbody>
</table>

5.3 Future Scenarios for Nd Demand
Four scenarios designed in this section aim at forecasting neodymium demand in a near future (till 2035) with main driving force from environmental concern and climate policies. Scenario A represents an evolutionary growth with the assumption that all the neodymium application would grow at a uniform rate as the historic one. The other three scenarios convey revolutionary development and utilization of neodymium in the short term. Key calculations and predictions are based on IEA’s proposed scenarios for climate change mitigation as well as energy security. Three scenarios, including New Policies, 450 Scenario, and Delayed CCS 450 Case, are introduced into this study. Detailed explanation is listed in Table 4 (IEA, 2011, p. 240).

<table>
<thead>
<tr>
<th>Demand Scenario</th>
<th>Description</th>
<th>Average Annual Additions (2011-2035)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Evolutionary scenario</td>
<td>Uniform historical growth rate</td>
</tr>
<tr>
<td>B</td>
<td>New policies scenario</td>
<td>52.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>C</td>
<td>450 ppm scenario</td>
<td>75.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.7</td>
</tr>
<tr>
<td>D</td>
<td>Delayed CCS 450 scenario</td>
<td>90.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.3</td>
</tr>
</tbody>
</table>

For Scenario A, a historic growth rate of 4.3% is obtained by using equation 2. Meanwhile, some estimation is made based on available data and references. According to DOE’s report on criticality of rare earth elements (DOE, 2010), neodymium content is around 31% of total magnet weight, which is calculated to be 600 kg/MW for high case and 400 kg/MW for low one. Thus, material intensity for neodymium is estimated to be 200kg/MW for direct driven gearless turbine installation. In the same time, current ration of direct driven wind turbine is applied in this paper, which indicates 14% (Schüler et al., 2011) of newly planned wind power plants belong to the category. And in terms of material intensity for electric vehicles and plug-in hybrid electric vehicles, it is really difficult to find out or even determine the neodymium amount in need for manufacture. Since NiMH batter that requires neodymium is most common one in current industry, but in the same time Li-ion battery are making rapid progress to take the lead. Also, it increases the amount of neodymium when a high efficient motor is installed. All these factors will be heavily influenced by the technology, market price, and material availability in the future. Thus, a general estimation of 1kg neodymium needed for each permanent magnet involved vehicle and a moderate assumption that 50% of these vehicles implement NiMH battery is made. Since it requires 0.3-0.65 kg Nd for each vehicle motor and 0.2-0.31 kg per NiMH battery (DOE, 2010), while other results of neodymium content in electric vehicles can vary from 0.19kg to 1.8 kg (Schüler et al., 2011). Furthermore, the 50% market share of neodymium intense vehicle models in all electrical vehicles is assumed due to the high uncertainty of future technology development and economic factors.

Four projected future demand scenarios are shown in figure 20 along with the former produced supply trend trajectories. The four demand trends have similar growth shape but Scenario C and D reach higher number of neodymium demand over all when compared to the evolutionary and New Policies one. In the year of 2035, Scenario A would require 48.5kt of neodymium, and Scenario B, C, D demands 48.9kt, 58.8kt, and 59.9kt respectively. In other words, three IEA scenarios with different annual additions of new technologies that require neodymium have small impact on the total demand, but they do expect more neodymium in use.
According to the comparison between projected supply and demand trends, all three curves of future supply trends can meet the demand of Scenario A and B, which represents historic growth model and New Policies. When it comes to more aggressive demand scenarios that aims at achieving 450 GHG target, moderate production model (Gompertz) will not have sufficient production to keep up with the demand. And the logistic model cannot meet the demand at first but with faster growth rate, it would be able to surplus the demand of Scenario C and D. Similar behaviour can be observed in the light of Richards curve, but it takes longer for it to catch up with the demand.

Obviously, there lies more complex detail and result beneath the surface due to the methods this paper apply and assumptions that have been made here. Thus, a detailed discussion based on the analysis of the result will be carried out in the coming section.
6. Discussion

6.1 Status of Current Neodymium Market

The rare earth production has increased at a rapid pace in order to meet the demand upsurge since 1950s. As one of the rare earth elements, neodymium is experiencing a major increase in production due to larger market of portable electronic devices and clean technological applications.

As mentioned in the background section, rare earth elements are not rare and they are not characterized as scarce in terms of occurrence, but instead are referred to their relatively low concentration for feasible extraction. It might be more appropriate to use tricky to describe rare earth elements, especially for energy critical elements like neodymium. A rising concern of neodymium availability leads to this study of neodymium demand and production. From the current analysis of global neodymium market, several major characteristics can be observed. Since neodymium shares similar properties as other rare earths as a whole, one can get quite a sufficient look at neodymium issue by looking into the overall rare earth elements under certain circumstances.

As shown in Fig 12, the global total reserve of REO still expands even though extraction activities and in-stock utilization are rising. The reserve of REO appears to be satisfactory but the problematic part of rare earth supply is not only physical reserve constraint. There are a lot of variants that affect the production.

Without any doubt, the uneven distribution of reserve deposits is one of the restrictive properties and probably not going to change in the near and medium term outlooks because of the long time lag for finding and developing REE-deposits for actual extraction elsewhere. Based on the data obtained from USGS, the global distribution of rare earth deposits as well as the one inside China was obtained. It is obvious that China possesses a large proportion of reserves (48% in 2012), as demonstrated in Fig 13, and of which locates mainly in a few giant deposits. What makes the global rare earth market abnormal is the more unevenly distributed production capacity. Since 1980s China has accounted for major production activity (97% at peak level), as illustrated in Fig 14. Inner Mongolia (province) and Gansu province contribute more than half of the annual production with 87kt in 2011. At this moment, the monopoly of China apparently becomes the biggest concern of global rare earth market and in particular of critical elements for clean technology, which plays a crucial role on the way to future energy security and climate change mitigation. This limitation significantly influences the market price of these elements. A constant rise of rare earths prices has been witnessed over the last few years due to a reduction of mining and export quotas from China (Piedra, 2012).

Apart from geographical aspect, the ore properties of rare earths result in more difficulty in production. Since rare earth elements always occur together instead of individually in the earth, they must be extracted by co-mining, which determines the REE production by the reserve geology, economics of recovery and separation techniques. Concern arises when dislocations in relative demand of different elements emerge, for example, the demands of critical elements like Nd and Dy. And this is regarded as a complex and intricate situation for producers from the economic point of view. The increasing demand and production of Nd would lead to overproduction of other REEs when stagnant or decreased demand for these REEs would occur, followed by likely price collapses.

Furthermore, the status of REE is hard to obtain due to significant uncertainty. It is apparent that there is not enough available data for rare earth study. Thus, a lot of calculation and analysis have to be based on crude estimations.

6.2 Future Outlook of Neodymium Market

6.2.1 Projected Future Neodymium Supply

As in the result of our projection, three models regarding future global neodymium production trend shows different properties. The logistic curve has a distinctive higher peak, with a peak production capacity of 230kt in the year of 2077. On the other hand, Richards model shows a peak year in 2089 with 130kt production amount, followed by the Gompertz curve, which has a comparative late peak that appears in 2099 with 94kt production volume (Fig 16 and Fig 17).

From the shape of the curves, the analysis if the overall fitting scenarios correspond to these models was carried out. Though restricted by the same maximum depletion rate of 5%, these three curves present different growth patterns of depletion rate. The logistic model reaches higher depletion rate and Gompertz has the lowest. Thus, logistic style of production would exploit the resource with a more unstable speed that conveys a relatively good
approximation of "free-market exploitation", but Richards and Gompertz represent milder extraction behaviour. From the generated graph, both Gompertz and Richards models can still keep production at a stable level till 2110. Contradictory, the logistic curve would have gone through a dramatic rise and drop of production volume as from peak 230kt in 2077 to only approximately 120kt in 2110, which will cause severe impacts on the global market in terms of price and extraction, when influencing various industry and energy sectors in the same time. When it comes to the cumulative production projection, it is clear that logistic production grows faster and it shows up with steeper curve, by the end of the projection, these three models has up to 7Mt difference of cumulative production amount. Especially for logistic curve, it has a cumulative production of 15Mt, which is very close to the total URR. But in fact, there are a large proportion of reserves are located in dispersedly in various regions, which adds up the difficulty in sufficient extraction in terms of amount and timing.

In fact, the logistic model did show validity in Hubbert’s forecasting U.S. peak oil crisis in 1970s, and this method can be applied in other finite resources (Ghosh and Prelas, 2009). To some extent, it reflects real world exploitation behaviour of exhaustible resources by the influence comes from market supply-demand interactions. On the contrary, what the Gompertz and the Richards projections represent is more sustained curves, which might be determined by different development strategy for exhaustible resources management. The main driven force here could be can be economic factor (price), technological breakthrough (efficiency and/or substitution), political interference (production/ export quotas, strength in regulation), and pressures lead by social or environmental concerns.

A closer look into China’s future supply trend is also taken in the paper (Fig 18 and Fig 19). Compared to the global trajectories, the future China productions of neodymium are armed with much earlier peak periods when the URR of neodymium in China is set at 8.75 Mt. The logistic model generates a peak in the year of 2061 with 139.1kt of production; the peak of Gompertz appears with 79.9kt in 2062; and Richards peak occurs with a maximum production of 103.5kt in 2059. In terms of curve shapes, logistic has similar steep drop after the peak, while the other two have comparatively smooth increase and declines. But from the peak year perspective alone, the difference between projections of China and the ones of global production is ranges from 15 to 40 years, which brings about the conclusion that with current extraction policy, China will soon come to a decline stage of production, a very near one, due to the feasibility of extraction. In this way, not only China but also the whole global market cannot avoid the risk of insufficient supply, then other countries have to accelerate the production to meet the demand of all kinds.

In the light of cumulative production projection, the logistic production obviously grows faster with steeper curve, although in the end all three models would reach quite close amount of total cumulative production, with only 1- 2Mt gap. Different from the global prediction, the forecast cumulative production amounts of China are all close to upper URR limit.

Needless to say, there lies a huge uncertainty in China’s case, since the government is carrying out a series of policies that aim at reducing extraction quota, limiting exportation, as well as banning illegal extraction, in order to preserve its rare earth resource. Meanwhile, limitations result from co- mining, environmental destruction caused by extraction and element processing, are also pulling China’s production back. In consequence, more constrains would be imposed on production while the market price would rocket and thus encourages the supply in return. As shown in the Fig 18, a rapid drop of production appeared after 2009. And there are some countries with large REO deposits making effort to start production in order to compete and gain initiative in the global market (Hocquard, 2010). But without any doubt, neodymium production in China is confronted with big challenges if the extraction continues as it is in the future. Peak of neodymium production would show up around 2060.

6.2.2 Future Scenarios of Demand

Based on IEA’s future climate mitigation outlook, great efforts must be made in increasing energy efficiency, deploying renewable energy source, and reducing GHG emission in order to achieve 450 ppm GHG goal. Practical policies including setting carbon dioxide emission limits, implementing carbon capture and storage technique, and profound transform to clean technology are on the schedule. But different scenarios are designed according to the practise and concrete policies carried out by different stakeholders. The New Policies scenario is reported based on current actions taken by different countries and initiatives, while 450 Scenario and Delayed CCS 450 Case being the gaol and probably occurring one.

The forecast of demand in this paper mainly focuses on the need from wind turbine and different types of electric vehicles, since these two applications are the main consumers of neodymium industry. The generated demand trends are illustrated in Fig 20 along with the supply trajectories. The main difference of these four
demand trends comes from the demand from permanent magnet and batteries. Scenario C and D have higher demand of neodymium when compared to the evolutionary growth and New Policies one. Annually, Scenario C and D demand around 10,000 tons of neodymium more than Scenario A and B. In other words, the aggressive IEA scenarios have higher requirement for neodymium supply, and on the other hand, New Policies Scenario does not show much ambition in wind energy and electric vehicle deployment, and it is very close to the Scenario A with evolutionary growth.

6.2.3 A Comparison of Results
According to the current rare earth status, the key concern with neodymium availability is not whether it is geologically abundant, but rather whether neodymium production can grow at a sufficient rate in order to meet future demand, with all the unbalance distribution and co-mining limitations.

From the comparison between generated supply and demand curves, all three assumed production models can meet the demand of Scenario A and B. But the more aggressive demand scenarios C and D that are designed to achieve 450 GHG goals would surplus the low production model (Gompertz). Both the logistic and Richards models manage to maintain an excess over demand although they cannot catch up at the first place. However, there are also a lot of reasons and different explanation that are worth discussing based on the observed phenomena.

Above all, the future demand scenarios only focus on permanent magnet and battery applications in wind turbine and electrical vehicle sectors. There are still lots of other technology sectors that require large amount of neodymium, such as portable devices, audio systems, magnetic resonance imaging (MRI) and so on. These applications in the future might also bring about rapid growth of demand. The projections are generated by only adding up average annual additions of these applications to the general growth model. Thus, they do not represent the real growth pattern. It can only be regarded as a moderate and approximate growth forecast. That is why it does not give much validity in terms of detail interaction between supply and demand analyses. But attention should be placed on the overall trending as well as the ultimate relations between them.

It is also discovered that the impact of wind turbine construction in these scenarios are comparatively small when compared to electric vehicles. It would not be the main reason of neodymium shortage. But doubtlessly, the sufficiency of supply would have great influence or even impose threats on the future planning of permanent magnet involved wind turbines. Since nowadays there are already initiatives that are considering taking a step backward to a trade off between permanent magnet utilization and power plant efficiency due to the unstable price and supply of neodymium (Patton, 2012). In the same time, the potential risks of supply also turn into a push to make motors with less dependence on rare earth elements (Witkin, 2012).

On the other hand, though it turns out to that the Richard and logistic models can cope with the demand of all scenarios by the end of 2035, it is likely that a more aggressive scenario would be designed due to much delayed of the implementation of CCS and other technologies. And such scenario might be very moderate in the near future because of the reluctance in action and other practical barriers, but as pressure from climate change gets bigger when it approached the expected 450 ppm target with much faster pace, the call from clean technology and renewable energy would become more urgent and consequentially lead to unprecedented demand of neodymium in a very short period of time. As mentioned above, neodymium issue is much about whether we can obtain a sufficient rate in order to meet the future demand or not, and it is often forgotten in many energy projections that do not consider material constraints for actual turbine constructions.

Furthermore, even given that the production is capable of exceeding the demand, for example, the logistic model, it is definitely not the best or sustainable production pathway. If REO, or neodymium, would peak within one hundred years, or even earlier, the world would be facing a lot of problems. Not only climate change, but also probably stagnation of new technology development due to depletion of REO, unless there would be new breakthrough to substitute or even replace these critical elements with much more abundant materials.

6.3 Neodymium - An Intricate Case of Peak Mineral
6.3.1 China’s Monopoly and Policies
Deng Xiaoping once drew an analogy between China’s rare earth to oil reserve in Middle East region to show the significance of its role. The price of rare earth ore dropped from $11,700/ton in 1992 to $7,430/ton by 1996, right after China entered the global market. Later on the U.S. government had to sell off its stocks and the
famous Mountain Pass was no longer competitive due to the high production price, especially when the ecological costs of the mine kept on growing (Margonelli, 2009).

As mentioned earlier in this paper, China is now considered as the dominant power in global REO production and reserves. But this monopoly brings about great challenges not only to the rest of world, but also to China itself. Disorderly development and poor management practices are most commonly witnessed in China. And other issues like smuggling, illegal mining activities, destructive environmental impacts, and the growing challenge of ensuring domestic needs of rare earth, continue to add additional pressure on its future prospect (Hurst, 2010).

Currently, one of the most concerning issues related to rare earth industry to the international community is China’s controversial restriction on production and export quotas. The Ministry of Land and Resources announced a regulation that started to be implemented from 2009. It limits export quota for rare earth ores but encourages the sales of finished products. The first target was set at 82.3kt of rare earth elements for exports in 2009. The curbs in quota caused trade disputes with some of the world’s major users, such as the U.S. and Japan, due to unstable price and supply of key rare earths (Yuan, 2013). Most recently, China announced the first of two production quotas for 2013 at 46.9kt of REO, which is about half the total production quotas in 2011 (93.8kt) (MLR, 2102).

From China’s point of view, it aims not only at a better control of mining activity, ensuring its own domestic demand, and preservation of environment, but also in the same time at securing supply for its own industries and regaining control over its domestic operations. And in terms of domestic demand, China’s consumption of REO has experienced a tremendous growth from 52,000 tons in 2005 to around 73,000 tons in, and is about 380 percent higher than the consumption in 2000 (Tse, 2011). This is ideal for China because it would obtain control over the industry and create more job opportunities of manufacturing in China. However, countries that are dependent on REEs have to move their production bases into China. Consequentially, it might further leads to a drop of job opportunities, and perhaps also compromise in terms of national security, or proprietary of related critical technologies (Hurst, 2010).

For China, it has to tackle the problems including illegal extraction, smuggling, environmental issues, and strategic planning for securing future rare earth supply, when maintaining its reasonable exports and competitiveness in a long run.

On one hand, a rapidly increasing number of buyers are resorting to the smuggled REEs due to the growing demand and reduced export quotas form China. In 2008, around 20,000 tons of rare earth was reportedly smuggled from China when the official customs statistics only indicted a total exported amount of 39,500 tons in the same year, which means the smuggling activity accounted for more than 1/3 of the rare earth exports (Hurst, 2010). And according to the report from the State Council Information Office of the People's Republic of China, the discovered smuggling amount was 1.2 times higher than the legal exportation in 2011 (SCIO, 2012). Rare earth smuggling is potentially detrimental to the industry because it lowers the prices and speeds up the resource depletion. It also reflects a lack of control over the industry and brings about repercussions like more devastating damage to the environment and risks in mining safety. In order to curb the rare earth smuggling, China introduced the “Rare-Earth Industry Development Plan of 2009-2015”, which aim at reinforcing the control and punishment by carrying out a series of regulation and policies (Hurst, 2010).

On the other hand, the rare earth mining-related environmental issues still remain as a huge concern. Certain actions have been taken in the past few years. Not only restrictions are imposed on production and exports quotas, but also the government will approve no more new rare earth separation projects before the year of 2015. Meanwhile, monazite mining is banned if the monazite contains radioactive elements and rare-earth producers are required to meet the environmental standards in terms of emission; otherwise, the extraction will be shut down (China Ministry of Environmental Protection, 2011). With new standards, enterprises are required to invest in environmental protection and upgrade production technologies. But the government does not provide any help in these investment or incentives (Hurst, 2010). Thus, it is hard to tell whether these policies can be carried out or fulfilled successfully. Furthermore, China continues to urge rare-earth producers to merge in order to eliminate duplicate projects. The consolidation is believed to benefit the rare-earth sector in China because it would reduce unnecessary competition as well as associated financial losses (Tse, 2011).

6.3.2 Global Market as a Determinant
Mineral production has always been heavily influenced by the economic factor but the status of reserves and stocks also affect the market. Unfortunately, such a dynamic system cannot be perfectly studied in this paper
due to the limitation of the modelling methods (as mentioned in Methodology section). As the result of our projections shows, wind turbines with permanent magnets that based on neodymium usage might not be the cause for a shortage of REO supply, but it would be affected by the potential supply risks of REO, mainly due to the fluctuations of price. The price in the market, the cost of extraction and processing, along with investment in product manufacturing, determine if the reserve is economical viable for production. In return, a too fast growth of demand would also pull up the price and further increase the production that is driven by available profit. On the contrary, a sudden drop in demand or overproduction of other REOs might also trigger a decline of price, and mining of neodymium or other critical elements might find it hard to continue in consequence.

6.3.3 Environmental Concerns
From the shutting down of the Mountain Pass mine in US, to the exposure of unsustainable mining activity in China, environmental concerns has always been one of the main focuses when it comes to REO extraction. But not until recently did the contrast of clean technology and the dirty ores behind start to catch the attention in renewable energy development.

First of all, mining alone is not the only part that causes severe trouble in terms of resource depletion and environment damage, since processing the concentrates is also an important part of the REO production chain. The processing includes separation, purification, and compounds elaboration (Hocquard, 2010). Despite all the application in lots of environmental friendly products, REO processing is where the most pollution comes from. It is also known as the confronting REO paradox between “dirty ores” and “clean technology”. Apart from the commonly known fact that the separation and purification processes are destructive to the environment and extremely energy intensive, the associated uranium and thorium radioactivity are also doing great harm to the ecosystem and human health (EPA, 2012, p. 6-1). And in Malaysia, there raised a heated discussion about whether an Australian owned rare earth metal plant should be built inside the country (Dijkstra, 2011).

The negative impact imposed on environment in China mainly results from lax mining practices in the REO mining and processing. There are a large number of REO mines that driven by the revenue potential, operating illegally without proper mining licenses and with obsolete mining technology that leads to environmental damage, especially in the Guangdong, Jiangxi, and Sichuan provinces (Tse, 2011). It undoubtedly leads to more severe environmental hazards and exacerbates the existed situation.

Three main threats are placed on the environment form REO mining and processing. The first one is waste and energy consumption. For example, every ton of production of rare earth using concentrated sulphuric acid high temperature calcination method would generate approximately 75 cubic meters of acidic wastewater and 9,600 to 12,000 cubic meters of waste gas, all of these are containing dust concentrate, hydrofluoric acid, sulphur dioxide, sulphuric acid, and about one ton of radioactive waste residue that is contained in the waste water. In Baotou, Inner Mongolia, the heart of China REO production, the production in this region creates and discharges about 10 million tons of these wastewater without effective treatment. And the water flow not only into potable water source for nearby region, but also into the surrounding ecosystem and farmlands (Hurst, 2010). While during the refining process, the by- product form chemicals like ammonium bicarbonate and oxalic acid would result in burns and itchiness to the skin, eyes through touch, and respiratory tract through
inhales. The second hazard is the disposal of tailings that become waste materials after extraction. 2,000 tons of tailings would be produced when one ton of rare earth is extracted. According to Hurst, strict controls are imposed on such tailings in other countries like the U.S., but in China, the industry is not willing to pay for environmental investment since once they do it, they would probably lose the competitiveness compared to others, especially when the regulation is still comparatively loose. Meanwhile, some shortcomings of the political structure and institutional issues regarding power distribution are also restrict better regulations. Again, the waste form tailings in Baotou ends up in the environment, but this time it finds its way into the Yellow River, which supports around 150 million people in terms of fresh water needs. Last but not the least, the radioactive contamination comes along with the extraction. The source of the radioactivity stems from the element thorium in monazite ore. The contaminated water is dumped into nearby lake and leads to severe pollution and ecosystem destruction (Hurst, 2010). A photo (Fig 21) of a processing plant in Baotou gives a general picture of the situation in 2011.
7. Possible Solutions and Current Actions

7.1 More Mining Projects at a Higher Speed?
In order to create a more balanced and healthy production market, the world cannot rely on China alone. It is neither good for present trading activities, nor optimal for a long-term supply and development. Thus, lots of countries are eager to start REO projects, some are planning extraction, when the others are exploring new reserves. According to the research team from Japan’s Agency for Marine-Earth Science and Technology with lately published findings in Nature Geoscience, vast underwater reserves of rare earth minerals are found scattered across a huge swath of the Pacific, including south and east of Japan. If such new rare earth discoveries proved to be viable, the landscape of REO production could be considerably changed in the future (Null, 2011).

Apart from discoveries of more reserves, currently there are 10 main advanced REE mining projects going on outside China. The most promising ones are from Arafura Resource LTD (Australia), Lynas Corporation Ltd (US), and Molycorp Minerals LLC (US) (Hocquard, 2010). However, these initiatives are still faced with unsolved problems like impossible to start production in a short time, the composite of the ore in deposits are not desirable, and difficulties result from financing or processing techniques (Greenwire, 2010).

But this solution might also impose potential depletion risks in the long-term. Thus, a balanced and scientific strategy is required in order to sustain the future stable production when dealing with present situation.

7.2 Sparing the Rare Earth
The alloy of iron, boron and neodymium is regarded as the best rare earth magnets used nowadays. By adding neodymium atoms can increase greatly the resistance of some of the magnets. That is what makes neodymium, or rare earth elements, so unique in technological fields. With all the pressure and risks of future supply, scientists are looking for ways to spare the rare earth elements in some areas. One of the main focuses is searching for alternatives to REEs. Generally, this includes research both into alternatives materials or research into alternative product designs (EPA, 2012, p. 5-10). But it is difficult to find more abundant or common materials to substitute neodymium, which being both light and powerful in the same time, in the permanent magnet application.

There are lots of research projects going on all over the world; for example, Toyota has kicked off a program that makes effort to get rid of rare earth elements in its cars that requires permanent magnet by developing electromagnets motors. The main mechanism behind it is structuring magnets as nanocomposites (Powell, 2011). In this way, the new generation of hybrid vehicles would be able to run with less or even without inputting any rare earths. Meanwhile, the Department of Energy has set up a research lab for research on making rare earth mining more economically viable in more places as well as on looking for alternatives to rare earth elements and other critical raw materials (LaMonica, 2013). More projects and detail information can be found in EPA’s review report on production, processing, recycling and associated environmental issues regarding rare earth elements (2012).

In addition, a trading off between installing permanent magnet for higher efficiency and lower the potential risks of neodymium supply caused by unstable price are taken into consideration in some wind manufacturing and planning procedures. Although ambitious plans for more wind turbines might not be the main cause for neodymium shortage, the wind industry indeed need to reconsider investing in direct-driven turbines that might be affected by the neodymium supply issue in the future.

7.3 A Prospect of Recycling
As early as in 1984, the research on recycling and recovering REEs was launched. However, it is not until recently that the industry and society have started to pay more attention to it due to rapid growth in REO demand, potential risks of REO future supply, unstable price, and policies that mandating recycling for these critical elements (EPA, 2012). As noted in a status report in 2011, currently REEs has only less than 1% of the end-of-life recycling rates (UNEP, 2011).

According to UNEP’s International Resource Panel (2011), four key steps, including collection, dismantling, separation, and processing, are involved in the recycling process for both pre-consumer and end-of-life products. There are factors contribute to the effectives of recycling efforts. Most influential ones are economical (material value being higher than recycling cost), technological (recycling friendly design), and societal (public awareness and available infrastructure). It is reported that 20-30% of rare earth magnets are scrapped in the processing.
Different form post- consumer recycling initiatives, this type of pre- consumer waste has also proven to be a future recycling opportunity (EPA, 2012).

At present, there are fast developing government policies and research initiatives that are aiming at securing continuing supply of REEs by launching programs and carrying out policies to support REEs recycling. Countries and regions like the United States, Japan, South Korea, and European Union have already taken a step forwards in terms of planning related projects (EPA, 2012).

7.4 A Matter of Resource Management
Recent regulations in REO industry present a higher level of resource management in different countries. Apart from China’s reduction in REE exports quota to stabilize the prices and preserve environment and domestic stock, other countries have also taken steps to secure their REEs supply. For example, Japan, EU, and Us have launched regulations that intensify the research for REE substitutes; push more collaboration with Australia and Canada in order to reduce their dependency on China’s production. Also, smaller countries like Malaysia, has licensed foreign mining companies (like Lynas Corp from Australia) to process REEs in Malaysia (Piedra, 2012).

Mineral resource management is as much about ensuring the resource quality and accessibility as it is about securing resource quantity and availability in a long run. China’s rare earth endowment has contributed significantly to the both national and international wealth and development. However, a better resource management strategy with efforts from different stakeholders is fundamental for long- term productivity. Since the current global rare earth production is currently unsustainable, not only due to resources being finite, but also because of impacts associated with extraction and processing, as well as monopoly issue.

An integration of extraction plan (not only restricted in China), innovation and development in technology (extraction and processing techniques, substitutes to REO), and a more sustainable style of REO consumption (recycling and reuse) is of crucial significance in order to deal with peak neodymium, or more generally speaking, with peak REO or peak mineral issue.

7.5 A Limit to Growth
The mainstream of belief in our time is that “the soundest foundation of peace would be universal prosperity”, which is leading us to pursue a perpetual growth (Schumacher, 1989). But as we are confronted with current chaotic situation of our development from a global perspective, such growth in population and consumption enmeshes us in a classic self- reinforcing loop, which strongly indicates that the current development pattern cannot continue unabated on our finite planet (Heinberg, 2010). In the book Limits to Growth (Meadows et al., 2004), the author pointed out that sustainable development of our society should strive for a qualitative development, rather than a physical expansion, for a more equal and even distribution of wealth, rather than a blind race for a economic growth.

According to Meadows et al. (2004), one of the suggested guidelines for a more sustainable development is to minimize the usage and prevent the erosion of renewable resources. It is thus suitable and beneficial for the case of peak mineral, or more specifically, peak neodymium.

Similarly, some other comparatively promising renewable alternatives for future energy production and clean technologies are facing the same material constraints. In order to reach desired emission and resources cuts, more efforts should be made than people’s general perception. And such targets for a sustainable future cannot be achieved without confronting the structure of market economics, as stated in the book the Prosperity Without Growth (Jackson, 2011).
8. Concluding Remarks

This paper applies three different curve models (logistic, Gompertz, and Richards) in the prediction of future global and China’s neodymium production respectively and generates projections of corresponding demand from wind turbines and electric vehicles based on IEA’s climate change mitigation scenarios. By comparing these supply and demand prognoses, it does not appear that geological constraints will limit neodymium supply. And in the foreseen future China would still dominate the global neodymium production market, since the rest of the world still needs time for realizing sufficient production outside of China. It is also clear that current style of supply and consumption is not sustainable.

In terms of the key question that is raised in this study, the result shows no evidence that the growing demand of wind turbine construction would lead to shortage of neodymium itself. But the wind industry would not be able to avoid the impact results from the potential risks of neodymium supply due to an increase in its utilization in other sectors, especially the ones for clean technologies. Thus, the future investment in neodymium based wind turbines should be taken into reconsideration from this point of view.

Moreover, the analysis of a sustainable production and consumption of neodymium is much more than the presented result alone. Peak neodymium is more than just overcoming the geological constraint. There are many other determinants that influence the issue, such as economic factors, political interference, as well as technological constraints. Not only better resource management, but also a joint effort from different stakeholders in different countries are required in order to sustain the stable production for an increase demand in various fields.

When it comes to future studies, further work regarding better projection and analysis are worth being carried out. Needless to say, the observed uncertainty, which is the main limitation in this study, should be mitigated with better data, more detailed processing, reduction of assumptions, and so forth. More dynamic and holistic analysis would be beneficial for a better picture of peak neodymium issue and its impact on future clean and renewable energy development. In addition, further exploration of intriguing topics that shed light on other critical materials like dysprosium, yttrium, lithium, etc. or with a focus on implementing different future demand scenarios or curves with different properties could be introduced as well.

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10. Reference


