Title

An Investigation into the Drivers of Supply and Demand of the Rare Earth Element Market

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DECLARATION

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ABSTRACT

Rare earth elements (REEs) consist of 17 naturally occurring elements and are split into light and heavy REEs. REEs have significant uses in high-technology and clean energy applications. The rare earth element market has been significantly affected by supply risk in the past, owing to China's monopoly across the entire value chain. Since the last REE crisis between 2009 and 2013, the rest of the world has made little progress to bring new REE projects online. Reasons for this include environmental, financial and metallurgical constraints that face most REE projects. Currently, global REE production is approximately 170,000 tonnes. China is responsible for more than 80% of this production and is essentially the sole producer of heavy REEs such as dysprosium and terbium. Australia and the USA are the next largest producers of REEs, primarily due to the Mt Weld and Mountain Pass mining operations respectively. Although it is unclear how large the Chinese resource inventory is, due to its non-transparent reporting, it is certain that its REE endowment largely overshadows that of the rest of the world. Due to China's supply dominance, there is still a supply risk, resulting from geological and jurisdictional scarcity, that affects the rest of the world.

Drivers of REE demand include population and economic growth as well as a global desire to reduce carbon emissions in order to combat climate change, in accordance with the Paris Agreement. The expected increased future demand for certain REEs, notably neodymium (Nd), praseodymium, dysprosium (Dy) and terbium, raises concerns around supply of these metals. These elements are primarily used in clean technology applications such as permanent magnets. Permanent magnet technology is expected to grow at much higher rates than other REE applications, due to their uses in electric vehicles and wind turbines. By 2025, a total of 28,385 and 7,880 tonnes of Nd and Dy respectively will be required to satisfy the permanent magnet demand for wind turbines, electric vehicles and electric bikes alone. With forecasted production rates, this will likely result in a Nd deficit of more than 1,000 tonnes and a Dy deficit of more than 5,000 tonnes by 2025.

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LIST OF ABBREVIATIONS AND ACRONYMS

EV	Alternative Energy Vehicle
BEV	Battery Electric Vehicles
CCP	Coal Combustion Product
CFA	Coal Fly Ash
EU	European Union
EV	Electric Vehicle
FCV	Fuel Cell Vehicles
GDP	Gross Domestic Product
GW	Gigawatt
HEV	Hybrid Electric Vehicle
HREE	Heavy Rare Earth Element
HTS	High-Temperature Superconductor
ICE	Internal Combustion Engine
LED	Light-Emitting Diode
LREE	Light Rare Earth Element
Mtoe	Million tonnes oil equivalent
MW	Megawatt
NdFeB	Neodymium-Iron-Boron
NiMH	Nickel Metal Hydride
OLED	Organic Light-Emitting Diode
PHEV	Plug-in Hybrid Electric Vehicle
REE	Rare Earth Element
REO	Rare Earth Oxide
SmCo	Samarium-Cobalt
TREO	Total Rare Earth Oxide
UK	United Kingdom

1 INTRODUCTION

1.1 Research Rationale

Rare Earth Elements (REEs) have many applications across a variety of industries due to their physical and chemical properties. REEs are considered critical metals due to their supply risk and lack of substitution options (Golev, et al., 2014). From the 1960s, the unique chemical and physical properties of REEs were required in order to develop high-technology (high-tech) applications. This global demand for advanced technology resulted in increased demand for REE. The main applications being their use in catalysts in the automobile and petroleum industries, and magnets which are commonly used in the manufacturing of computers, wind turbines and electric vehicles (EV's) (Massari and Ruberti, 2013; Goonan, 2014). In 2009, a trade war developed between China and Japan, the largest producer and consumer of REEs respectively. There were issues surrounding REE supply brought about a dramatic increase in demand which resulted in inflated prices from 2010 to 2013. These supply concerns prompted other countries outside of China to expedite the identification of alternative sources of REEs and forced manufacturers to investigate substitutes to mitigate the supply risks, which was largely unsuccessful (Habib and Wenzel, 2014).

Almost a decade after the realisation of the supply risk associated with REEs, viable substitutes still do not exist, and the intensity of exploration decreased significantly after prices stabilised post 2013. Currently, the REE issue is in popular news, due to a trade war between the U.S. and China and once again, focuses largely on the rest of the world's capability to meet growing global REE demand, without the assistance of China. In 2010, this same issue prompted hundreds of junior exploration companies to explore for new REE deposits outside of China, but the majority of projects under investigation had no real chance of becoming a viable operating mine, due to low grades, environmental concerns and complicated mineralogy, which ultimately requires expensive and difficult metallurgical processing (McLeod, 2019).

Despite the supply risk and depressed prices in recent years, the trend is that new emerging economies are becoming more reliant on technology and clean energy, suggesting this may cause demand for REEs to increase significantly.

This research aims to assess the REE market forces with a focus on the development trajectories of emerging market economies and will also attempt to shed some light on whether this trend is likely to continue. In order to achieve the aims of the research it is important to establish and understand the true drivers of demand and their effect on supply. Current supply will be assessed in terms of production outputs, jurisdictions, and associated risks, recycling of REE products, as well as the resource pipeline that will determine the risk to future geological, primary raw material supply. There will also be a focus on potential substitutes and how this may affect REE demand going forward. Cost of production for producers will also be analysed through the examination of company reports and annual financial statements to determine the effect that price movements have had on producers. The price movements are an indicator of the global supply-demand balance and will indicate the status of global demand which will lead to an investigation or some insights into supply and demand drivers.

1.2 Research Questions/Hypothesis

The hypothesis for this research project is:

"The rise of emerging technologies and economies indicate that there will be an increase in demand for REE".

The questions that will be asked are:

a) Does the rise of clean technology suggest there will be a demand for REE?

b) Will REE supply be enough in the event of an increase in demand?

c) What are the drivers of demand and how do these affect the pricing of REE?

d) Will developing nations/economies contribute to either supply or demand?

1.3 Research Objectives

This research aims to identify the key drivers that affect global supply and demand with a focus on REE requirements. In order to understand the effect of key drivers of supply and demand, various objectives will be met and are summarised below:

- Analysis of the global REE market from the 1950s to present day;
- Analysis and quantification of the current global REE supply, the expected demand of critical REEs and the subsequent impact on price;
- Determine whether the rest of the world (excluding China) have enough resources to maintain supply for future demand; and
- The supply risk of REEs has been a concern in the past and will also be discussed in relation to market drivers. In order to assess the REE market, an evaluation of REE applications will be undertaken, with a focus on possible substitutions and replacement technologies.

1.4 Research Methods

1.4.1 Scope of Research

The scope of work includes the determination and outlook of the REE market, based on clean technology, political plays between China and the rest of the world, developing and developed economies and their respective emerging technology requirements.

1.4.2 Methodology

This research undertakes a quantitative approach, where data will be sourced from the public domain and collated. Data sources will include:

- Peer-reviewed journal articles;
- Company technical reports,
- Authoritative organisation research; and
- Government policy and strategy research.

Interpretations are made from the collated data. The analysis of the data allowed for the understanding and estimation of global available REE supply as well as potential sources of supply.

The supply/production of REEs is largely dictated by demand, and the literature was also examined to determine the demand of specific REEs that are expected to increase in the future due to their use in clean energy applications. The data was then averaged to create a realistic benchmark for REE demand for each application.

Part of the methodology includes the resulting balance of supply and demand, with reference to impact on REE pricing going forward.

The methodology also examines global Gross Domestic Product (GDP) forecasts, REE consumption and population growth, with a focus on future outlooks. Analysing the intensity of use of emerging countries is used to make realistic conclusions on market forces of REEs.

1.5 Outline of Chapters

The outline of Chapters that will be presented in this research project are as follows:

1.5.1 Chapter One – Introduction

This chapter introduces the rationale for the research which includes a brief description of the market dynamics experienced to present day. The chapter will also include the problem statement, research questions and hypothesis as well as the methodology of how the research was undertaken

1.5.2 Chapter Two – Review of the Rare Earth Market

This chapter includes a detailed review of relevant literature building on the brief review provided in the proposal. The chapter defines REEs before providing a detailed description of the REE market to date in terms of historical supply, scarcity and relatively recent monopolisation of the market by China.

1.5.3 Chapter Three – Geological Distribution and Deposit Types

Chapter 3 elaborates on the geological distribution of REE deposits, as well as the types of deposits found throughout the world. The various REE-bearing minerals are described, and mineralogical complexity is discussed. This chapter serves as a precursor to the availability of REE supply, as a direct result of their deposit types and uneven geographic distribution.

1.5.4 Chapter Four – Availability of Rare Earth Elements

This chapter will provide a snapshot of known, current REE supply, both possible and realistic. The supply of REEs will be presented in detail and contain a quantitative assessment of primary and secondary sources of REEs, as part of the global availability. This information is shown from current resources and reserves from active mines, as well as resources and to a lesser extent, reserves, from code-compliant projects currently in development. An investigation into alternative sources of REEs will be presented and will include quantitative report on the recycling of end use products and the use of Coal Fly Ash (CFA).

1.5.5 Chapter Five – Extraction and Processing

This chapter elaborates on the production rates, including the countries that are mostly responsible for current supply. A detailed description of current REE producers is discussed, including resources, reserves, production rates, REE assemblages as well as any difficulties these producers are faced with regarding processing and REE supply chain. Chapter 5 also discusses the commonly employed processing methodologies of REEs, as well as outlines the method constraints before the global supply chain is summarised.

1.5.6 Chapter Six – Uses, Applications and Market of Rare Earth Elements

Chapter Six details the general uses for REEs, across many industries. A description of these industries is provided which leads into the applications that are expected to dominate the REE industry going forward, namely, clean technology applications. These applications include magnet-powered wind turbines, electric vehicles and e-bikes, Ce-bearing catalytic converters, LREE-bearing phosphors and LREE-bearing batteries. Each of these is then assessed in terms of its respective expected market growth or decline. Historical and current consumption of REEs and their respective applications are discussed before a quantitative approach to the future demand for these applications is presented. This lays the foundation for the demand forecast to 2025, for a specific group of REEs. Subsequently, the REE market pricing structure is explained in some level of detail, despite information being difficult to source.

1.5.7 Chapter Seven – Supply and Demand Balance

Information regarding production/supply and demand is integrated in Chapter Seven. A supply-demand balance is presented for 2025 for specific REEs, based on their expected increase in demand. Various rates of production and origins of supply are investigated in several scenarios to ascertain the elements that are truly at risk of being in short supply.

1.5.8 Chapter Eight – Drivers of Demand

The demand drivers will be investigated, by establishing the REE requirements for key applications and how much the demand for the applications are expected to grow in the future. Firstly, the concepts of intensity of use and material composition of products will be explained and discussed with reference to economic and population growth. Secondly, clean energy policies and initiatives developed by various governments will be discussed in reference to their effect on demand. Third, China's monopoly on supply will be discussed in reference to the current and ongoing trade war, as a driver for demand, particularly from a political/jurisdictional scarcity perspective. Finally, a brief investigation into how recycling, element substitution and / or alternative technology may affect demand in the future.

2 REVIEW OF THE RARE EARTH MARKET

REEs are important for many high-technology applications and, as a result, their resources have been a focal point of academic and institutional research output for many years. Owing to the complexity of rare earths, including their uneven geological distribution, common environmental issues with extraction and processing, lack of effective substitutes, one-sided supply chain, at risk markets and ongoing geopolitics, researchers have attempted to confront the problem in dissimilar ways. Tse, (2011), Massari and Ruberti, (2013), Imholte, et al. (2018) have historically presented their findings on production, demand, resources and reserves. Other studies have reported on one or several deposit styles and their distribution and other work has focused on a specific group of elements and/or applications (Goonan, 2014, Goodenough, et al., 2017). This research aims to provide a broad and current overview of the market in terms of deposit style, geological distribution, supply, demand, uses and applications as well as the drivers of demand. Most REEs will be considered, however a specific suite of elements will be looked at in more detail.

2.1 What are Rare Earth Elements?

Rare earth elements were first discovered in Sweden by Karl Arrhenuis in 1787 after collecting an unknown mineral, later named ytterbite, near the town of Ytterby. Ytterbite contained ytterbium, an element which was only separated from the mineral by Finnish chemist, Johan Gadolin, in 1794 (USGS, 2013; Fernandez, 2017). Shortly after this discovery, more elements with similar chemical and physical properties were identified, within the same mineral. By 1907, the REEs that are known today had been discovered (USGS, 2013).

REEs consist of 17 elements comprising the 15 lanthanides and yttrium (Y) and scandium (Sc) (Figure 2-1). These lanthanides are separated into two categories, namely light rare earth elements (LREEs) and heavy rare earth elements (HREEs), which are determined by their atomic mass. The LREEs include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), and samarium (Sm) and the HREEs include europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

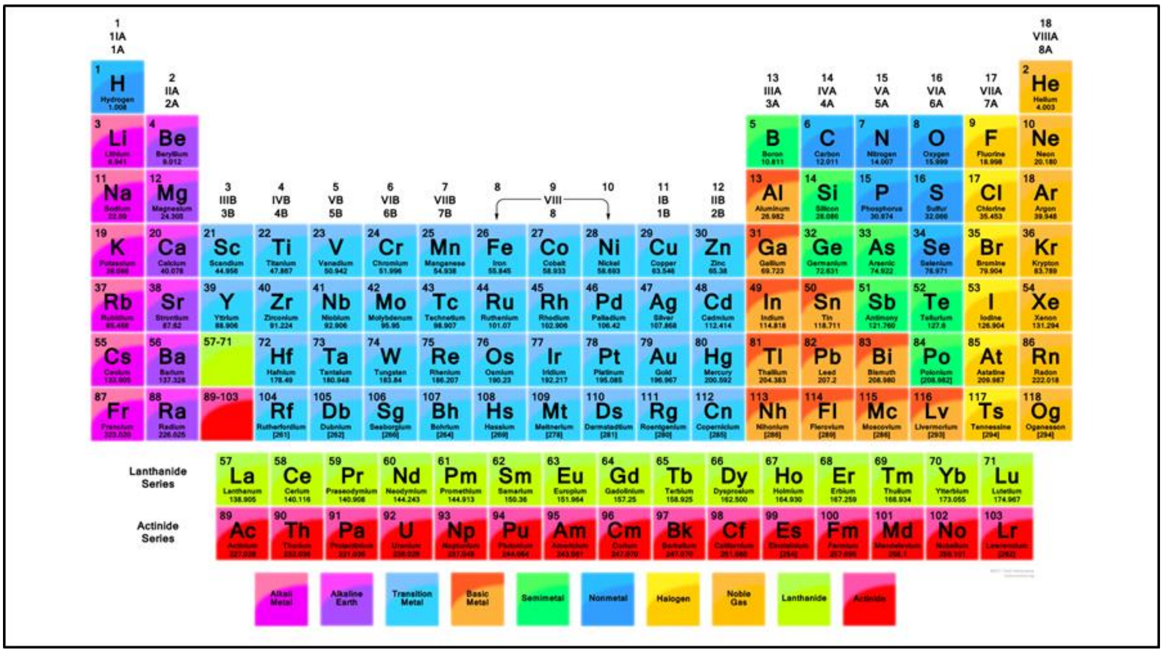

Figure 2-1: Periodic Table of the Elements (after Helmenstine, 2019)

Sc and Y are also treated as REEs due to their physical and chemical similarities and because they are commonly found with REEs in similar geological settings, although they are not true REEs. Additionally, yttrium has a lower atomic mass than the LREEs but is treated as a HREE due to comparable properties with this group of elements.

Besides Pm, which is an unstable REE occurring naturally in extremely low abundances (Christmann, 2014; USGS, 2014), REEs are actually relatively abundant in the earth's crust, compared to metals such as copper (Cu) which has average crustal abundances of 50 ppm (Cordier, et al., 2011a, b). The average crustal abundances for each REE is shown in Table 2-1, which also indicates that LREEs are more abundant relative to HREEs.

Table 2-1: Average Crustal abundance of REEs (after Haque, et al., 2014)

Element	Crustal Abundance in ppm
La	32
Ce	68
Pr	9.5
Nd	38
Pr	NA
Sm	7.9
Eu	2.1
Gd	7.7
Tb	1.1
Dy	6
Hm	1.4
Er	3.8
Th	0.48
Yt	3.3
Lu	NA
Y	30
Sc	22

Despite not actually being rare within the earth's crust, significant concentrations of the REE's are required in order to meet the criteria for economically viable extraction. However, REEs seldom occur in concentrations that are considered economically viable for extraction and are generally found as mineral compounds within ore deposits. These compounds are termed rare earth oxides (REOs) (Haxel, et al., 2002).

2.2 History of Supply and Scarcity

The rare earth market has undergone its fair share of chaos, with drastic supply shifts, global economic and jurisdictional scarcity as well as exaggerated price increases. At the same time, there have also been important technological breakthroughs in the clean energy space and military applications, that utilise different rare earths, which have been the main drivers of demand to up to now.

Factors that affect supply and demand in mineral markets are not typically straight-forward and can result in rapid shifts in the market. On the supply side, these factors include monopolies, political instability, labour and policy issues whereas new applications and substitutions often affect the demand (Henckens, et al., 2016). The history of REE supply is described by Fernandez (2017), based on data collected by Kelly and Matos (2014) from the United States Geological Survey (USGS), which shows commercial production statistics of REOs from the early 1900s (Figure 2-2).

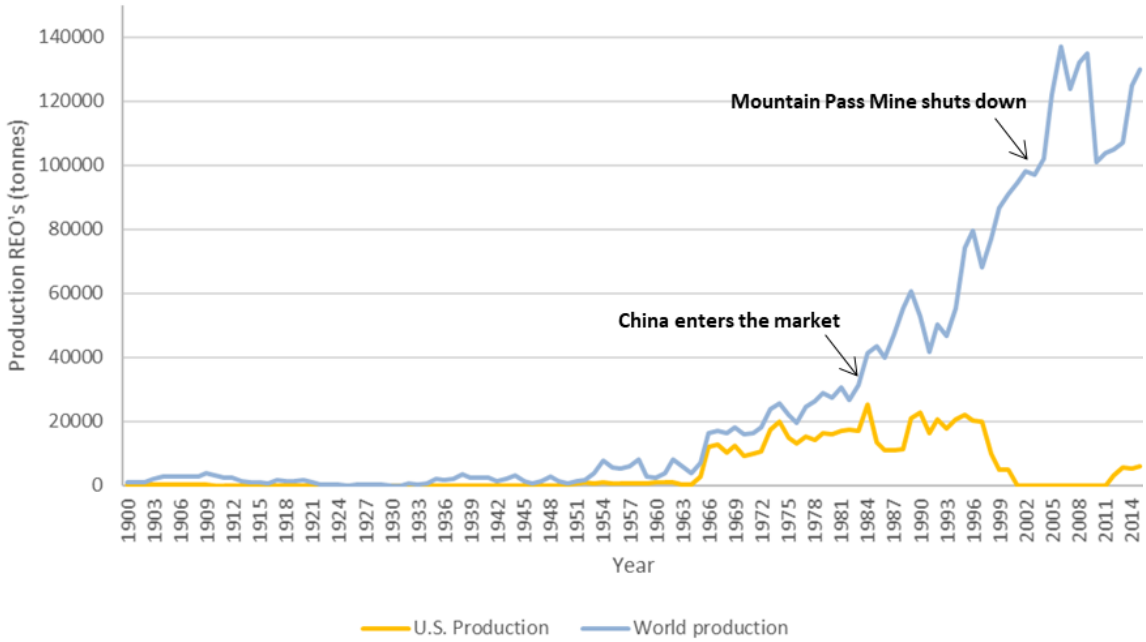

Figure 2-2: World REO versus U.S. REO production (modified after Kelly and Matos, 2014)

Global production increased significantly in the mid-sixties and was a direct result of the Mountain Pass deposit coming online a few years' prior, making the U.S the leading global supplier of REEs (UNCTAD, 2014). As global leaders in REO production, the U.S. pioneered the development for innovative technologies and applications for REEs (Seaman, 2010). The U.S. held its position, for almost 20 years, until the mid-eighties. During this time, the U.S. was responsible for an average of 65% of global supply (Fernandez, 2017). From 1985 to 2015, the U.S. share of global production decreased from 31% to less than 2% respectively. Its undoing was brought on by China, who prior to 1980, decided that REEs had an increasingly strategic significance. China's political will, in conjunction with low-cost labour, and lax environmental laws, resulted in very low production costs compared to the rest of the world. This resulted in supply dominance by China, who was responsible for approximately 80% of global REE supply at the turn of the century (Hurst, 2010; Seaman, 2010) and by 2011, supplied 97% of the world's REEs (Figure 2-3) followed by India and Brazil with a total supply of 2.5% between them (Lackner and McEwen-Fial, 2011).

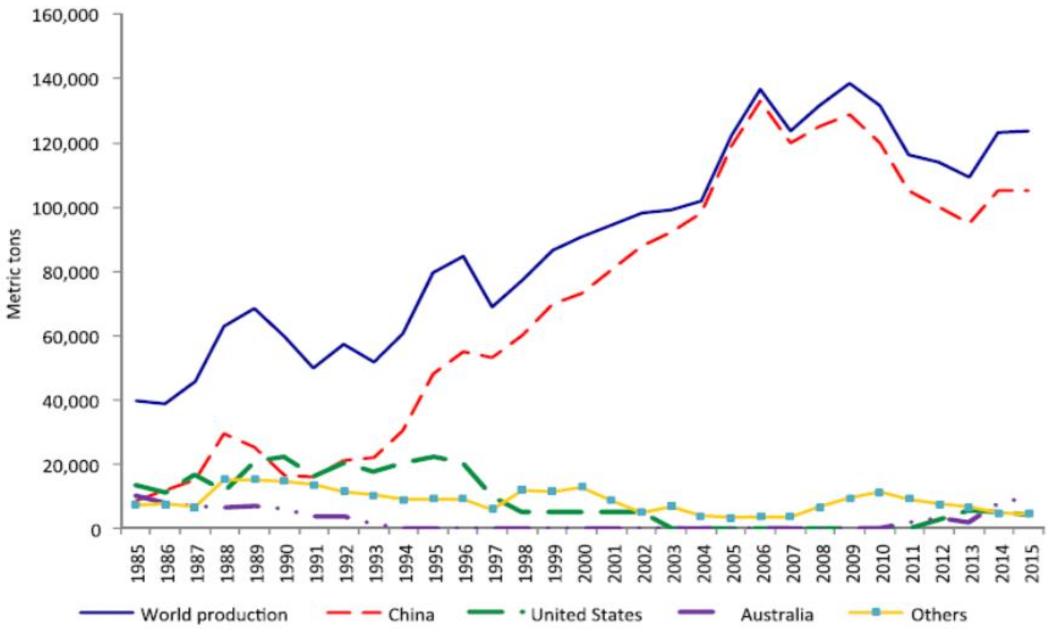

Figure 2-3: World REO production versus major producing countries (after Fernandez, 2017)

The low Chinese production costs directly affected REE operations outside of China causing many mines to shut down as they were unable to compete in the global market (Seaman, 2010) despite China only having approximately 35 to 40 % of the world's REE resources (Long, et al., 2010).

Issues of mineral scarcity in mineral markets have existed for decades, as there has been growing concern that primary deposits will become depleted or cost too much to mine (Gordon and Tilton, 2008). Understanding scarcity is critical in order to analyse market forces in terms of supply and demand on a global scale. Mineral scarcity denotes both geological and economic scarcity (Henckens, et al., 2016). Mineral scarcity is considered an old way of thinking, especially for producers, customers, end-users and policymakers. The business and economics of mineral exploitation is a constantly changing one. It is for this reason that geological scarcity is not considered an issue as previously uneconomic resources can become economic due to commodity price movement, operational cost cutting mechanisms and the onset of new mining and processing technologies (Kooroshy, et al., 2009). Therefore, according to Kooroshy et al. (2009), geological scarcity relates to the quantities that can be exploited profitably and not to the decrease of known resources. However, economic scarcity, often unrelated to geological scarcity, means that market forces can impact pricing due to continual fluctuations in supply and demand, often caused by uncertainty in the market (Henckens, et al., 2016).

China's global control of REE supply culminated in a crisis when it declared REE exports were to be drastically reduced in 2010 with total exports equal to 30,258 tonnes; down almost 40% from 2009 exports which totalled 50,145 tonnes. China cited its domestic market requirements as reasons for the export reduction (Lackner and McEwen-Fial, 2011). This crisis was initiated as an unrelated political stand-off between China and Japan, who at the time were China's largest customer of rare earths (Doss, 2012). As a result of trade restrictions, reductions in Chinese export quotas and an increase in export taxes, the economic scarcity resulted in driving up the REE prices substantially outside of China compared to the prices of

REEs within China. This created a comparative disadvantage for companies buying REEs outside of China, as they were expected to pay inflated prices. This resulted in many consumers relocating their manufacturing plants to China in order to benefit from the cheaper selling price (Bradsher, 2010; Zhang, et al., 2017). The global response to China's export ban in 2009 was to lay complaints against China to the World Trade Organization (WTO). Fearing the financial repercussions that the WTO could impose, China quickly lifted these bans and once again began exporting unprocessed REEs to the rest of the world (Zhang, et al., 2017).

Subsequent to China's decision to starve the rest of the world of REEs, and because of REEs clean energy applications in an ever-growing climate-conscious society, both LREEs and HREEs were classified as critical metals in several jurisdictions. These include but are not limited to the European Union (EU), the United Kingdom (UK) and the United States (US) (Figure 2-4) (Chapman, et al., 2013).

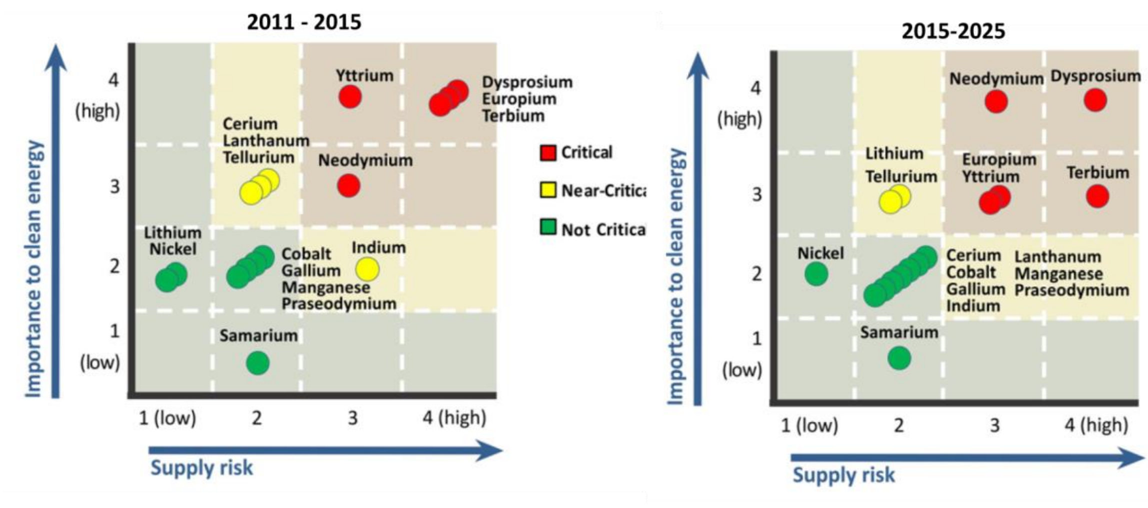

Figure 2-4: Short-and medium-term criticality matrices for the various REEs in the U.S (U.S. Department of Energy, 2011)

At one point, HREEs were considered even more critical compared to LREEs due to China's complete monopolisation of the supply, where they were responsible for supplying as much as 99% of HREEs, followed closely by 87% of LREEs (Garcia, et al., 2017). As of 2014, only two large, high-grade REE mines exist outside of China, and are also producers of LREEs. These mines are Mount Weld in Australia which began production in 2011 and Mountain Pass in the U.S. which reopened after closing in in the early-2000s due to environmental concerns (Morrison and Tang, 2012). For the manufacturing of many electronic items and other high-tech applications, HREEs are required in order to increase their performance. China has the only meaningful supply of HREEs which is thought to remain this way for some time to come (Morrison and Tang, 2012).

According to The U.S. Department of Energy (2011), cited in Golev et al. (2014) and Garcia et al. (2017), the United States declared that Nd, Eu, Tb, Dy and Y as the most critical REEs in the short to medium term, spanning a timeframe from 2015 to 2025. This is largely a result of their use in high strength magnets. These supply concerns prompted manufacturers to investigate substitutes as a way forward (Habib and Wenzel, 2014). However, REEs share comparable chemical characteristics with each other, such that they cannot easily be substituted by other elements in the technologies and clean energy manufacturing space. This, in conjunction with the monopoly of suppliers, explains why they are considered critical (Haxel, et al., 2002; Golev, et al., 2014).

2.3 Chinese Monopoly

In order to understand the global rare earth market, it is imperative to make sense of the Chinese market. The Chinese market is considered opaque and has been for several years, due to lack of information available outside of China (Long, et al., 2010; Tse, 2011). As a result, certain market fundamentals have been difficult to establish. These include Chinese supply, demand, reserves and resources, costs of production, stockpile and production amounts (UNCTAD, 2014). For this reason, much of the data sourced for this research excludes Chinese resources and reserves, particularly on a deposit scale, however information was used when available, mostly as estimates reported from literature within the public domain. These unknowns pose a real threat to future REE pricing, because China's ability to sell at a cheaper rate than the open market, causes instability in the REE market (Klossek, et al., 2016).

Due to China's abundant rare earth resources, many types of REE products are produced. According to Tse (2011), the dominant industries in China up to 2011 included the magnet, metallurgical, chemical, glass and ceramics and agriculture industries which accounted for about 75% percent of all Chinese REE production, with magnet manufacturing making up about half of that. China aims to maintain its position as the world leader in REE supply and plans to do this by the process of vertical integration of its REE value chain. The intention is to export mostly end products that possess a greater value compared to the unprocessed REOs further up the value chain (Zhang, et al., 2017).

China has known REE resources and reserves in 21 of its provinces, discovered over a period of 80 years. Until 1998, the Chinese government reported it had a total REE resource of 90 million metric tons. A decade later, it was reported that of those resources, approximately 18 million tons of REO had been classified as reserves (Tse, 2011). However, as Chinese production and consumption of REEs increased, by 2009, there were no publicly available reports with resource and reserve information due to an increasingly opaque REE market.

One of the contributing factors to the opaqueness of China's REE market and low confidence in fundamental mining information is that Chinese producers often partially or fully ignored environmental and safety laws in order to maintain low costs of production. Low production costs during the 2000s became the only way for many small producers to stay operational, because of the vast number of small deposits that were being exploited. Additionally, illegal REE mining became a prolific problem and resulted in as much as 30% of all REEs being exported from China being mined illegally in 2008 and 2009 (Doss, 2012).

Post 2016, during the overall market uptick, prices for a few REEs have increased, predominantly Nd and Pr, kickstarting the REE market. This is due to several factors including Chinese supply constraints due to both environmental failures, and a tightening of environmental law in China as well as an increasing demand for electric vehicles (EVs) and Neodymium-iron-boron (NdFeB) magnets, common in wind turbines (Roskill, 2017). Chinese restrictions still result in international technology producers having to purchase rare earth oxides at higher prices and once again highlights the rest of the world's dependence on China's dominant supply. According to the U.S International Trade Commission, cited in Mills (2018), over 60% of REEs imported into to the U.S was supplied by China, almost six times more than Japan and France, the next biggest exporters to the U.S.

China is expected to still dominate the global supply of REEs, but other countries are pushing forwards on establishing profitable producing mines that can compete with China. Despite this, the Chinese market is still able to shock the global market owing to it having the majority of REE reserves, as research reported by Adamas Intelligence, cited in Mills (2018) indicates. Mills (2018) explains that during the first half of 2017, the Chinese were selling extra quantities of separated and refined rare earth product to both Chinese and international buyers, predominantly in the EV, electronics, clean energy and military space. However, in late 2018, Chinese rare earth separation and refining were reduced by 35%, resulting in only enough rare earth material for Chinese manufacturers to purchase. This had concomitant knock-on effects for other manufacturers elsewhere in the world.

2.4 Chapter Summary

The REE market has undergone intense supply constraints in recent years, mainly due to geopolitics and apparent geological scarcity. China's control of the global REE supply chain has brought about short-lived hysteria about the accuracy of REE scarcity. These supply constraints are primarily a concern to the rest of the world due to their uses in clean technology and military applications. The rest of the world, including the U.S, EU states, Australia and Japan need to ensure they can secure a more reliable supply of REEs from other sources, outside of China. In order to understand this further, the geological distribution and deposit types must be investigated.

3 GEOLOGICAL DISTRIBUTION AND DEPOSIT TYPES

Exploitable concentrations of REEs are found in specific geological environments that have an uneven geographic distribution. These geological settings include alkaline intrusive, ion-adsorption clay, alluvial monazite-xenotime (heavy mineral sands) and carbonatite deposits. Despite these geological settings abilities to concentrate REEs, many of them are not considered economic. Figure 3-1 illustrates the location of known REE deposits, mines and occurrences, most of which are not considered economic.

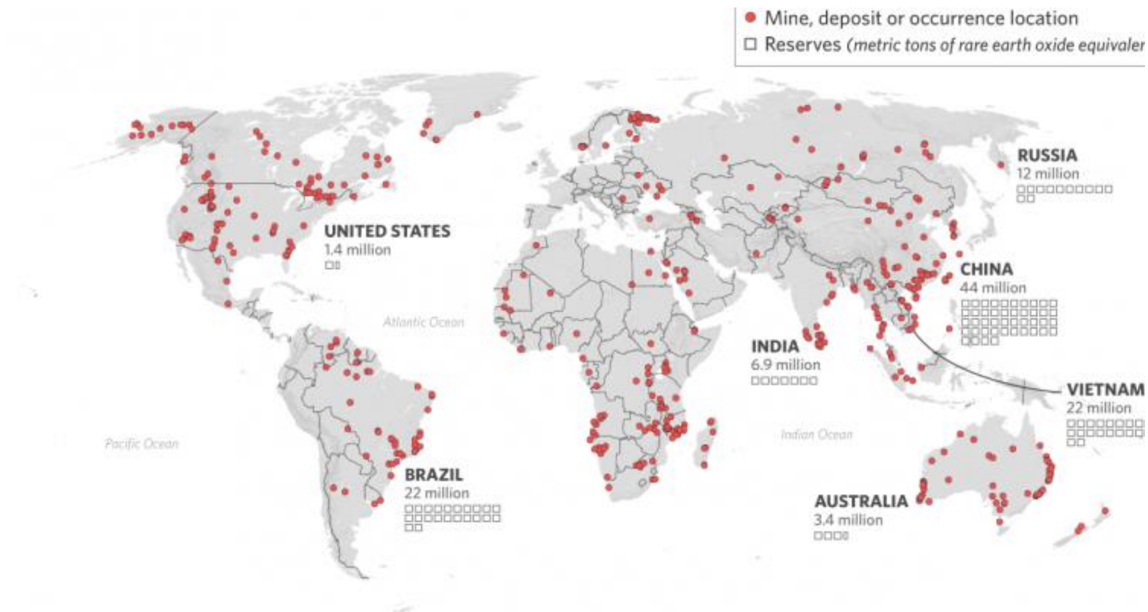

Figure 3-1: Distribution of REE deposits, mine and occurrences (after Stratfor Woldview, 2019)

To demonstrate this, out of 500 recorded carbonatites only one percent contains economic concentrations of REEs (USGS, 2014). Due to their geochemical similarities and mineralogical associations, single element deposits do not exist. Instead, deposits with two or more coexisting REEs occur (Christmann, 2014). As a result of their chemical similarities, complex mineralogy and geological occurrence it is difficult to extract a single rare earth element, and often requires large amounts of capital that ultimately rendering many deposits uneconomic. Metallurgical processes to extract the REE are complex and are often deposit specific.

There are greater than 190 REE-bearing minerals. However, economic abundances are predominantly found in the minerals known as bastnäsite [(Ce,La)(CO_3)F], loparite [(Ce,Na,Ca)(Ti,Nb)O_3], monazite [(Ce,La)PO_4)], xenotime (YPO_4), apatite [(Ca,REE,Sr,Na,K)$_3$$Ca_2$($PO_4$)$_3$(F,OH)] and ion-adsorption clays. The latter are often found in the lateritic environment (USGS, 2019). Currently, these minerals, from which rare earth elements are mostly derived, occur as primary geological resources. Of the abovementioned minerals, over 95% of all REE reserves are derived from monazite, xenotime and bastnäsite, making them the most important (Golev, et al., 2014). Deposits in the U.S. and China comprise the greatest proportion of economic resources of REEs, largely consisting of the mineral bastnäsite. Conversely, the next largest proportion of resources occur as monazite-xenotime deposits such as those that exist in Australia, South Africa, China, India and Brazil (Fernandez, 2017). Russia is the only country to recover REEs from loparite, mined from in the Murmansk region (Indian Bureau of Mines, 2014).

Rare earth deposits occur in various geological settings but have been broadly characterised as high and low temperature occurrences. High temperature occurrences are related to both hydrothermal and magmatic processes and include alkaline rocks and carbonatites. Conversely, low temperature occurrences are associated with the weathering environment in which deposit types include ion adsorption clays, and lateritic deposits (Wall, 2014). According to Goodenough and Wall, (2016), the leading problem with the various deposit types is the complicated rare earth mineralogy with only a fraction of known rare earth bearing minerals resulting in liberated REEs. Most REE resources are hosted within carbonatites, comprising about 295 million tonnes REO globally, which makes up just over 60% of total resources, across 65 carbonatites. In addition, the next largest source of REEs is alkaline igneous, iron-oxide-copper-gold (IOCG), placer, and ion adsorption types (Zhou, et al., 2017). The section below describes the different geological sources in more detail.

3.1 Carbonatites

Carbonatites are intrusive igneous rocks in which more than half its mineralogy consists of carbonate minerals. Carbonatites also commonly host some of the world's largest ore deposits with almost a 10% chance of a large ore deposit existing in a newly discovered carbonatite (Laznicka, 1999). Despite that, only one percent contains economic concentrations of REEs (USGS, 2014). Carbonatites are significant sources of several metals, including REEs, Nb, phosphate (P_2O_5), Y, Zr, Cu, Fe_2O_3 and Sc. Maoniuping and Bayan Obo in China, Mountain Pass mine in the U.S and Mt. Weld in Australia, are all examples of producing mines, that exploit carbonatites (Kynicky, et al., 2012; Smith, et al., 2016). Carbonatites' origin is highly contested, as they are not as common as other types of intrusive igneous rocks but they are very often associated with alkaline silicate magmas both in space and time (Mungall, 2007). According to Verplanck (2016), cited in Goodenough et al., (2017) carbonatites are characterised by enrichment in LREEs, and often have a variety of REE-bearing minerals such as bastnäsite, parisite and synchysite.

3.2 Alkaline igneous rocks

Alkaline igneous rocks are incredibly variable and essentially translate to rocks that are enriched in alkali compounds, namely Na_2O and K_2O and specific concentrations of silica. Geologically, silica undersaturated alkaline rocks occur as nepheline syenites such as the Pilanesberg Complex in South Africa whereas silica oversaturated alkaline rocks form peralkaline intrusions (Goodenough, et al., 2017). Many economic concentrations of rare metals occur in alkaline igneous complexes, such as REE deposits and they signify one of the most significant sources of REE and Y. These types of rocks can host economic concentrations due to primary magmatic process but also as a result of secondary, hydrothermal REE enrichment. Mineralisation of rare earths is often located in layered alkaline intrusions, late-occurring crosscutting dykes as well as trachytic and/or rhyolitic volcanic rocks which are the extrusive varieties of the intrusive igneous complexes (Dostal, 2017).

There are over 250 REE mineral varieties that occur in alkaline igneous rocks. The primary REE mineralogy includes minerals such as eudialyte, bastnäsite, gittinsite, loparite, xenotime, monazite, zircon, and fergusonite. However, it is usually only bastnäsite, monazite and xenotime that have high enough REE concentrations to be exploited economically. In these deposits, bastnäsite, monazite are significant sources of LREEs compared to xenotime, which is an important source of HREEs and Y (Dostal, 2017).

3.3 Vein-hosted

Vein-hosted rare earth deposits are notably rare, and any associations to carbonatite or alkaline igneous rocks are not currently known. REE mineralisation occurs in vein sets and some examples of this deposit type include the famous Bastnäs deposit in Sweden, the Gakara deposit in Burundi and Steenkampskraal in South Africa. The Bastnäs deposit marks the location for where many of the REEs were identified for the first time. Mineral assemblages include iron-oxides, Ca-Mg-REE silicates, REE fluorocarbonates, and base metal sulphides (Holtstam, et al., 2014). Other examples of vein hosted REE deposits are the Gakara project in Burundi (The MSA Group, 2016), and the Steenkampskraal deposit in South Africa (Steenkampskraal Rare Earths, 2019). Steenkampskraal and Gakara are low tonnage deposits but have higher total rare earth oxide (TREO) grades than other deposit types, although mostly comprising LREEs. The main ore minerals in these deposits include bastnäsite and monazite. Steenkampskraal for example, has a TREO grade of 14.4% with a Nd grade of 2.58%, which is a higher grade than most deposits (Steenkampskraal Rare Earths, 2019).

3.4 Placer

Pacer deposits for REEs, also known as mineral sands, have been a relatively easy and inexpensive source of REEs for a long time. REEs in mineral sands often occur as xenotime and monazite, and are found in several locations globally, including in India, Australia and Malaysia. Rare earth minerals are often mined as a by-product from titanium and zircon-bearing mineral sands (Indian Bureau of Mines, 2014). Mineral sands are often found in coastal or fluvial environments and are the result of direct erosion of REE-bearing igneous rocks. Placer mining is cheap and easy to process which offsets the typically low-grade deposits. They are also good sources of magnet REEs, such as Nd, Dy and Pr (Goodenough, et al., 2017).

3.5 Laterite

Laterite REE deposits are a result of weathering of REE-bearing igneous rocks, that occur or have occurred in temperate to tropical environments. During the laterization process, REEs are leached into the secondary, weathering environment resulting in the enrichment of REEs in specific horizons within the weathering profile. In addition to concentrating REEs, the process of laterization is common in concentrating secondary sources of many important metals such as gold, nickel and other base metals (Cocker, 2012). An enriched REE horizon within the laterite profile is commonly described, with primary REE mineralisation nearby, usually directly below. A well-known case of this style of mineralisation is the Australian deposit, Mt. Weld, which is a carbonatite deposit overlain by a weathering profile that is almost 75 m thick, enriched in REEs (Jaireth et al., 2014 cited in Goodenough, et al., (2017)). Weathered carbonatites, with laterite development, have also been identified at numerous other deposits across the world which are largely enriched in LREEs (e.g. Zandkopsdrift in South Africa, Ngualla Hill and Panda Hill in Tanzania, Mrima Hill in Kenya; Dong Pao in Vietnam; Tomtor in Russia; Araxá in Brazil).

3.6 Ion adsorption clays

Ion adsorption clay deposits are specific to certain areas in the world. Typically, these areas of rare earth enrichment are often high in tonnage, but low in TREO concentrations with grades ranging between 0.05 and 0.2%. Despite their low grades, ion adsorption clay deposits are considered extremely economic due to high tonnage, and simple metallurgical processing and recoveries (Golev, et al., 2014). The formation of these clays is due to slow dissolution of the enriched primary source rock, such as a carbonatite, or alkaline igneous suite of rocks. During the dissolution, rare earth ions enter the hydrous solution. As the solution passes through the surrounding rock, the adsorption of rare earth ions onto clay minerals takes place (Long, et al., 2010; Yang, et al., 2013). Ion adsorption clay occurrences are limited and only occur when specific criteria are met. Such criteria include extended periods of weathering, restricted erosion and increased concentrations of clay minerals (Vahidi, et al., 2016). Currently, ion adsorption clay deposits are only being exploited for REE in China, which is a significant source of HREEs. There are, however, ion adsorption clay deposits outside of China but do not necessarily show enrichment in HREEs (Goodenough, et al., 2017).

3.7 Chapter Summary

There are several deposit types in which economic concentrations of REEs exist, namely carbonatites, alkaline igneous rocks, vein-hosted, placer (including heavy mineral sands), laterite and ion-adsorption clays. Importantly, these deposit types exist across the globe with carbonatites and alkaline igneous complexes as the largest source of REEs. These deposit types exist in many countries around the world. However, economic deposits are scarce. Large concentrations of ion-adsorption clays occur exclusively within China which provide high tonnage, low grade ore to China. In addition to world class carbonatite deposits i.e. Bayan Obo, China is endowed with significantly more REE resources relative to the rest of the world. In order to quantify the global REE resources, an investigation into known resources is necessary. This investigation can contextualise Chinese resources compared to the rest of the world.

4 AVAILABLITY OF RARE EARTH ELEMENTS

In order to understand potential availability of primary REEs, to keep up with the growing demand, a quantitative approach was undertaken to establish a baseline number for global rare earth resources. There are generally large inconsistencies in several estimates of global REE resources, mostly because of opaque market dynamics and a lack of geological or deposit knowledge, particularly in China. Furthermore, variable resource estimates provided in the past suggest there is high level of economic sensitivity as well as political concern (UNCTAD, 2014).

Nevertheless, this section attempts to establish REE resources on a global scale through the analysis of publicly available information including resources and reserves data from known mining operations and exploration projects as well as academic journals and expert reports. Many of the deposits considered are not currently being pursued for development as they are deemed uneconomic due to factors such as size, grade and metallurgical constraints. However, these projects may be developed in the future should the modifying factors change, or the rare earth prices allow it.

Determining the amounts of any commodity can be done in a number of different ways. Firstly, by defining a mineral resource which can be described as a concentration of minerals, that satisfies certain criteria, making it reasonable and realistic for eventual economic extraction. Secondly, by defining reserves, which are usually substantially smaller than the resource, and make up the part of the resource that can be extracted after the application of modifying factors such as costs, political, legal, social, environmental, metallurgical and financial (Figure 4-1) (Camisani-Calzolari, 2004).

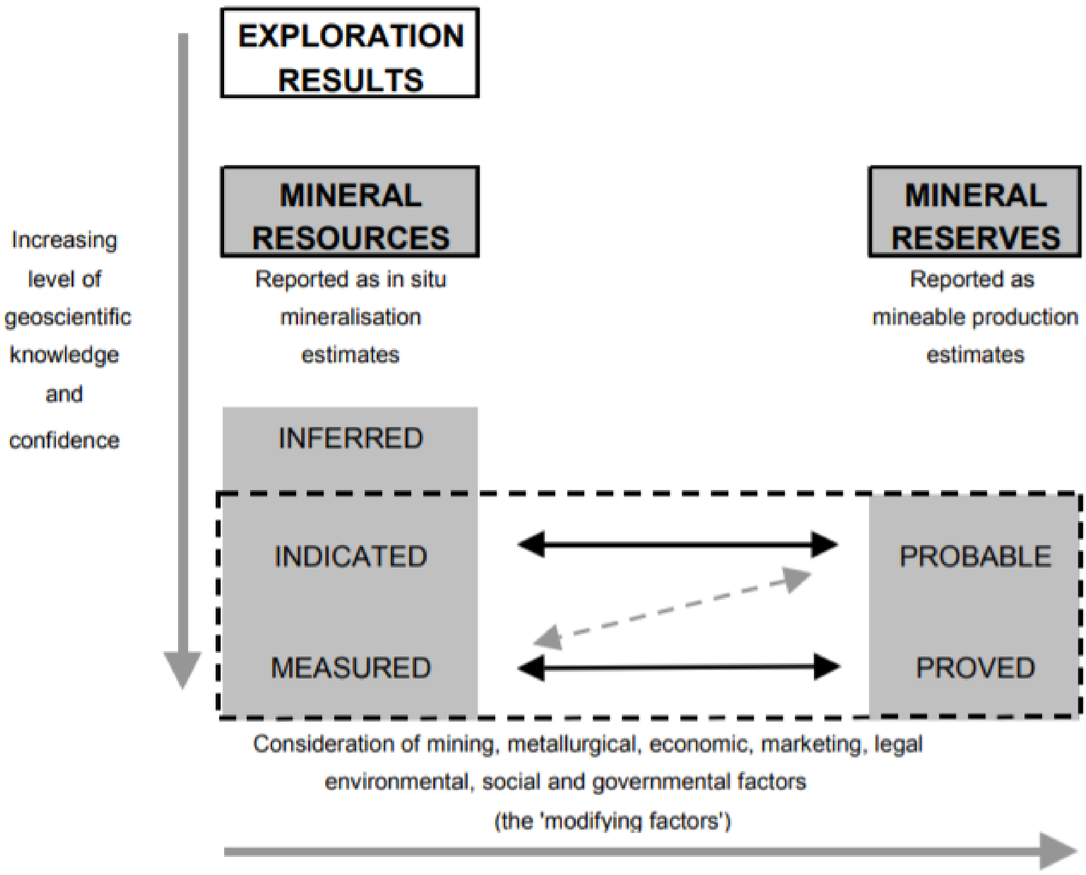

Figure 4-1: Relationship between resources and reserves (after Camisani-Calzolari, 2004)

The sources of the data are largely technical reports. Such reports are mostly compiled by consultants who provide independent project reviews, often in compliance with internationally recognised reporting codes for mineral resources. The main reporting codes used for reporting of mineral resources are the Joint Ore Reserve Committee (JORC), CIM National Instrument (NI) 43-101 or the South African Mineral Resource Committee (SAMREC). Compliance to the various mineral resource reporting codes, requires that all technical reports and press releases must be submitted to the relevant stock exchanges such as the Australian Securities Exchange (ASX), Toronto Securities Exchange (TSX), Toronto Securities

Exchange – Ventures, (TSX-V), Johannesburg Stock Exchange (JSE) and the London Stock Exchange (LSE).

Data were also derived from peer-reviewed journal articles, authority reports (e.g. USGS, Roskill), open-source company databases (e.g. Opaxe/RSC), and press releases, all of which exist in the public domain. Other data sources used include corporate and investor presentations, which are released to the public domain but often not code compliant as they are used primarily as a marketing tool. However, the resources reported are considered adequate for the purpose of this research.

4.1 Primary Sources of REEs

There are over 850 REE deposits that have been identified globally, largely as a result of opportunistic junior explorers, trying to capitalise on high REE prices during the last REE boom caused by supply concerns (Barakos, 2017). Of these known deposits containing REE mineralisation, information on 179 of them have been researched and collated by Zhou et al. (2017) and was used in this report. Of these 179 deposits, active mining operations and projects in development are included. Despite a large number of projects, many of them are not currently being pursued for eventual economic extraction but have undergone some form of resource estimation or definition in the past. As a result, the resources demonstrated provide a possible resource base, not an economically feasible one and therefore are higher than figures estimated for active mines and projects in development (Zhou, et al., 2017).

Table 4-1 summarises the key resources for the potential resource base, established outside of China.

Table 4-1: Summary of REE resources, excluding China (after Zhou, et al., 2017)

Possible REE Resources	Total Resources (million tonnes)	TREO Resources (million tonnes)
n=179	52,574	313.66

Considering the current REE market, it is unlikely that many of these deposits will come online due to the complicated mineralogy that exists in many deposits, low grades and in some cases environmental concerns such as radiation due to abundant thorium (Th) concentrations (McLeod, 2019). However, the resources make up potential economically feasible deposits in a different REE market. Figure 4-2 and Figure 4-3 illustrate the geographic distribution of ore tonnes and contained TREO globally.

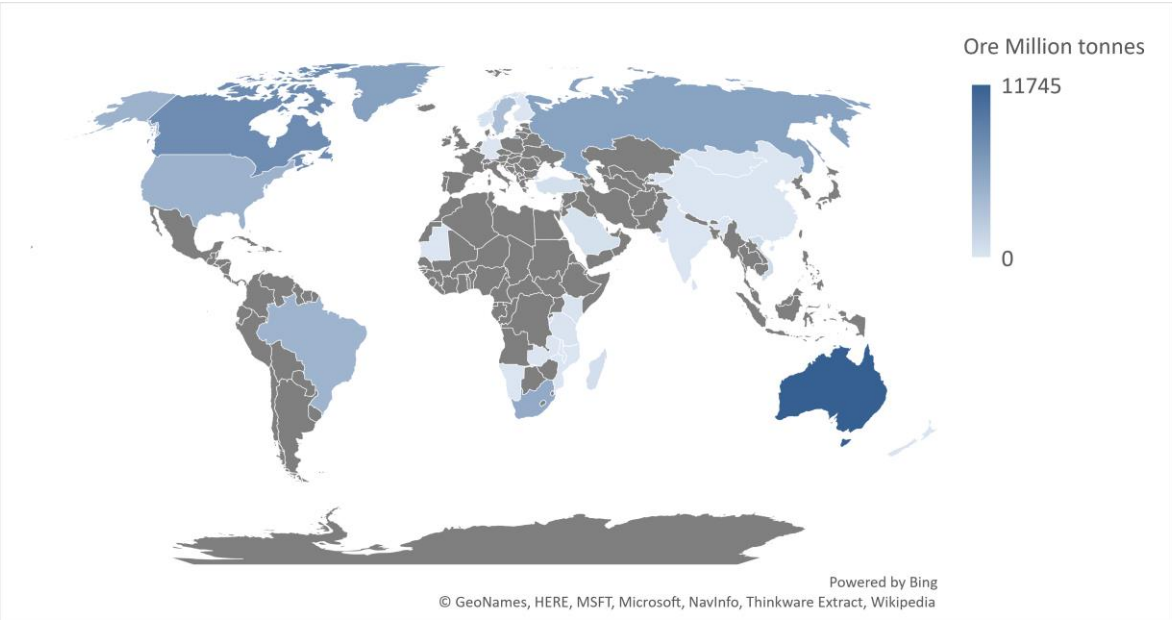

Figure 4-2: Ore tonnes of known REE resources

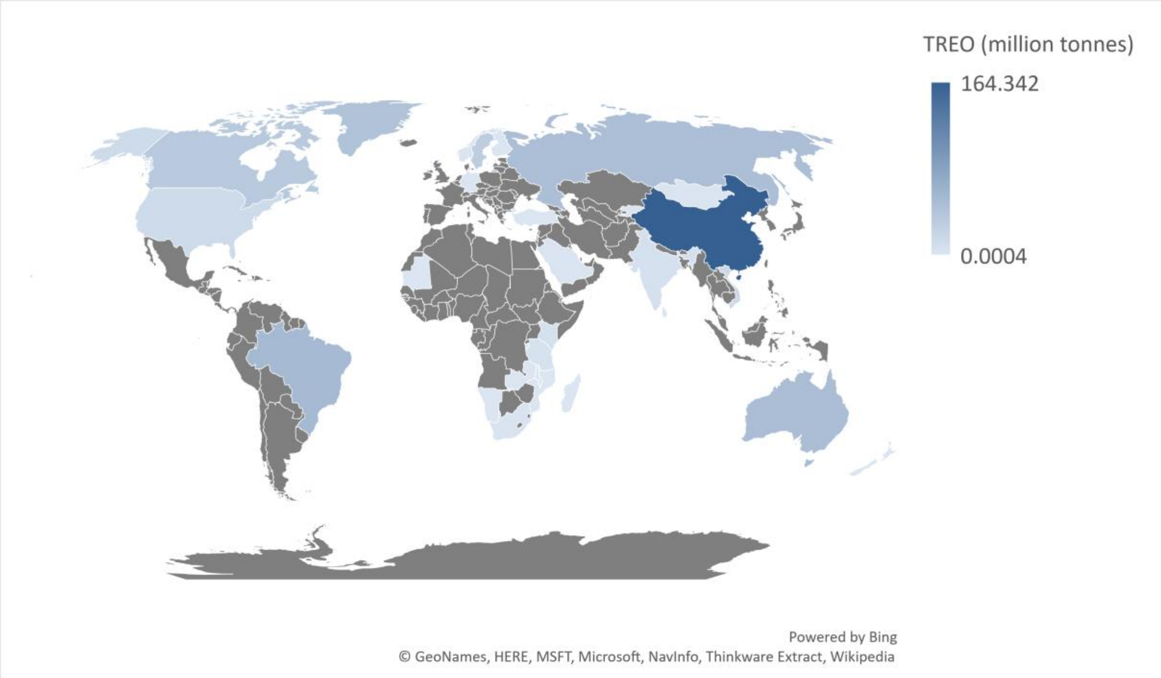

Figure 4-3: Contained TREO of known REE resources

The global REE ore resources are estimated to be at least 52,574 million tonnes. Ore tonne data from Chinese deposits were not available and are therefore not shown in Figure 4-2. Despite the lack of data pertaining to Chinese deposits, China is still considered the world leader in REE resources both in terms of ore tonnes and contained metal. This is largely based on their annual production output which is derived primarily from their ion adsorption clay deposit types. When considering the rest of the world, Australia is observed to be the leader in known ore resources with an estimated 11,745 million ore tonnes, equating to 22.34%.

In comparison, Figure 4-3, which includes information on Chinese deposits, depicts China as global leaders in terms of contained metal (TREO), with an estimated 164.34 million tonnes TREO out of a global estimate of 478 million tonnes of TREO reported, suggesting that China possesses 34% of the global TREO. Following China, most of the resources occur within Brazil (55 million tonnes), Australia (49 million tonnes), Russia (48 million tonnes), and Greenland (43 million tonnes). Most of the balance is situated within Canada, Sweden, USA.

4.1.1 Code-Compliant Resources

Of the 179 deposits described above, there are currently only 44 active projects, comprising 35 exploration or development projects and 9 mining operations. Only 5 of the 9 mining operations have reliable, code compliant resource estimates from which data can be sourced (Table 4-2) (Appendix 1).

Table 4-2: Summary of REE resources and TREO in 2019, compiled from literature (excluding China)

Project Status	Total Resources (million tonnes)	TREO Resources (million tonnes)	Total Reserves (million tonnes)	Total Production (tonnes)
Development/Exploration (n= 34)	9210,11	77.17	439.30	NA
Mine (n= 5)	132.36	4.43	67.54	57,053

There has been a drastic decrease in the number of projects since 2012, where over 800 projects were being developed. The data derived from the analysis of these 44 projects is a more accurate representation of the global resources that exist outside of China (Figure 4-4) and can be used to establish a baseline number of REOs that can be made available to the market or have a greater chance of becoming available in the short to medium run, should the modifying factors allow for resource to reserve conversion.

The exploration projects in question are at different stages of resource definition and are thus classified according to inferred, indicated and measured resources, for both ore tonnes and contained metal, with a corresponding grade for each estimation category.

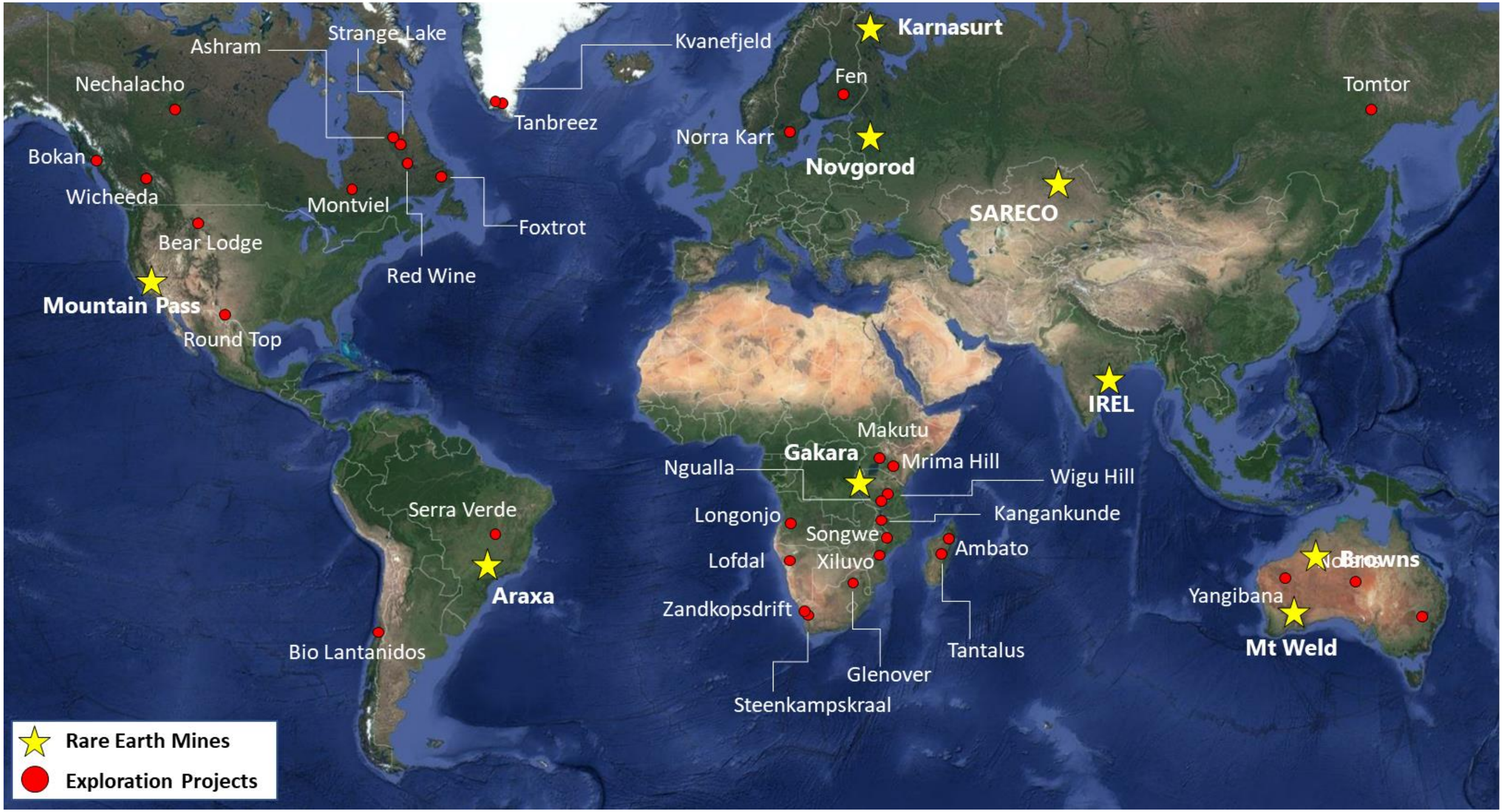

Figure 4-4: Location of global rare earth exploration projects and mines (excluding China) (Modified after Backeberg, 2019)

Table 4-3 summarises the resource tonnes and TREO for all resource categories, for projects in development and mining operations.

Table 4-3: Total Resources (ore tonnes and TREO) for Measured, Indicated and Inferred categories for global exploration and mining projects outside of China

Project Status	Total Resources M+I (million tonnes)	TREO M+I (million tonnes)	Total Resources Inferred (million tonnes)	Contained TREO Inferred (million tonnes)
Development	1,841.66	11.63	7,368.43	65.53
Mine	80.24	3.48	52.12	0.95
Total	1,921.90	15.11	7,420.55	66.45

The data indicates that a total of 1,921.90 million tonnes of measured and indicated ore resources have been established across all projects, including active mining operations. Of this amount, approximately 80.24 million tonnes of resources are attributed to current mining operations. In comparison, a total of 6,894.56 million tonnes of Inferred resources are reported, of which approximately only 52.12 million tonnes are from current mining operations.

In some cases, it is observed that only inferred resources have been defined for a deposit and likely represents low resource confidence. Projects like this will have to undergo further exploration to increase the resource confidence and move resources classification from Inferred to Indicated and then Measured. It is also observed that most deposits have greater amounts of inferred resources as opposed to measured and indicated.

Figure 4-5 presents the sum of measured and indicated resources compared to inferred resources for each project. Tanbreez, a Greenlandic project owned by

Tanbreez Mining Greenland, is currently one of the world's largest rare earth resources, with over 4 billion tonnes of inferred resources. The geological setting is an alkaline igneous complex, in which the resource has the potential to be a large contributor of REEs, despite a grade of only 0.65% TREO (Barakos, 2017). The project is high in HREEs, as well as Ta, Nb and Zr. The image shows the four largest projects in terms of measured and indicated resources as Greenland's Kvanefjeld, Brazil's Serra Verda, Madagascar's Tantalus and Canada's Strange Lake. These four projects collectively make up a large proportion of global resources currently being defined, with 1,316.7 million tonnes of measured and indicated as well as 1,724 million tonnes of inferred resources. Inferred resources for the top five, including Tanbreez, will extend up to 6.8 billion tonnes of ore.

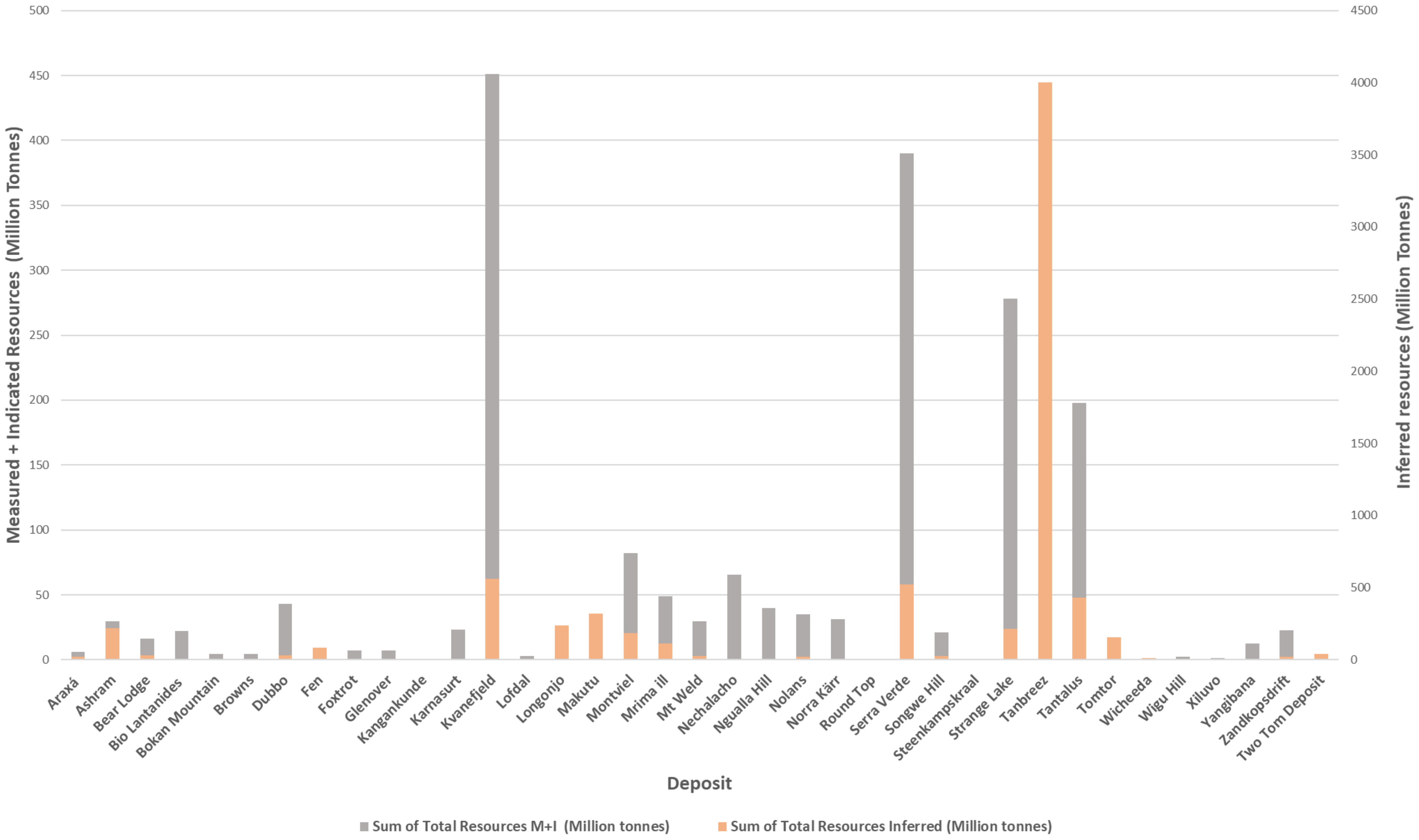

Figure 4-5: Inferred versus Indicated and Measured Resources for all REE projects and mines outside China

Contained TREO is a good way of indicating resource size, and when compared to grade, shows where individual deposits are situated relative to others, in terms of grade and contained metal (Figure 4-6). Tanbreez, praised for being the largest resource in terms of ore tonnes, is depicted as being a high tonnage, low grade deposit.

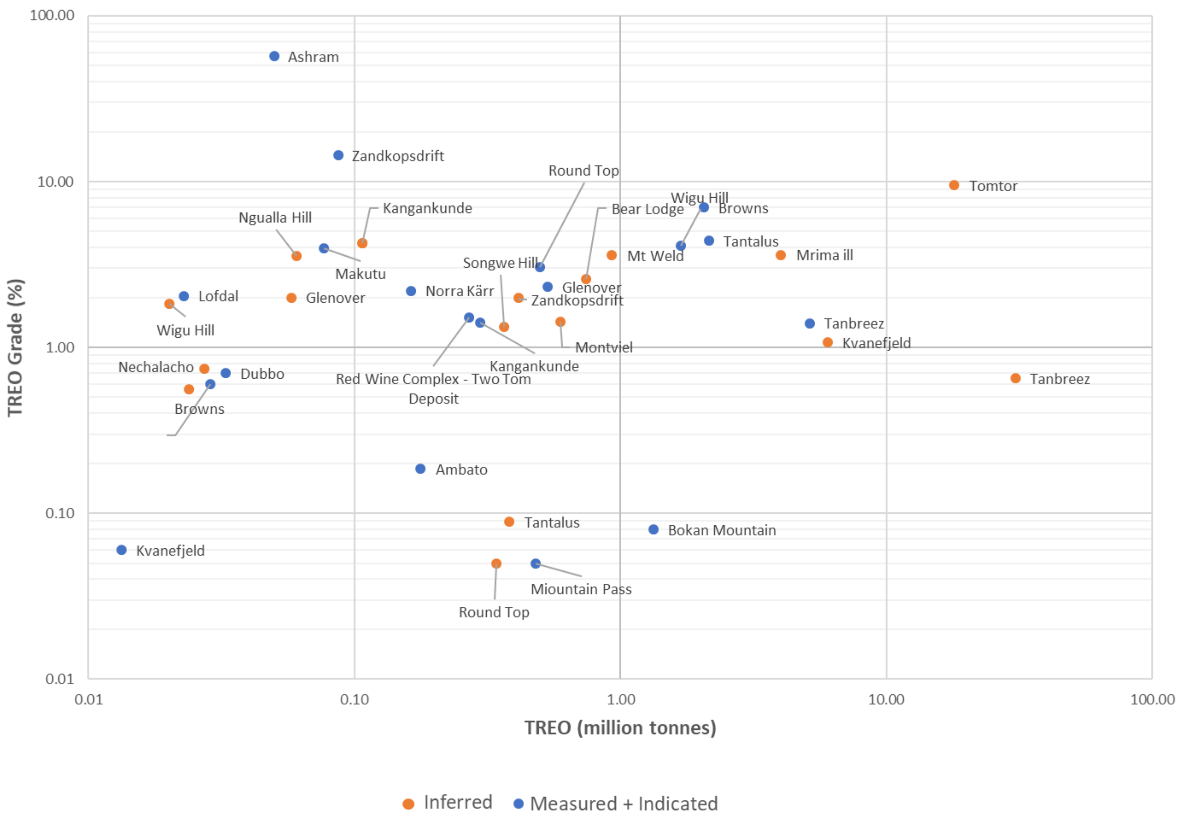

Figure 4-6: TREO (million tonnes) vs TREO grade (%) of advanced stage projects (after Zhou, et al., 2017) outside of China

4.1.1.1 <u>Geographic Distribution of Resources</u>

Figure 4-7 indicates the countries where the highest classified resources are found. These include Greenland, Canada and Brazil with 479, 463 and 396 million tonnes of measured and indicated resources respectively and 559, 676 and 543 million tonnes of inferred resources. Madagascar has particularly high inferred resources, i.e. 430 million tonnes from the Tantalus deposit. Tantalus is an ion adsorption clay deposit type, characterised as high tonnage and low grade.

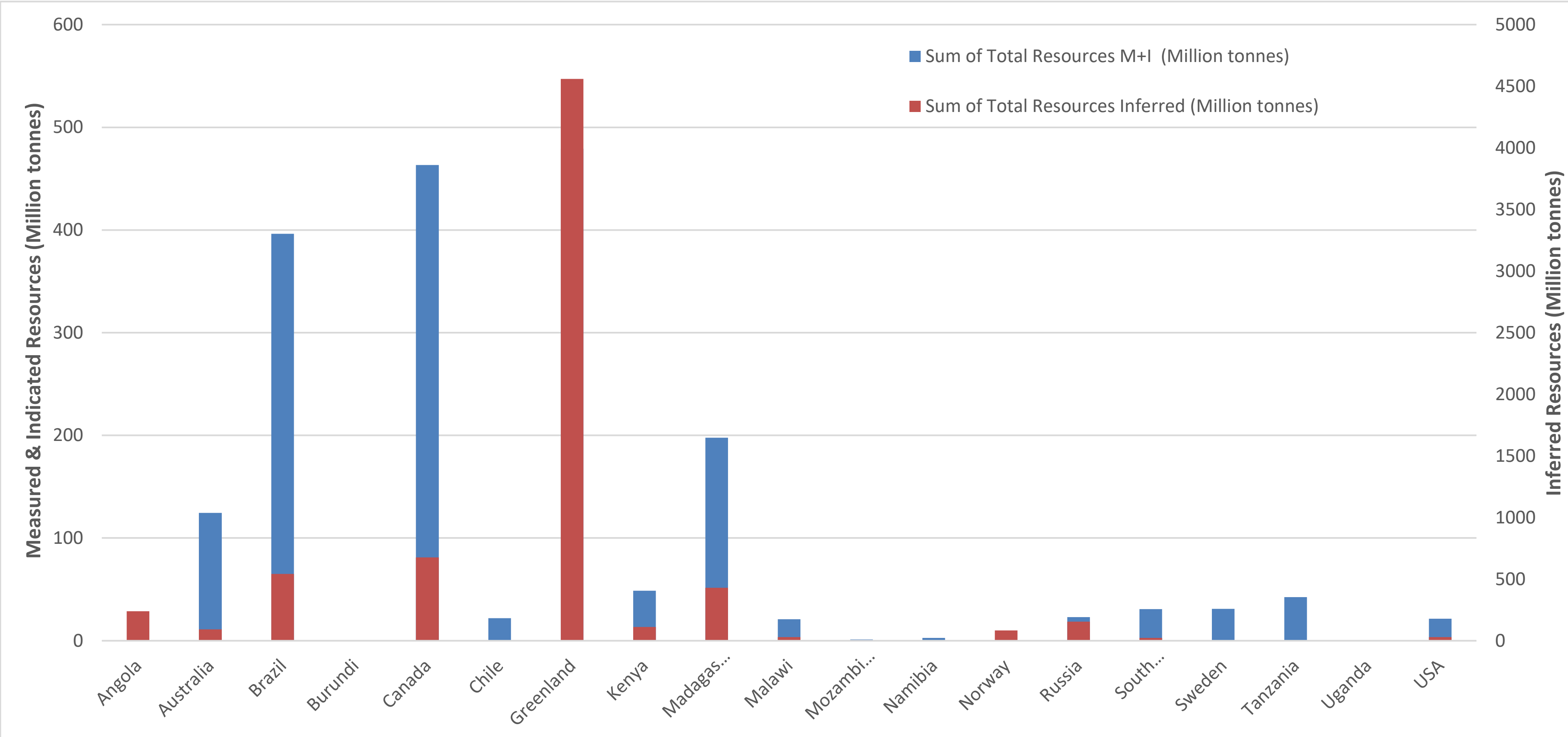

Figure 4-7: Inferred versus Indicated and Measured Resources by Country (excluding China) for exploration, advanced and mining projects

From the data collected, total Reserves, for advanced projects not yet in production, equates to 439.30 million tonnes, whereas current reserves from rare earth mines outside China total 67.54 million tonnes of ore material. This suggests that there is a substantially higher supply pipeline from the rest of the world, from projects expected to come online over the next few years. Contained TREO in reserve classification totals 1,444 thousand tonnes and indicates the most immediate available REO material once these projects are operating mines. It is important to note that if the global REE demand continues to grow, it will undoubtedly raise the price for elements in demand, resulting in an increase in reserves, bringing millions of resource tonnes of resources into reserves, increasing the amount of recoverable TREOs significantly.

4.2 Secondary Sources of Supply

Various secondary sources of REE supply do exist such as recycling of end use products and supply from coal combustion products (CCPs). At this point in time, these sources of supply are not expected to make a significant impact in terms of meeting global demand but some of these sources do have the potential to provide significant amounts of REEs to the market in the future, but is difficult to quantify at this stage.

4.2.1 Coal Fly Ash Resources

Coal Fly Ash (CFA) contains REEs and can be used as another, potentially significant, source. Although the concentrations of REEs in CFA and coal by-products are commonly significantly lower than primary REE deposits, HREEs are actually found in similar abundances in both CFA and primary REE deposits (U.S. Department of Energy, 2017). The concentration of REEs in CFA varies, but has been shown to be high in coal producing nations such as the U.S, China and South Africa (Nugroho, et al., 2019). In several localities in the U.S, substantial amounts of CFA are recorded, where REEs including Nd, Tb, Eu, Dy, Y and Er are present in abundance between 35 to 40% of the CFA (Laurino, 2016). According to the Alvin (2018), the U.S burns about 750 million tonnes of coal each year. From this, approximately 75 million tons of CFA is created. Laurino (2016) reports that the U.S. produces 45 million tonnes CFA, from almost 120 million metric tonnes of CCPs. This could potentially be a large contributor to the REE supply of the U.S. and result in as much as 32,000 metric tonnes of REE + Y per year (Alvin, 2018), and remove dependence on primary REE deposits, namely Mountain Pass.

However, at this stage, commercial application of REE recovery from CFA has not been done. This is largely due to the issues that arise from the quality of the coal produced, which affect the separation process when REEs are extracted from CFA. In Indonesia, the potential for abundant REEs from CFA is high but due to an abundance of iron-oxides, separation processes are too expensive and result in lower recoveries (Laurino, 2016; U.S. Department of Energy, 2017; Nugroho, et al., 2019).

In order to establish the quantities of REEs CFA can supply, considerably more research needs to be done to determine efficient and cost-effective recovery methods. It is likely that only countries with limited to no primary sources of REEs, will expedite these investigations. It is suspected that in several jurisdictions across the world, with effective recoveries, CFA can be a sustainable supply of REEs in terms of satisfying local demand in the country it is produced.

4.2.2 Recycling

Recycling of REEs could potentially alleviate some of the supply concerns from primary sources, particularly as demand for REEs increases. However, at this stage, REE recycling is being performed at a small scale and as a result only very small percentage of REEs are recycled, totalling approximately 120 tonnes (Binnemans, et al., 2013; Tanaka et al. (2013) cited in Golev et al. (2014); USGS, 2019). Jowitt et al. (2018) summarise several reasons why REE recycling is not yet common practice in Table 4-4. Recycling focuses on areas where scrap with abundant REEs are found in addition to and more sought after, critical REEs within the scrap.

Table 4-4: Difficulties in increasing REE recycling (modified after Jowitt et al., 2018)

Difficulty
Final product intended to be recycled contains small amounts of required REE (mg to g)
No incentive due to low quantities – primary sources make more financial sense
Current commercial recycling is not able to recover small concentrations of required metals
End-products intended for recycling contain complex array of metals that may change in the future due to technological advancements in production
End-product collection for recycling is not well established around the world – costs and logistics involved unclear

As a result, recycling of permanent magnets, phosphors, NiMH batteries are most common (Golev, et al., 2014). The little bit of recycling that does occur throughout the world is categorised as the following types (Li, et al., 2017):

- Recycling of scrap material straight from the manufacturing process; and
- Collection and recycling of products at the end of their useful life.

Sources of REE from each of these types of recycling are described below in Table 4-5.

Table 4-5: REEs recycled based on type of recycling (modified after Jowitt et al., 2018)

Type of recycling	REE recycled
Scraps and residues from manufacturing and industrial processes	LREE such as La and Ce from Fluid Catalytic Cracking (FCC) but ultimately any REE can be recycled as it depends on what material was used in manufacturing
End of Life (lighting and phosphors)	La, Ce, Tb, and Y
End of Life (permanent magnets)	Largely Nd and Dy but also other REEs in smaller concentrations
End of Life (NiMH Batteries)	La, Ce, Pr and Nd

As the amount of scrap material is expected to increase in the future, recycling at a commercial scale and economically viable recycling will likely increase, particularly with REEs that are expected to be in higher demand in the future, such as Nd and Dy. According to Reimer et al. (2018), approximately 60 tonnes per annum of Nd is recycled as a result from scraps and residues from manufacturing. This is assumed to increase on a linear trend as production of NdFeB batteries increases.

With respect to magnets, recycling potential is expected to increase slowly over the next decade, and then ramp up significantly. This is due to increasing market penetration of EVs, e-bikes and other mobility applications for magnets (Reimer, et al., 2018). Geomega, a North American based company is concentrating on the recovery of rare earths though the recycling of permanent magnets. The recycling of these magnets is expected to be small scale and the recovered rare earth material will likely supply a very small part of the magnet manufacturing sector as it is still very much reliant on primary production of REEs (Backeberg, 2019). Current recycling is recorded between 60 and 80 tonnes per annum of REEs. Until 2028, recycled Nd and Dy amounts to less than 250 tonnes per year whereas over 1,000 tonnes per annum can be expected by 2033. Essentially, from recycling of NdFeB magnets calculated only from mobility applications and wind turbines, where most recycling is expected, it is forecast that 233,000 tonnes of NdFeB will be recycled between 2016 and 2044. This corresponds to about 66,000 tonnes of Nd and 7,900 tonnes of Dy (Reimer, et al., 2018).

Recycling of REEs will likely increase should there be any significant market deviations that result in a shortage in REEs. The shortage can either be due to supply issues of increases in demand due to wider range of applications. As the prices increase, so will REE recycling (Goonan, 2014). Several companies are currently producing REEs through the recycling of various end use products. These companies include REEcycle, Rare Earth Salts (RES), Ucore and Geomega (owners of Montviel project in Canada). RES has established a separation facility and recently started producing separated rare earth products from the recycling of lamp phosphors. The facility is expected to produce about 450 tonnes per year of rare earth oxides (REO). Initially, these REO products will include 145 tonnes per year of Y-oxide, 25 tonnes per year of La and Ce-oxide and 13 tonnes per year Tb and Eu-oxide. By 2022, the facility is expected to reach a total of 3,000 tonnes per year (Backeberg, 2019).

4.3 Chapter Summary

China possesses the most significant resources across various deposit types relative to the rest of the world. In order to reduce the rest of the world's dependency on China for REEs, resources outside of China must be developed. There are many REE resources around the world that are already known, albeit not necessarily in economic concentrations or conducive to extraction due to various modifying factors. Globally, classified resources total approximately 313 million tonnes TREO, defined from 179 deposits. Currently, outside of China, only 35 exploration projects and 9 mining operations contain just over 81 million tonnes TREO. Of these projects, Greenland, Canada and Brazil are expected to become significant players in the REE space, if the deposits they possess are developed further. Furthermore, potentially significant resources could come from coal fly ash, which contain variable amounts of REEs, and recycling. Both are considered more likely for the future and do not currently resolve the supply issues that plague the rest of the world.

5 EXTRACTION AND PROCESSING

5.1 Current Production

Despite many known REE deposits, there are only a handful of operating mines that are producing REOs. Some of the largest include Mt Weld in Australia, Mountain Pass in the U.S. and Bayan Obo in China (Haque, et al., 2014). Due to limited information for China on a deposit scale, the data sourced largely reflects production and resources for the rest of the world. Establishing global production of REEs from current operating mines indicates the immediately available REE supply to the global market.

As previously established, extraction is mostly conducted by China, where over 80% of global REEs are currently produced, mostly through open pit mining of bastnäsite and monazite or through the leaching of ion adsorption clays (Vahidi, et al., 2016). Vahidi, et al. (2016) indicate that ion-adsorption clays are the largest sources of REEs and the most important source of HREEs globally. The REEs in these deposit types are also relatively easier to extract due to them being at or near surface and unconsolidated.

Figure 5-1 shows output by country from 2004 to 2016 in terms of TREO production. Two obvious trends can be observed, namely the sharp increase in Australia's production, which is accredited to Mt Weld, and China's decreasing share of global production shown as a percentage, down 15% from 2010 to 2016.

Country	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Australia	-	-	-	-	-	-	-	2,200	3,200	2,000	8,000	12,000	14,000
Brazil		-	730	650	650	550	550	250	140	330	-	880	1,100
China	95,000	119,000	119,000	120,000	120,000	129,000	130,000	105,000	100,000	95,000	105,000	105,000	105,000
India	2,700	2,700	2,700	2,700	2,700	2,700	2,800	2,800	2,900	2,900	3,000	1,700	1,700
Malaysia	250	750	200	380	380	350	30	280	100	180	240	500	300
Russia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2,400	2,500	2,500	2,800	3,000
Thailand	2,200	-	-	-	-	-	-	-	-	800	2,100	760	800
U.S.A.	-	-	-	-	-	-	-	-	800	5,500	5,400	5,900	-
Total (rounded)	102,000	123,000	123,000	124,000	124,000	133,000	133,000	111,000	110,000	110,000	123,000	130,000	126,000
% of China	93%	97%	97%	97%	97 %	97.0 %	98 %	95 %	91%	86 %	85 %	81 %	83%

Figure 5-1: Global REO production by country from 2004 to 2016 (after Barakos, 2017)

Rare earth production per element and estimates of element resources are shown in Table 5-1. When analysing production on a per element basis, La, Ce and Nd have the most resources and are the most widely recovered elements on a global scale, highlighting the relative abundance and popularity of LREEs compared to HREEs (Table 5-1). The data below is derived from known rare earth mines in 2014 and subsequently, may have changed. However, developing rare earth deposits has been sluggish over the last several years and as such, the numbers presented are considered reliable. The total production figure of 59,320 tonnes for the world, excluding China, is comparable with cumulative data collected from technical reports presented in this section.

Table 5-1: Resources and production statistics of individual REEs (after Haque, et al., 2014 and Binnemans, et al., 2018)

Element	Resources Tonnes (ex-China)	Production tonnes per annum (ex-China)	Global Production REOs Average 2010-2014)
La	22,260,000	12,500	35,146
Ce	31,700,000	24,000	51,430
Pr	4,800,000	2,400	6,500
Nd	19,700,000	7,300	22,391
Pm	NA	NA	NA
Sm	2,900,000	700	2,714
Eu	244,333	400	407
Gd	3,622,143	400	2,307
Tb	566,104	10	407
Dy	2,980,000	100	1,357
Ho	NA	10	424
Er	1,850,000	500	950
Tm	334,255	50	170
Yb	1,900,000	50	1,042
Lu	395,000	NA	163
Y	9,000,000	8,900	10,300
Sc	NA	2,000	2,000
Total	**102,251,835**	**59,320**	**137,708**

In 2018, approximately 170,000 tonnes of REOs were produced from primary sources globally (USGS, 2019). Comparably, Jowitt et al. (2018) report that primary REE production is produced from about 130,000 tons of REO per year. Chinese production estimates alone have in recently totalled up to 120,000 tonnes per annum (McLeod, 2019).

Although the numbers are quite similar between various reported production figures, larger discrepancies exist at a country level. The greater variance is attributed to the presumed production of the non-reported market (Kalvig and Machacek, 2018), the largest variance undoubtedly originating from China. As the rare earth demand increases due to supply constraints, trade wars between China and the U.S, and because of increasing need for high-tech applications it is expected that production of known reserves will increase. Despite certain countries having large REE reserves, it does not always translate to high production figures. Production of LREEs globally is likely to almost triple, from about 120,000 tonnes to 345,000 tonnes, over a period of 11 years, from 2011 to 2022. Projects under development that are focusing on LREEs include Wigu Hill in Tanzania, and others with a specific intention of supplying REO concentrate to high-powered permanent magnet manufacturers, include, Nolans and Yangibana in Australia, Ashram, Montviel, Wicheeda and Red Wine Complex in Canada. These projects will focus on the production of Nd and Pr. In comparison, HREE production is also expected to rise from about 13,000 tonnes to 45,00 tonnes over the same time period (U.S. Department of Energy, 2017). Projects that intend to produce and supply HREEs include Tanbreez in Greenland, Nechalacho in Canada and Serra Verda in Brazil, mainly with a focus on Dy and Tb.

According to the Indian Bureau of Mines (2014) and USGS (2019), the total annual REO production is offset against a global reserve base of approximately 122 million tonnes, measured from active and producing mines. Of this total, about one third belongs to China, with approximately 44 million tonnes. Brazil, Russia and Vietnam also have between 15 and 20% each of global reserves. Despite their REO reserves, Brazil, Russia, Vietnam and Russia produce just a fraction of their REO reserves each year, whereas China repeatedly dominates as the global leader with respect to production (Table 5-2) (Indian Bureau of Mines, 2014).

Table 5-2: Rare earth reserves and production by country in 2018 (after McLeod, 2019)

Country	Reserves (Million Metric Tonnes)	Production in 2018 (Metric Tonnes)
China	44	120,000
Brazil	22	1,000
Vietnam	22	400
Russia	12	2,600
India	6.9	1,800
Australia	3.4	20,000
United States	1.4	15,000

According to data gathered from multiple technical reports, company websites and annual reports, the total production of REOs outside of China is recorded at 57,053 tonnes for 2018. This figure is comparable to that estimated by the USGS (2019), which reports 48,000 tonnes of REOs were produced outside of China. This total is derived from only seven (7) of nine (9) mines as they are actively producing. These include Browns and Mt Weld in Australia, Gakara in Burundi, Mountain Pass in the U.S, Novgorod and Karnasurt in Russia and Araxá in Brazil (Figure 5-2).

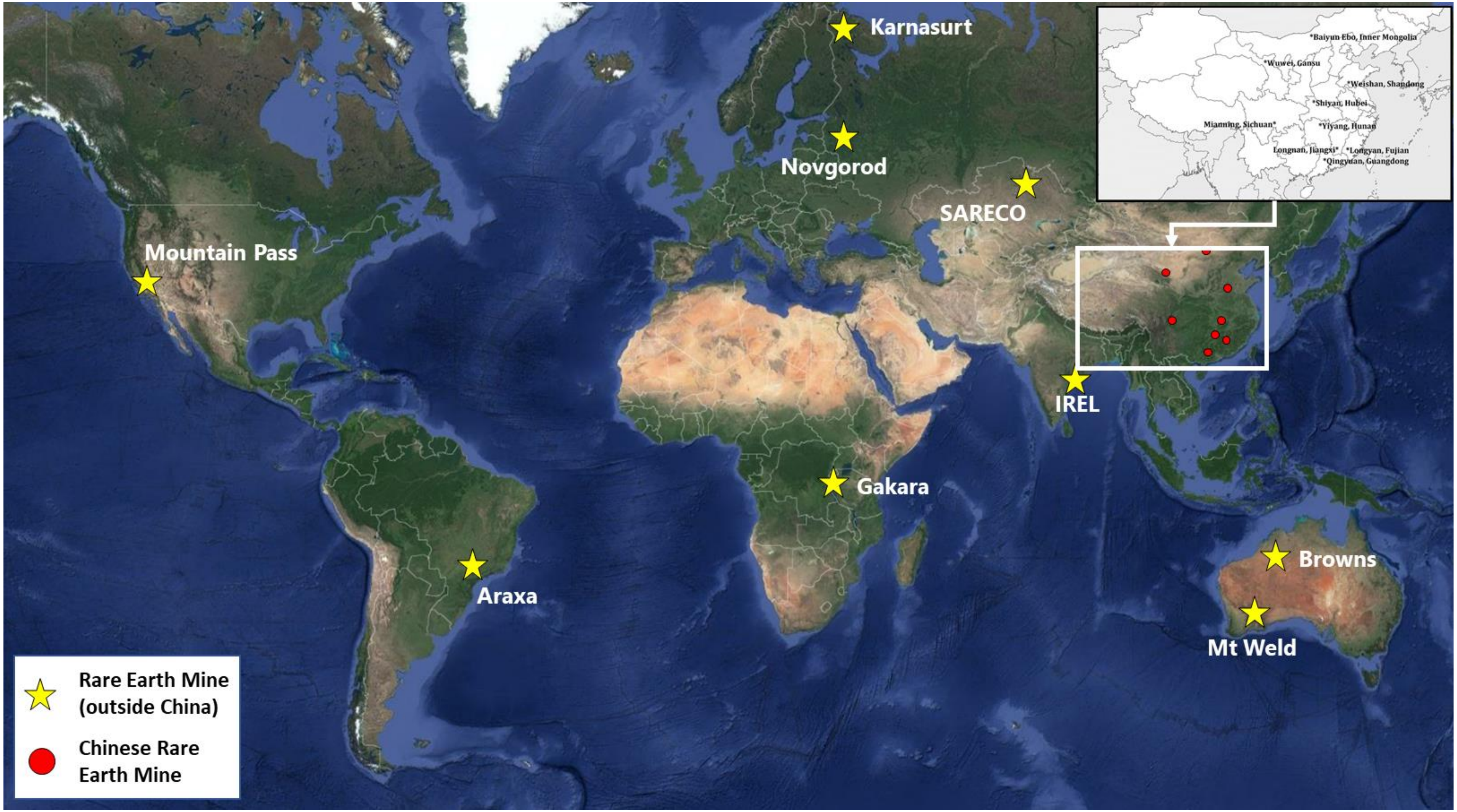

Figure 5-2: Location of global rare earth mines (including within China) (Modified after Backeberg, 2019 and Zhang, et al., 2017)

Figure 5-3 and Figure 5-4 show the 2018 mine production statistics and the percentage of REO production by country respectively, with Australia and the U.S. as two of the largest producers outside of China.

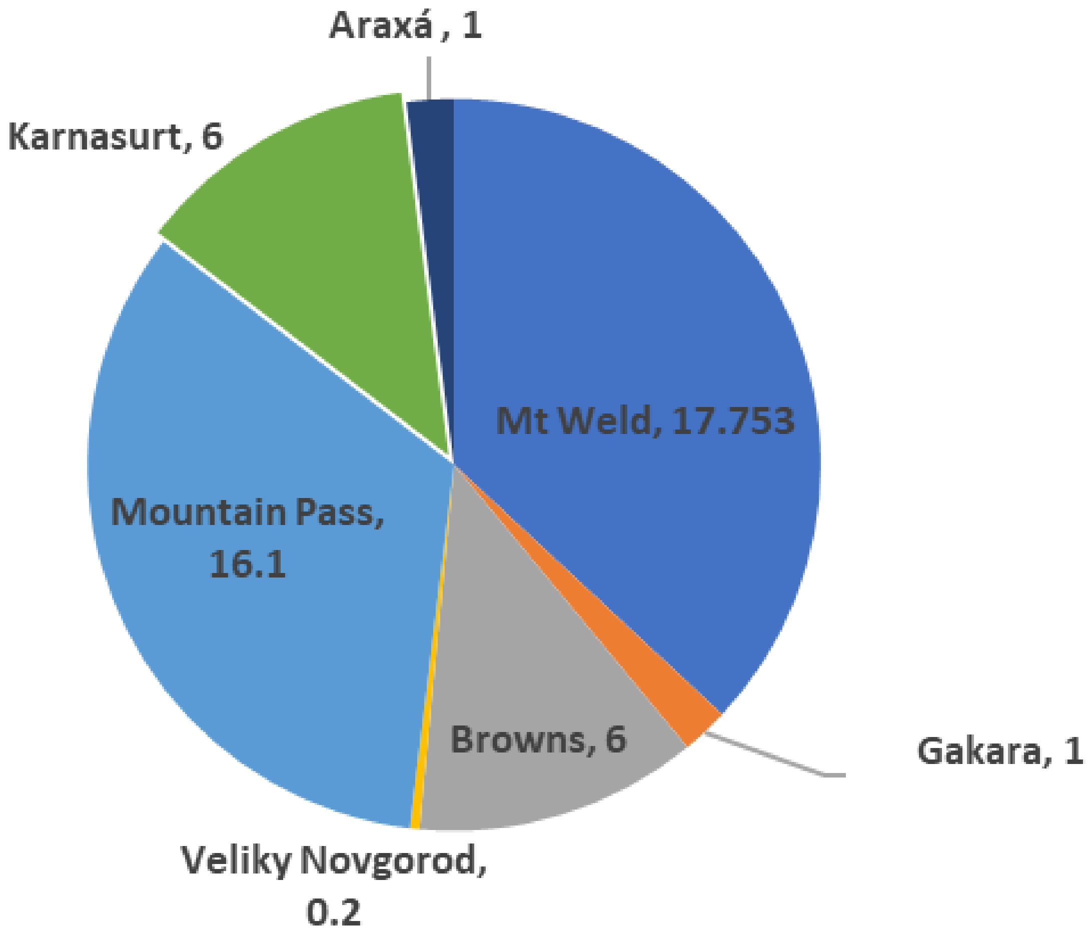

Figure 5-3: Production from publicly reported Rare Earth deposits outside of China in 2018 ('000s tonnes)

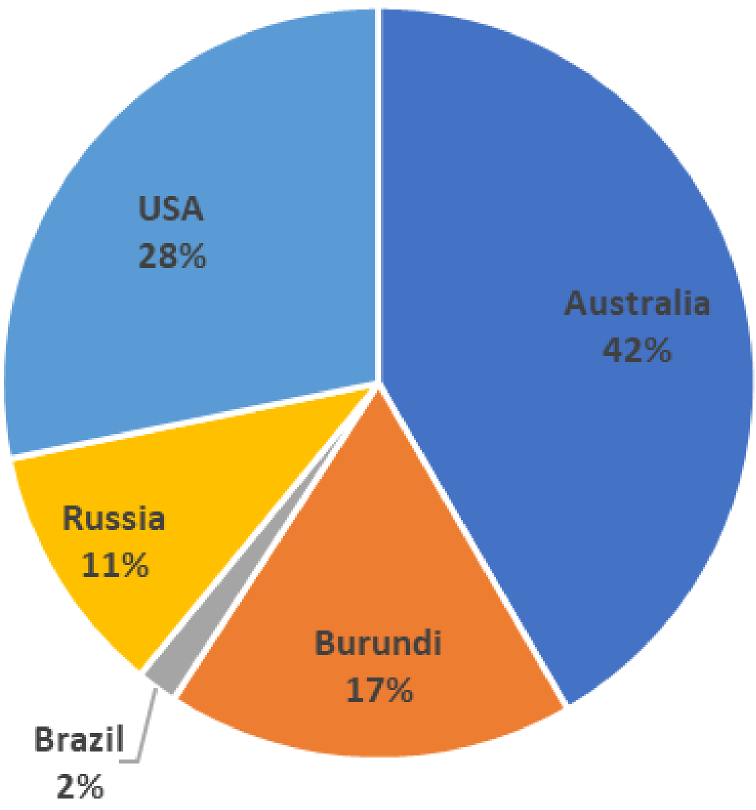

Figure 5-4: Percentage of production from countries based on publicly reported data outside of China in 2018 ('000s tonnes)

No reliable information is available for India Rare Earths Limited (IREL) in India, which likely operates more than one mine. In addition, Brazil's Araxá Mine has recently been suspended, in conjunction with Summit Atom Rare Earth Company (SARECO) in Kazakhstan, and are no longer producing REOs.

5.2 Current Producers

5.2.1 Australian Mines

Northern Minerals' flagship operation, Browns Range (Browns), a HREE deposit contained within hydrothermal breccia, produced its first rare earth carbonate in late 2018 as part of its pilot plant trial run. Going forward, the mine expects to ramp up production until it reaches maximum capacity, where it will produce 585,000 tonnes per annum (tpa) of ore through both underground and open-pit operations. Browns has reported 4.69 million tonnes of Measured and Indicated (M+I) resources, with an average grade of 0.7% TREO, and a contained metal content of 32.862 thousand tonnes TREO (Northern Minerals, 2019). Mineral Reserves to the tune of 3.75 million tonnes with a grade of 7.03% TREO with 26.375 thousand tonnes contained TREO have been reported. The main products from Browns Dy and Tb with Y, which are essential to the magnet manufacturing process. In the most recent report, Browns produced approximately six thousand tonnes TREO. Northern Minerals expects to reach a total production of 26 thousand tonnes, of which at least 2.3 thousand tonnes produced will consist of Dy.

Mt Weld, a carbonatite with overlying laterite, is situated in Western Australia and comprises several rare earth projects. Mt Weld is owned by Lynas Corporation. Of these projects, mineral resource estimates are available for two deposits, including the Central Lanthanide Deposit (CLD) and the Duncan Deposit. The total measured and indicated resources at Mt Weld are currently at 29.5 million tonnes, with 2,060 thousand tonnes of contained rare earths at a grade of 7%. The CLD however, is the only producing deposit and is one of the highest-grade deposits of REEs outside of China. The current Mineral Reserves are estimated as 19.7 million tonnes of ore, at 8.6% TREO with 1,690 thousand tonnes contained REO. The ore is processed at site in a Lynas-owned concentration plant, and a resulting rare earth concentrate is sent to a Lynas-owned plant in Malaysia for additional refining (Lynascorp, 2019). Mt Weld is a global producer of Nd and Pr. In 2015, a total of 5,440 tonnes of Nd-oxide was produced out of a total of 17,753 TREO production (Lynascorp, 2015).

5.2.2 African Mines

Rainbow Rare Earths' project Gakara, located in Burundi, is a vein hosted REE deposit. This deposit, although a producing mine, does not have code-compliant mineral resource or reserve estimates. This is because of insufficient sampling and non-compliant procedures (The MSA Group, 2016). The deposit has been reported as an exploration target, which will ideally be moved to an inferred resource as more information becomes available. As an exploration target, the deposit has been estimated to have a grade of 57% TREO with 50,000 tonnes of contained metal. In 2018, Gakara was on track to produce a total of one thousand tonnes of REO concentrate, after successfully producing 279 tonnes in their first quarter of production (James, 2018).

5.2.3 North American Mines

Mountain Pass, a carbonatite that is currently owned by MP Materials, is situated in Southern California, in western U.S. Mountain Pass mine has been a world-leading producer for several decades and primarily produces LREEs. The main products include NdPr-oxide and La-oxide in the form of a rare earth concentrate. In 2015, under the control of Molycorp, the mine was capable of producing 16.1 thousand tonnes per year TREO from a Reserve base of 17.8 million tonnes running at 8.1% TREO grade (Roskill, 2017). Since the mine has been under new ownership, publicly available information is difficult to ascertain.

5.2.4 European Mines

Novgorod, based in Russia, is a producer of Ce, La and Nd as well as concentrates of LREE and HREE from concentrate process flows. Despite having one of the largest reserves of REEs in the world, Russia's entire output per year is one of the lowest of all REE producing nations. Novgorod has an annual capacity of 200 tonnes of REOs (Acron, 2016).

In addition to Novgorod, the Karnasurt mine is also in Russia, is owned by the Solikamsk Magnesium Works and is located within the Kola Peninsula. The mine produced approximately 6000 tonnes of REOs in 2017. The REOs are exported to Estonia where further processing is undertaken at the Silmet plant, which is owned by Neo Performance Materials (Roskill, 2018). The resources, although non-code compliant are reported as 23 million tonnes grading at 1.35% with 311 thousand tonnes of contained REOs (Zhou, et al., 2017).

5.2.5 Asian Mines (excluding China)

Central Asia, including countries like Kazakhstan have plenty of REE potential. EU nations, such as France and Germany as well as Japan have entered into contracts and joint venture agreements with the intention of receiving REE products or from Kazakhstan producers. SARECO was established in 2010, and is the product of two companies, namely Japan's Sumitomo Corporation and Kazakhstan's Kazatomprom, the national nuclear energy department. Unfortunately, no reliable production and processing figures are available, but SARECO was ultimately set up to process uranium tailings to recover REEs and assumedly mine primary REE deposits at some point. SARECO indicated that by 2017 they plan to process between 5,000 and 6,000 tonnes of REO per annum.

IREL is an Indian state-owned company focused on REE production and falls under the Department of Atomic Energy. There are several locations from which IREL operate but is almost exclusively a placer REE miner where monazite is mined from beach placer deposits, along with rutile, ilmenite and zircon. In 2017, IREL produced over 950 tonnes of REOs (Indian Bureau of Mines, 2017). In addition, the Indian Government is ramping up processing capacity to increase India's REE output to 5,000 tonnes per annum. Once its production target is met, India will contribute approximately 5% of global REEs to the market (Das, 2018).

5.2.6 South American Mines

The Brazilian Araxá deposit, owned by TSX-listed company called MBAC Fertiliser company. Araxá mine, although not currently producing, is a primary source of HREEs and LREEs, Nb and phosphates. According to the Preliminary Economic

Assessment (PEA) by Clay and Ackroyd, (2013) of Venmyn indicted that the deposit is a high grade, high tonnage REE deposit with reported values of 6.34 million tonnes of M+I Resources, at an average grade of 5.01% TREO. The deposit has an additional 21.94 million tonnes of Inferred Resources, grading at 3.99% TREO. No production figures are available for when the mine was operational.

5.2.7 Chinese Mines

Chinese sources of REEs are focused in several provinces including Jiangxi, Sichuan and Inner Mongolia. Bayan Obo Mine is a world class resource with both abundant TREO tonnes and an average grade of approximately 8% TREO. This mine is located in Batou in Inner Mongolia, produces bastnaesite as a by-product, whereas it is produced as a primary mineral in Sichuan and Gansu (Zhao et al., 2017). Ion adsorption clay deposits in several of China's provinces such as Jiangxi, Guangdong, Hunan and Jiangsu, account for the majority of the global yttrium production and a substantial amount of HREEs (Indian Bureau of Mines, 2014). Chinese deposits and mining operations are significant to global supply however due to supply constraints, international trade tensions and difficulty obtaining reliable information, resource estimates have mostly been excluded from this research. Where information is available, it has been included.

5.3 Processing of REEs

Golev, et al. (2014) and Barakos (2017) indicate that rare earth processing and separation is difficult and time consuming due to the complex and variable mineralogy across deposits. Barakos, (2017) mentions the need to establish consistent and scalable processing methodologies that can be implemented across different deposits to decrease the cost and time implications of the processing. Currently, REE processing requires many steps, which often increases time, costs and requires specialised expertise.

Generally, processing of REEs after extraction consists of four main steps, namely, (1) beneficiation, (2) chemical treatment, (3) separation, and (4) refining and purification (Figure 5-5) (Suli, et al., 2017).

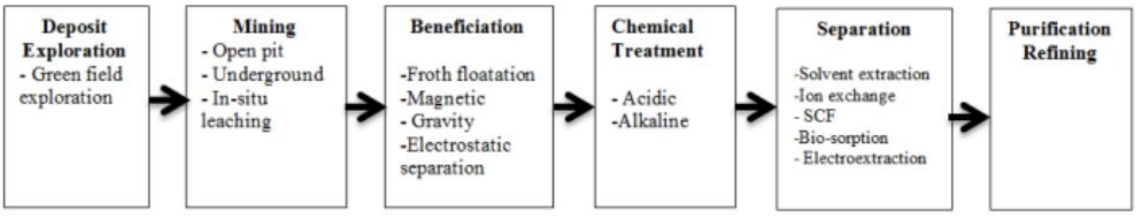

Figure 5-5: Steps involved in the Extraction and Processing of REEs (after Suli, et al,. 2017)

Firstly, the process of beneficiation of ore material involves communition through crushing and grinding to remove impurities and separate REOs from waste rock. Jaw crushers and ball mills are commonly used in this process. Some method of physical separation is then employed and is dependent on the type of deposit. These methods include froth flotation (Figure 5-6), magnetic separation and gravity separation methodologies which are used to further upgrade the REO concentration and separate out unwanted minerals such as silicates (Suli, et al., 2017).

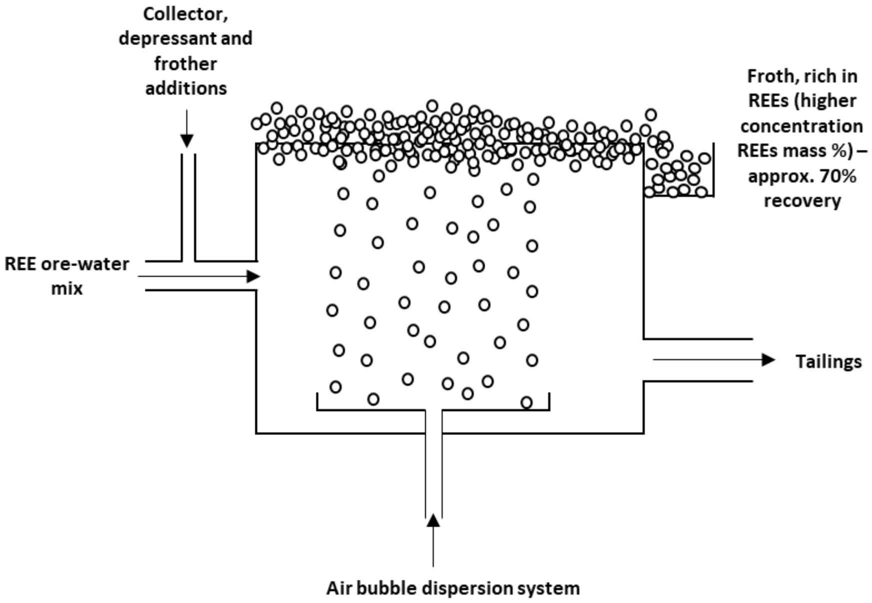

Figure 5-6: Schematic of the froth flotation process (after Suli, et al,. 2017)

Froth floatation is mostly used when processing hard rock and involves the use of chemicals to separate unwanted minerals from the ore minerals whereas magnetic and gravity separation use the physical properties to separate waste material from ore material. Gravity separation is more commonly used when processing ore from placer and mineral sand deposit types which is often followed by magnetic separation to remove minerals such as rutile and ilmenite from the REE-bearing material. Ion-adsorption clay deposits do not require any physical beneficiation and are normally processed by leaching (Golev, et al., 2014).

Subsequently, chemical treatment is applied to REE concentrate prior to separation of individual elements. This process is known as cracking and aims to further upgrade the concentration. During this process, either acidic or alkaline substances are added typically in the form of sulphuric acid or sodium hydroxide. The next step in the processing chain is separation of individual REEs which is notoriously difficult due the chemical similarities. Various separation techniques have been developed for REO processing and include electro-winning, ion exchange, biosorption, solvent extraction and supercritical. The most commonly used method of separation is solvent extraction which depends on different element reactions, by using different extractants (Suli, et al., 2017). In order to achieve higher levels of REO purity, this process is often repeated several times (Golev, et al., 2014). As described above, due to the complex mineralogy of REOs, the techniques used in metallurgical separation are mostly chemical intensive; particularly ion exchange solvent extraction. Large quantities of power, chemicals and water are used in the recovery and processing of REEs which can easily lead to environmental issues, which still remains one of the biggest problems with REE mining, particularly in China. Despite purification of up to 99% REEs throughout the processing chain, actual REE recovery is low, averaging about 10%. In low grade deposits, such as ion adsorption clay deposits, this effect is even more noticeable, where the net overall recovery can be lower than 1% (Koltun and Tharumarajah, 2014).

5.4 REE Supply Chain

Even though China possesses a third of the global REE resources, it has only recently gained control of the global REE supply chain (Stratfor Woldview, 2019). China was successful in removing the U.S. and European nations as leaders in the extraction and processing of REEs as well as production of end use applications. This was done through government initiatives which led to the transfer of expertise in processing technologies and applications (Haxel, et al., 2002). Since 2015, the REE industry in China operates at a much higher standard, and the many smaller processing facilities that operated without regard for environmental and labour regulation have now decreased to six, state owned processing companies which process the majority of REOs within China.

The dominance of the REE market by China can be traced back to the 1990's when a company called Magnequench, a subsidiary of GM, was sold to another U.S. company. Magnequench had pioneered high-powered Nd magnet technology in the 1980's with the intention of application in airbags and other mechanics in vehicles. At the time, little was known about their precision military applications. During a corporate restructuring in the mid-90s, GM divested from various business units including Magnequench which was subsequently purchased by a U.S company, that partnered with two Chinese state-owned entities, who had been trying to purchase Magnequench for several years (Tkacik, 2008; Morrison and Tang, 2014).

Magnequench continued to receive its rare earth supply from Mountain Pass mine, until its closure in the late 90s, after which, Chinese State-owned mining companies began supplying them with Nd produced in China. This shift in supply from the U.S to China is ultimately the start of the US's loss of the rare earth market (Tkacik, 2008; Mills, 2018).

In recent years, the supply chain outside of China has been in the form of partnerships, such as IREL-Toyota and SAREC-Sumitomo-Kazatomprom, both of which were formed to supply REEs to the Japanese market (Golev, et al., 2014). Figure 5-7 illustrates the current location of the main processing facilities, mines and projects in developments in addition to existing supply trade routes from various operating mines, processing plants and countires.

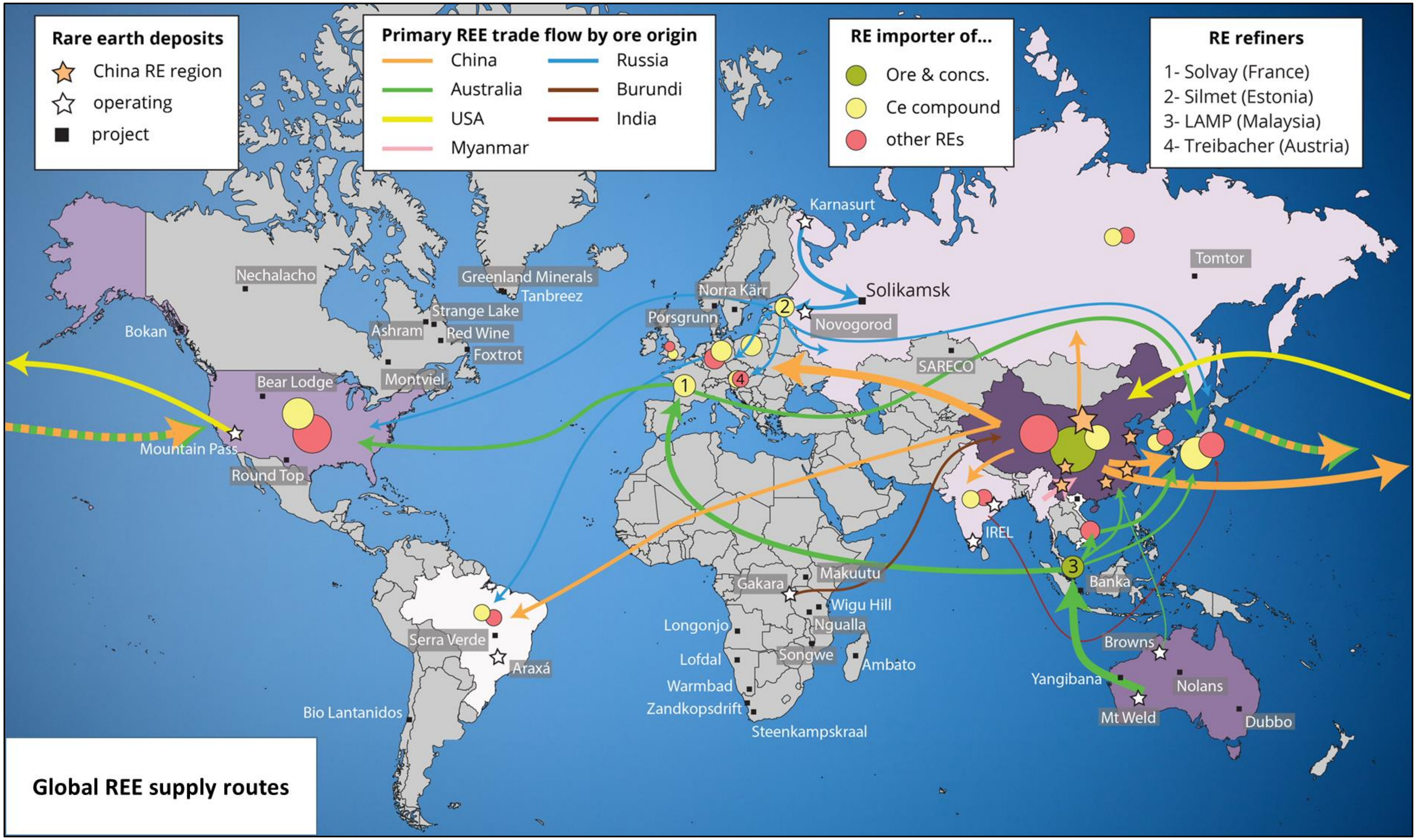

Figure 5-7: Map illustrating global supply routes together with REE mines and projects (After Roskill, 2019)

Currently several REO refineries exist outside of China, however, most of these facilities only process LREEs and are relatively small in terms of capacity. These include Solvay in France, Silvet in Estonia, and Treibacher in Austria (Figure 5-7) (Backeberg, 2019). There is only one major rare earth processing plant and it is owned by rare earth miner, Lynas Corporation (Lynascorp) and situated in Malaysia. The Lynas Advanced Materials Plant (LAMP) is considered a critical facility for consumers of REEs such as the U.S, Japan and Europe who intend to source more refined REEs outside of China. The facility is expected to supply approximately one third of LREE global requirements by 2022 (Stratfor Worldivew, 2019).

REOs are transported from Mt Weld to Kuantan, Malaysia. From the port, the ore is transported to the LAMP facility. Multiple processes of concentration and refining is undertaken to produce REEs (Lynascorp, 2019). Even though LAMP processes large quantities of REOs outside of China, the rest of the world still need to develop processing infrastructure if they are to regain competitive advantage and de-risk their supply needs.

Blue Line Corp, a U.S. based chemical company in partnership with Lynascorp are set to develop the first processing facility outside of China that specialises in HREE processing and more importantly, smaller batches of material. This facility is only expected to come online in 2023 and will be in Texas (Limitone, 2019; Stratfor Worldivew, 2019).

5.5 Chapter Summary

There are only a handful of operating mines that are producing REOs despite many known REE deposits. While China is the largest producer, responsible for over 80% of the world's REE supply, the information is difficult to source and validate. Australia is the next largest producer followed by the US, due to Mt Weld and Mountain Pass Mines respectively. These two mines are significant producers globally, accounting for about 33% of REOs produced outside of China per year. Other mines in Europe, South America, Africa and Asia (excluding China) also contribute to the global supply. One of the most noticeable trends is that some producing nations with significant REO reserves, such as Russia, only produce negligible amounts of REOs each year. Furthermore, most production of REOs from almost all mines outside of China ultimately end up in China due to its complete control of the entire value chain. This value chain dominance has been a progressive occurrence over the past three decades after China decided REEs were of strategic importance to them. This was largely due to the uses of REEs in hi-tech and clean energy applications.

6 USES, APPLICATIONS AND MARKETS OF RARE EARTH ELEMENTS

6.1 Uses and Applications

Across the board, both LREEs and HREEs are used in similar applications such as the manufacturing of permanent magnets, luminescence materials, batteries, catalysts and additives to glass and ceramics (Nieto, et al., 2013). Additionally, yttrium is essential to the manufacturing of light bulbs and televisions (Fernandez, 2017). REEs have received much more attention in recent times due to their uses in clean energy and military applications although their uses for high-tech applications have been known for several decades (Morrison and Tang, 2012). The components that require REEs are also not easily produced without them. Figure 6-1 summarises the uses for each REE in the manufacturing sector.

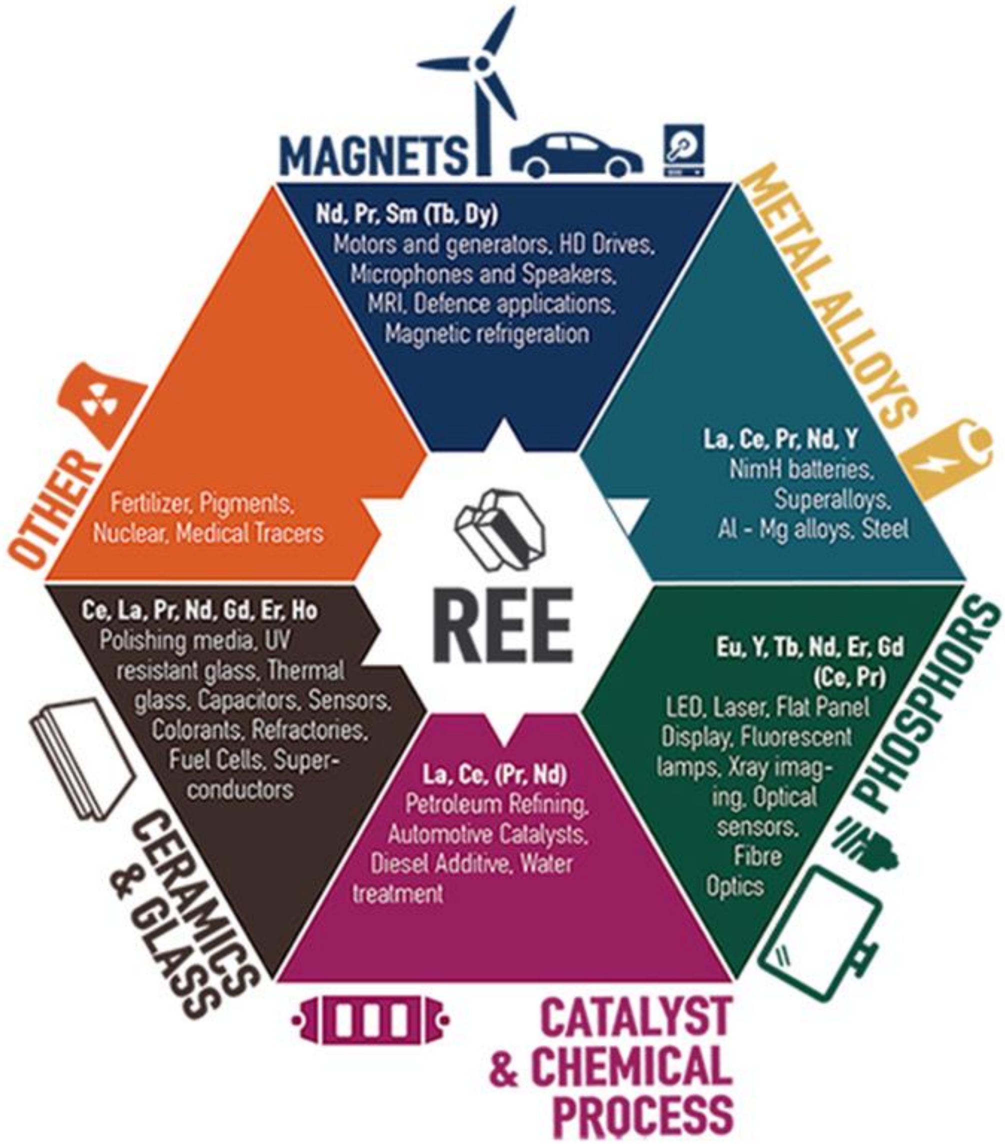

Figure 6-1: Common uses and applications of REEs (after Eu Rare, 2017)

This research provides an overview of most applications but will focus specifically on clean energy applications, such as high-powered magnets, batteries, lighting, and catalysts and the key elements required.

The abundance of a particular REE does not mean it can be used in a variety of applications. Ce, for example, although relatively abundant compared to other

REEs, is unique to just a few manufacturing processes. Ce is specifically used in glass polishing of mirrors, glasses and windows (Chu, 2010).

Alternatively, some of the rarer REEs which are also specific to their applications include Eu and Er. Computer monitors and television sets used to have colour cathode-ray tubes (CRT) but have since been replaced by the liquid clear display (LCD); both displays made use of Eu as the red phosphor and cannot be substituted. Er is used in fibre optic cables and act as laser repeaters and essentially amplify the signal that is transmitted along the cable. Fibre optics have all but replaced copper cables for the transmission of data in many countries around the world (Haxel, et al., 2002).

Industries that depend on REEs can be classified into two types, namely mature and emerging sectors. The mature sector includes industries such as catalysts as well as glass and lighting manufacturing, whereas emerging technologies use REE for the manufacturing of batteries, ceramics and high-powered magnets (Jowitt, et al., 2018). According to Goonan (2014), the emerging sector comprises almost half of all REE demand, but the sector is largely driven by alloys containing Nd, Sm, Gd, Dy or Pr for their use in permanent magnets.

6.1.1 Magnets

Magnet technology is constantly changing, however, magnets consisting of Nd and Dy, followed by magnets comprising Sm, are currently the lightest and highly magnetic (U.S. Department of Energy, 2011). Nd magnets, or NdFeB (containing Nd, iron, boron, Pr, Dy, Co) and Sm-magnets, or SmCo (containing Sm, Co, iron, Cu and Zr) magnets offer better force-to-weight ratios for almost any application than any other magnet (Constantinides, 2015). However, over the last several years, Nd alloy magnets have become increasingly more popular as opposed to SmCo magnets. This is because NdFeB magnets have a higher temperature coefficient, and Nd has higher magnetic properties than Sm. Ultimately, NdFeB magnets are also cheaper due to their simpler extraction which reduces the overall cost along the value chain (Stanford Magnets, 2019).

Chemical similarities also allow for some blending of elements without compromising the product. With respect to NdFeB magnet production, this is often done to reduce costs. This blend of Nd and Pr is called didymium (Binnemans et al., 2018) and varies according to manufacturers. Dy, sometimes a blend of Dy and Tb, is also required in NdFeB magnets as it allows magnets to operate more effectively in high temperature conditions. Typically, Nd-magnets contain about 10% Dy whereas Nd comprises approximately 32-33% by weight (Barteková, 2016; Lynascorp, 2019). These Nd high-powered magnets are used largely in motors and generators for electric vehicles, wind turbines and magnetic refrigeration but also in electronics (Haxel, et al., 2002).

These magnets have many high-tech applications due to their high magnetic strength, small size and light weight nature. These factors allow for the reduction in size of many components used in electronics such as appliances, cameras, speakers, headphones, computers, mobile phones, vehicles, communications and military (Haxel, et al., 2002). Some of the major applications for NdFeB magnets are explained further below.

6.1.1.1 **Wind Turbines**

Wind turbines utilise magnets, including NdFeB magnets. These turbines are becoming increasingly important as a source of clean renewable energy. Currently, three types of turbines are used, with differences largely in the power train of the turbine. The power train is the function that results in faster blade rotations, that in turn generate power.

Firstly, gearbox-fitted turbines, which are considered older technology but still predominantly used today, especially in onshore windfarms in the United States

(U.S). Gearbox-fitted turbines are problematic, as the gearbox is easily strained, causing mechanical failures resulting in entire turbine failure. The cost of repairs and the associated logistical difficulty makes it an increasingly unpopular choice of turbine (Morris, 2011). These turbines also use little to no REEs and do not make use of permanent magnets (Imholte, et al., 2018). Secondly, direct-drive turbines are also used (Figure 6-2) as they are lighter, more reliable (as there are no gearboxes and fewer moving parts) and are becoming increasingly cost-competitive compared to traditional gearboxes. This likely explains their increased application for larger and mostly offshore wind turbines. Thirdly, a hybrid wind turbine exists, which combines elements of gearbox-fitted and direct-drive turbines (Imholte, et al., 2018).

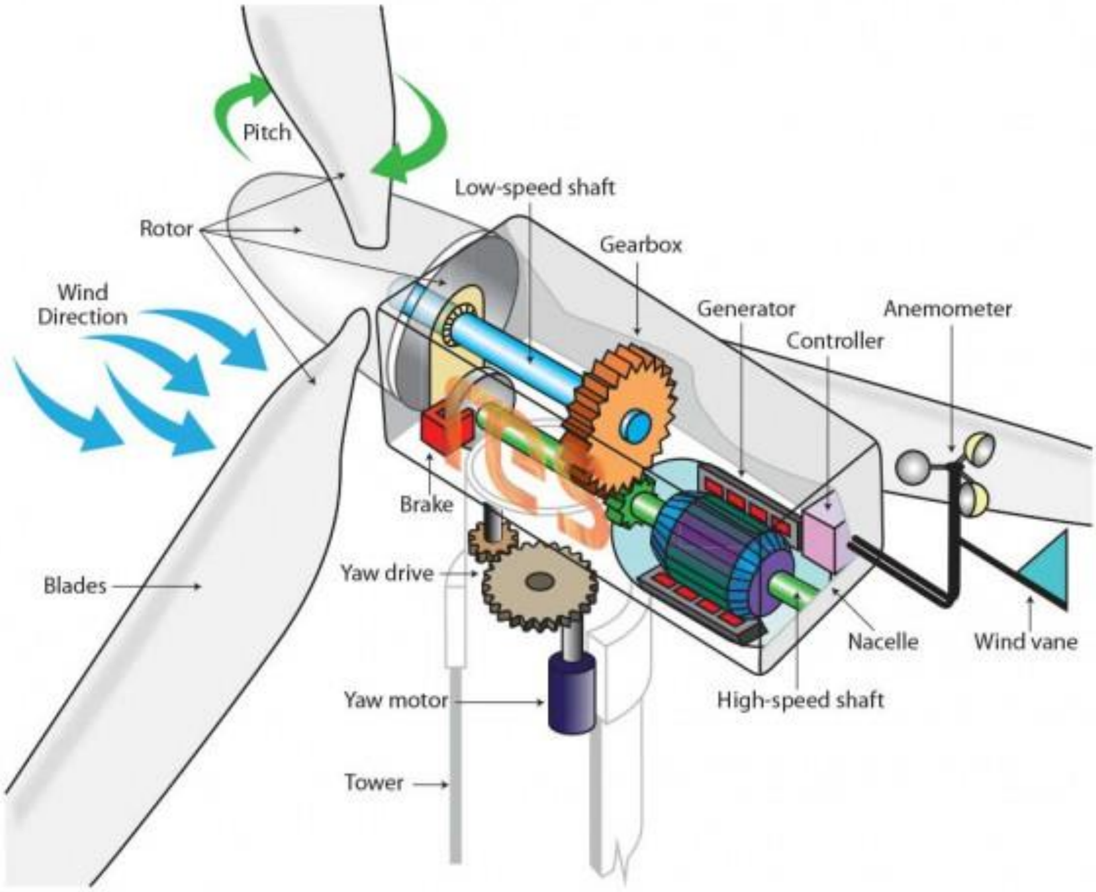

Figure 6-2: Mechanics of a typical direct-drive wind turbine (Loeriesfontein Wind Farm, 2019)

Both direct-drive and hybrid turbines use permanent magnets or high-temperature superconductor (HTS) generators. The quantity of magnets used in wind turbines differs according to the size and mass of the generator. The larger and heavier the generator, the more magnets are required and the more magnets present, the slower the turbine rotates and vice versa. Table 6-1 indicates the typical capacities of different speed turbines, as well as the usage of permanent magnets in kg/MW.

Table 6-1: Indication of magnet demand for different turbine speeds and their average power capacity (after Pavel, et al., 2017)

Technology and Speed	Permanent Magnet Usage (kg)/ MW	Typical Generator Capacity (MW)
Low speed	650	6
Moderate speed	160	5 - 8
High-speed	80	6

As previously mentioned, the permanent magnets used in direct drive and hybrid wind turbines require Nd and Dy, between 32-35% and 10% of the magnet weight respectively. Approximately 1 to 3 tonnes of Nd-oxide is used in permanent magnets for a single direct drive turbine, depending on its power output capacity (Lynascorp, 2019) which equates to about 120 kg of pure Nd (Zhou, et al., 2017).

6.1.1.2 <u>Alternative Energy Vehicles</u>

Rare earth elements are used in various components of alternative energy vehicles (AEVs) (Figure 6-3).

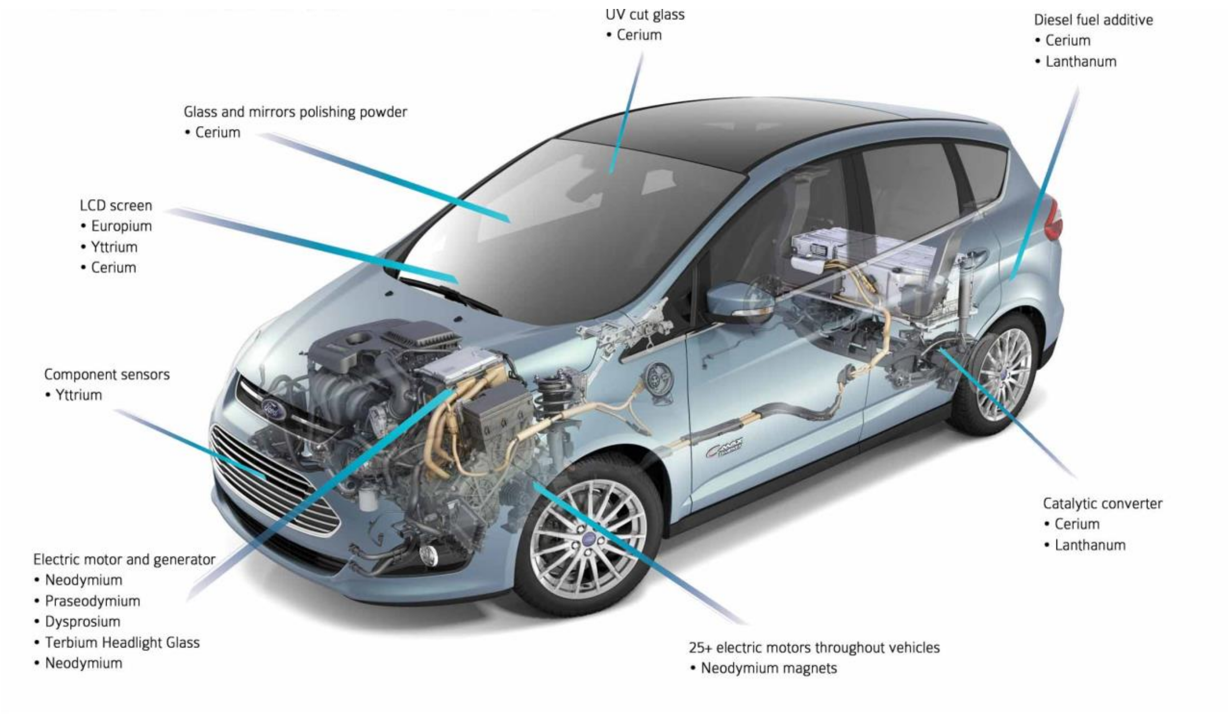

Figure 6-3: The use of REEs in modern HEVs (after Dickson, 2018)

AEVs that exist today include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). All these technologies require various rare earths, such as Nd, Pr and Dy in the form of a high-powered NdFeB magnets for use in cobalt (Co) and lithium (Li) for Lithium-ion (Li-ion) batteries, for NiMH batteries and platinum (Pt) for fuel cells (Fishman, et al., 2018).

NdFeB magnets, which require the largest complement of REEs, are also becoming increasingly popular in AEVs. These magnets are used in electric motors used to drive and regenerative power in EVs. The current estimated market for NdFeB permanent magnets in Tesla 3 EVs is up to $ 11.5 billion (Mills, 2018).

Rare earth materials for AEV manufacturing are considered critical due to high-risk, restricted supply and environmental issues associated with their production (Massari and Ruberti, 2013). EV sales have been increasing rapidly in the last decade, specifically battery electric EVs, and plug-in hybrid EVs indicating more

REEs will be required to satisfy a growing demand. To illustrate this, from 2010 to 2017, global EV sales increased from approximately 100,000 to 1,200,000 (Figure 6-4).

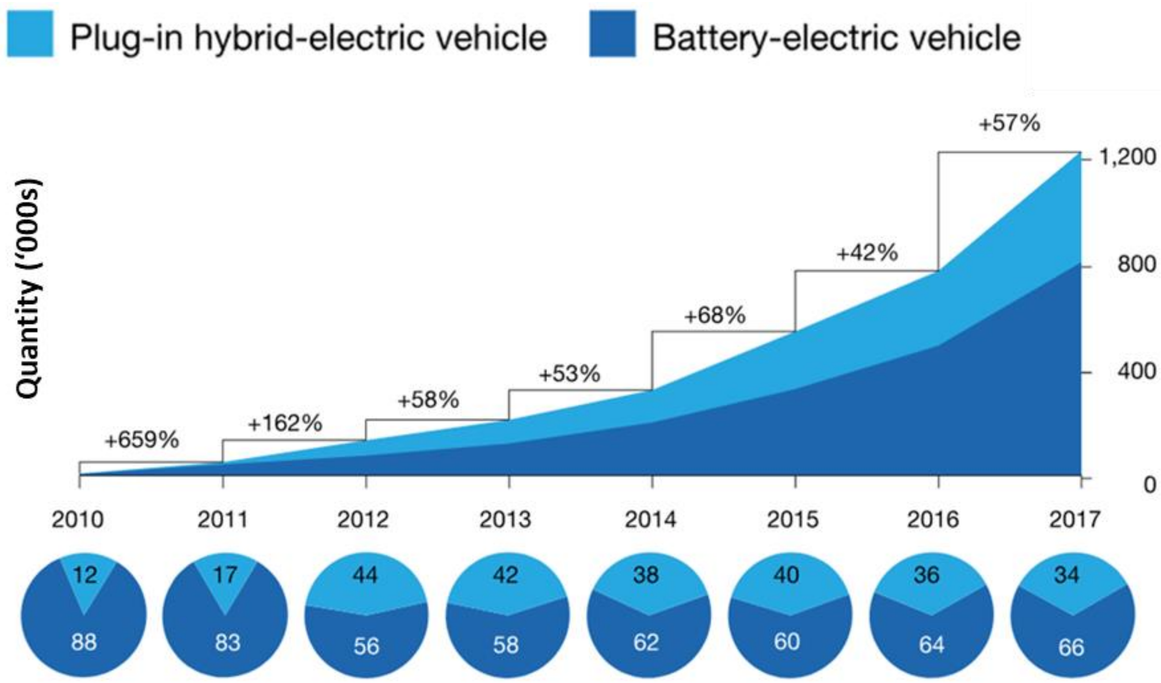

Figure 6-4: Global sales of electric vehicles from 2010 to 2017 showing a year on year increase (after Hertzke, et al., 2018)

AEVs offer a different type of power generation to internal combustion engines and are becoming more prevalent because of their environmental benefits in the form of reduced carbon dioxide emissions (Langbroek, et al., In Press), with increasing sales each year in one the world's biggest markets, such as China and the U.S (U.S Department of Transportation, 2016).

EVs have become more affordable over recent years and prices are expected to continue to decline as the technology develops. This is mainly because car manufacturers are launching increasing numbers of electric vehicle models in order to address the environmental issues associated with internal combustion engine vehicles. However, it can be slow for new models to enter the market, due to testing (Market Watch, 2018).

As part of the whole electric mobility drive, besides EVs, there is also a massive market for electric scooters and electric bicycles (e-bikes) which in the past has made up more demand for REEs than EVs (Bast et al., 2014 cited in Schulze, 2015). E-bikes use a lightweight electric motor that attaches either to the front or back wheel or the bottom of the body of the bike.

6.1.2 Batteries

Nickel metal hydride (NiMH) contain a variety of REEs, namely La, Ce, Pr and Nd. If pure, then these batteries only require La, however this becomes too expensive. NiMH batteries are a predecessor to Li-ion batteries and there is a lot of discussion about the pros and cons of each. These batteries are used predominantly in hybrid electric vehicles and to some extent, battery electric vehicles although the Li-ion battery is largely taking over the market. The presence of REEs allows the battery to accumulate the energy normally lost during driving, and re-use it when the vehicle requires it (Binnemans, et al., 2018; Fishman, et al., 2018).

6.1.3 Catalysts

REEs play a role in two different catalytic processes, namely catalysts in fluid cracking and as an auto catalyst in the exhausts of motor vehicles. La and smaller amounts of Ce, are used as a fluid cracking catalyst. The process of fluid catalytic cracking (FCC) is necessary part of oil refinery and creates light hydrocarbon products from heavy hydrocarbons within a closed system (Cuardos, et al., 2012). However, the process of FCC is not an environmentally friendly one, with large amounts of sulphur dioxide and carbon monoxide being expelled during the reaction (Yateem, 2011) but it is important for REEs as FCC still consumes a large percentage of REOs each year, up to 13%).

Catalytic converters are used in almost all petrol- and diesel-powered engine and help reduce pollution caused by motor vehicles by converting harmful gases to less harmful ones through the catalytic process (Bleiwas, 2013). Vehicle catalytic converters require Ce and to a lesser extent, La. Up to 20% of a catalytic converter is made up of CeO_2 which is responsible for several functions (Binnemans et al., 2018). CeO_2 is used in a part of the catalytic converter called the wash coat. Which is meant to enlarge the catalysts surface area. CeO_2 also acts as storage for oxygen during the catalytic process and enhances the strength of a catalyst (Albrecht, 2014). Additionally, REEs used in metal alloys throughout other parts of vehicles diminishes the vehicle weight thus decreasing their fuel consumption.

6.1.4 Phosphors

Phosphors is the term given to an item that provides luminescence (Figure 6-5). The phosphor market is large and includes lighting, monitors, TV's and cellular devices that make use of the trivalent ions of Dy, Tb, Sm and Eu. (Smets, 1987; Balachandran, 2014). The red-green-blue phosphors contain Y, Eu and Tb phosphors respectively (USGS, 2014) but according to Binnemans et al. (2018), there are smaller amounts of these elements required to produce the other colours.

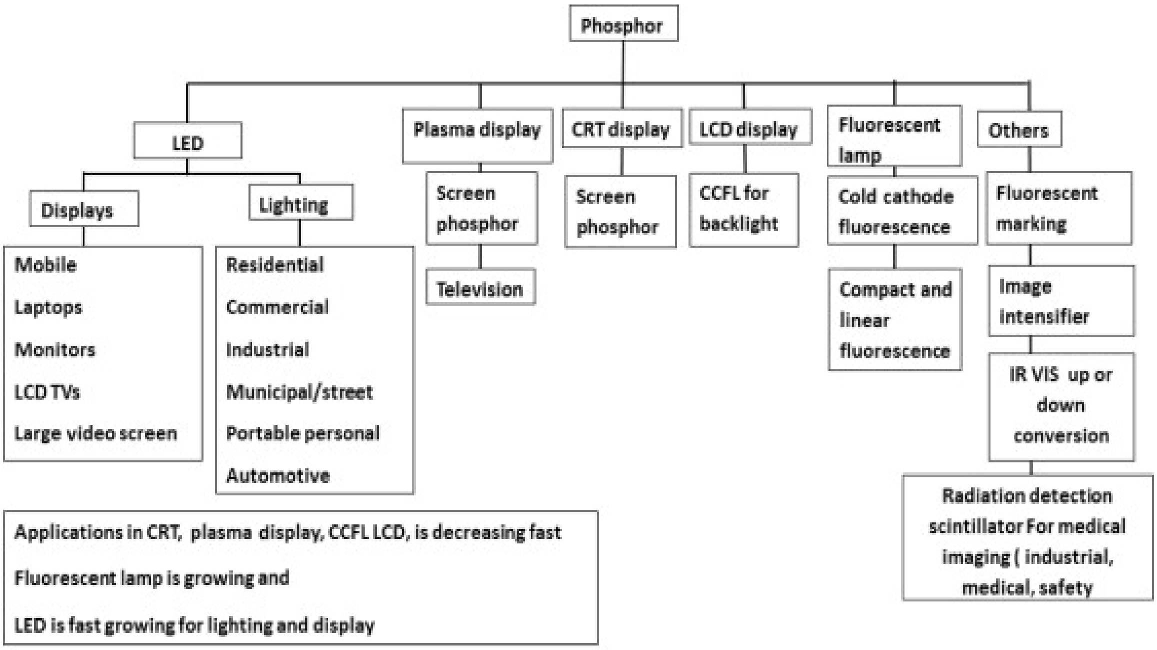

Figure 6-5: Range of applications of phosphors (after Balachandran, 2014)

REEs such as Y, La, Ce, Eu, Gd and Tb are also used in the manufacturing of energy efficient lighting, which is being adopted in many nations and will have a major impact on carbon emission reduction. Currently, the market consists of fluorescent lighting, in the form of linear fluorescent lamps (LFLs) and compact fluorescent lamps (CFLs), as well as light emitting diode (LED) lighting (Zhou, et al., 2017). Lighting accounts for significant proportions of energy use, making up almost 20% of American energy consumption. The market penetration of new technologies, such as rare earth phosphors in the form of LEDs and organic LEDs (OLED), are expected to reduce energy usage. Policy and legislation are in place in various jurisdictions, including the U.S. and other developed countries, to phase out older, inefficient incandescent lights, and replace them with new energy efficient phosphors. These policy changes, which began in 2007 involved limits to wattage and as a result, cause an increase in sales of fluorescent lamps that contain rare earth phosphor. Fluorescent lamps were the technology of choice at the time, however, falling costs of LED lighting have resulted in their increased use. Thus, the global demand is expected to grow substantially as more countries continue commit to this transformation (U.S. Department of Energy, 2011).

6.2 Historical and Current Demand

Rare earth demand is increasing year on year across the world. Currently, China is responsible for up to 70% of global consumption (Mancheri, et al., 2019). China is such a big consumer that it had to import REEs to meet its internal demand (Adamas Intelligence, 2019). China's REE requirements are largely due to its vast internal market, as it possesses almost a third of the world's population. Following China, the U.S, Japan, Germany and France are the next biggest importers of REEs, mainly due to their car manufacturing sectors (MIT, 2016), but also as part of their clean energy initiatives, through permanent magnets and batteries. The U.S. and China are also becoming increasingly more reliant on REEs for military applications.

Because REE end-uses have not remained constant, their products used by industry and commercial sectors have also changed. In the past, changes in the lighting industry included the use of Eu, then Tb and more recently to Lu, as well as La with glass manufacturing. In addition, the creation of permanent magnets has resulted in increased demand for Nd, Sm and Dy (Goodenough, et al., 2017).

Global REE consumption has increased dramatically over a short period of time, from about 75,000 tonnes in 2000 to approximately 130,000 in 2015 (Roskill, 2016; Barakos, 2017). Figure 6-6 shows how demand has changed by country for the period between 1965 and 2015. In the mid-90s, Japan and the U.S demanded 70% of all REEs. Currently, the same demand is being sought by China.

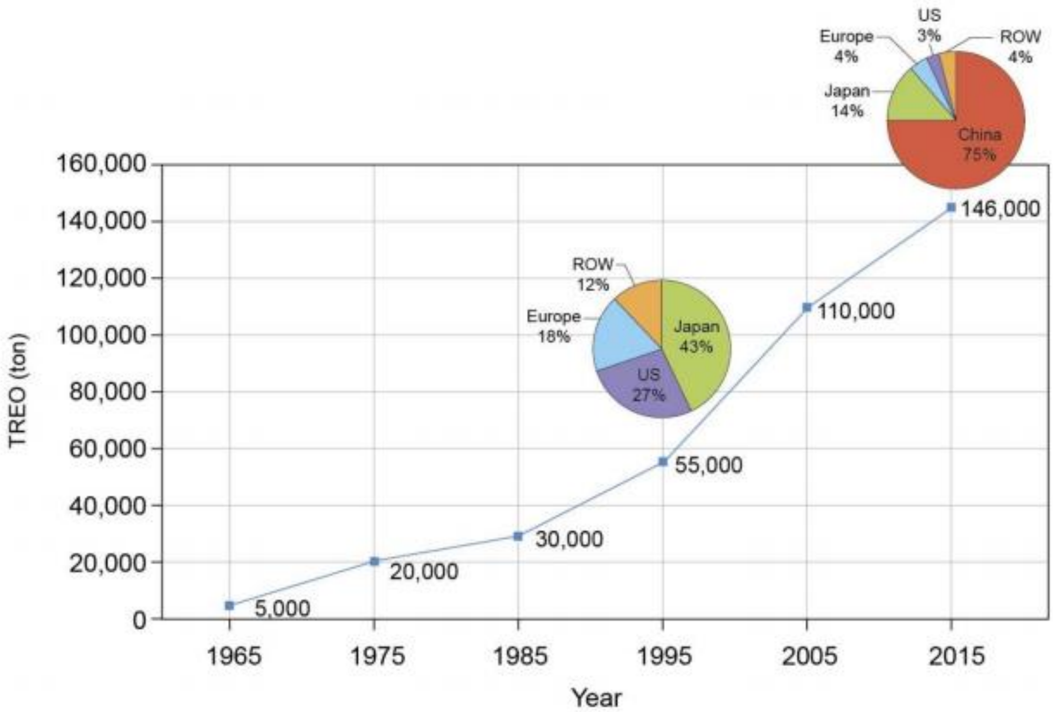

Figure 6-6: Demand shift by country from 1965 to 2015 (after GEUS and D'Appolonia, 2017)

Table 6-2 represents the global demand per country/region for specific REE end uses, for 2011. The total global demand was approximately 105,000 tonnes of REEs where permanent magnets, metal alloys and catalysts were in highest demand, comprising 59% of the global consumption.

Table 6-2: Demand for REEs for end use products globally (Modified after Hatch, 2012)

End Use	China	USA	Japan + SE Asia	Others	Total
Permanent Magnets	16,500	500	3,500	500	**21,000**
Metal Alloys	15,000	1,000	4,000	1,000	**21,000**
Catalysts	11,000	5,000	2,000	2,000	**20,000**
Polishing powders	10,500	750	2,000	750	**14,000**
Phosphors	5,000	500	2,000	500	**8,000**
Glass additives	5,500	750	1,000	750	**8,000**
Ceramics	3,000	1,500	2,000	500	**7,000**
Other	3,500	500	1,500	500	**6,000**
Total Demand	**70,000**	**10,500**	**18,000**	**6,500**	**105,000**
Market Share (2012)	**67%**	**10%**	**17%**	**6%**	**100%**

The next three to four years, from 2012, underwent significant growth in global consumption of all REEs, with estimated amounts approaching 200,000 tonnes per year (Laurino, 2016), as shown in Figure 6-7.

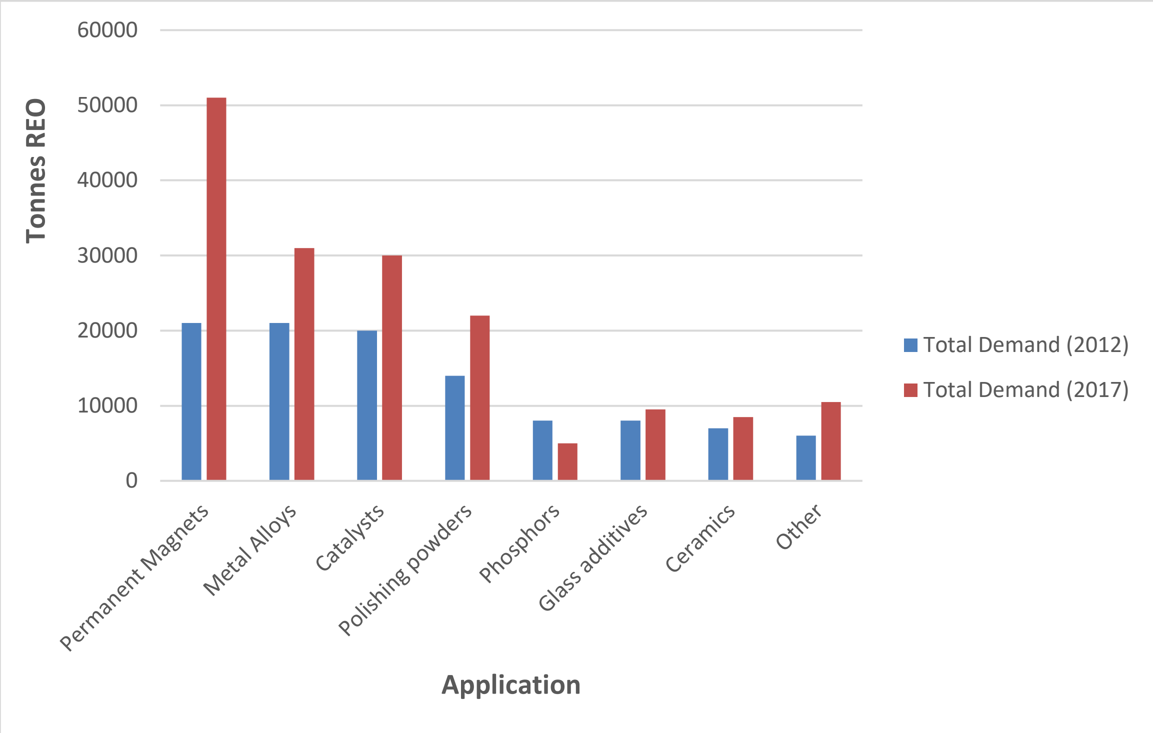

Figure 6-7: Global REO demand by application from 2012 to 2017 (modified after Hatch, 2012 and Mancheri et al. 2019)

Despite an overall increase, consumption of REEs has faltered throughout the last 15 years, particularly during the period from 2008 to 2011. There was an increasing trend in their consumption until 2008, after which demand decreased as a result of the GFC, for a period of two years. This resulted in a negative trend in REE end use products further down the value chain. High demand in 2008 suggests that very little stockpiling was done. Stockpiling, as a result of China's export restrictions of REEs in 2010, resulted in increased consumption from the rest of the world (Alonso, et al., 2012). In 2011, however, when REE prices surged, global consumption decreased due to a reduction in stockpiled material, and intensity of use as well as an increase in alternative elements (USGS, 2012; Barakos, 2017).

Looking ahead, REE demand is difficult to predict due to international relations between producers and consumers (i.e. trade war) and because of the numerous high-tech end use applications which use evolving technology. The forecast is expected to range from 5-10% annual total REE growth, over the next two decades (Alonso, et al., 2012). According to Adamas Intelligence (2016) cited in Kalvig and Machacek, (2018), over 80% of Nd-oxide that has been produced since 2015 has been used in permanent magnet production. Figure 6-8 depicts the demand for each REE expected in 2025 relative to 2015.

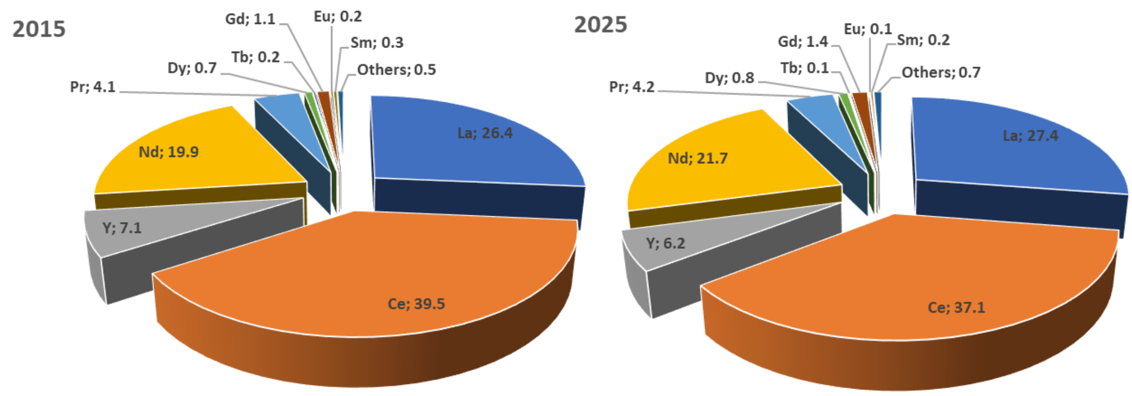

Figure 6-8: Demand by element in 2015 compared to expected demand in 2025 (Modified after Goodenough and Wall, 2016)

Total demand in 2025 for all REEs, as predicted by Hatch (2012), is set to grow to about 210,000 tonnes. Using this estimate with reference to the REE split in Fig 6-8, for all applications, Ce, La, Nd, Y, Dy, Eu and Tb would equate to 78.0, 57.5, 45.5, 13.0, 1.7, 0.2, and 0.2 thousand tonnes respectively. This data is slightly outdated and needs to be refined with more current views of expected growth of clean technology applications.

6.3 Demand Forecast

Although the demand for REEs will undoubtedly increase in the future, it is important to assess the growth of individual REE markets, as they are not expected to grow at the same rate. In order to understand the growth in demand for individual REEs, the demand for their end use applications must be analysed. This will aid in understanding the potential growth of this industry and the use of existing manufactured components to supplement the future demand. As a result, this research focuses on the demand of selected clean technology applications. These applications were highlighted in in the previous section and are expected to have significant impacts on the REE demand over the next few decades. The REE markets investigated include La, Ce, Nd, Dy, Eu, Tb and Y for their use in magnets, batteries, phosphors and catalytic converters.

Quantifying the demand for the abovementioned elements was done by benchmarking forecasts of end-use applications using various sources in the public domain. The outcome is an updated estimate based on more recent demand expectations for the respective technologies. However, with any future-looking scenario, there are various unknown factors, such as policy changes, technologies and shifts market forces which result in several assumptions being made in the benchmarking process. These assumptions include:

- No advancement in technology which reduces the required amounts of REEs; and
- Unless otherwise indicated, all future end use products will contain REEs (i.e. no substitution/alternative technology).

6.3.1 Magnets

6.3.1.1 **Wind Turbines**

In 2015, about 10% of the NdFeB magnet market was used for wind turbines, which was approximately 2,600 tonnes of REEs, required to satisfy the demand.

Currently, direct-drive turbines are being adopted relatively slowly, with only a 2% share of wind generated power in the U.S for 2017. However, the demand for direct-drive turbines is increasing, which will result in a higher demand for REEs into the future. If the U.S. wishes to achieve its long-term green energy goals by

2030 in which wind power accounts for one fifth of its electrical supply, it will need to adopt more direct-drive turbines (Imholte, et al., 2018).

Globally, wind powered electricity is expected to reach 900 gigawatts (GW) in 2023, up 400 GW from 500GW in 2016 (International Energy Agency, 2018). The 2018 wind capacity was 591 gigawatts (GW) (GWEC, 2019), suggesting this target is on track. Of this increase in wind power generation, about 10% (~40 GW) will be from increased amounts of offshore turbines, largely driven by the EU and China. According to GWEC (2017), offshore wind capacity has increased from 4.1 GW to 18.8 GW between 2011 and 2017 (Figure 6-9) and is estimated to increase to 120 GW in 2030 at a rate of 10 GW per annum. GWEC (2019) latest offshore capacity is at 23 GW. With this in mind, by 2025, the offshore capacity is expected to be 70 GW. This figure in line with the estimate made by IEA.

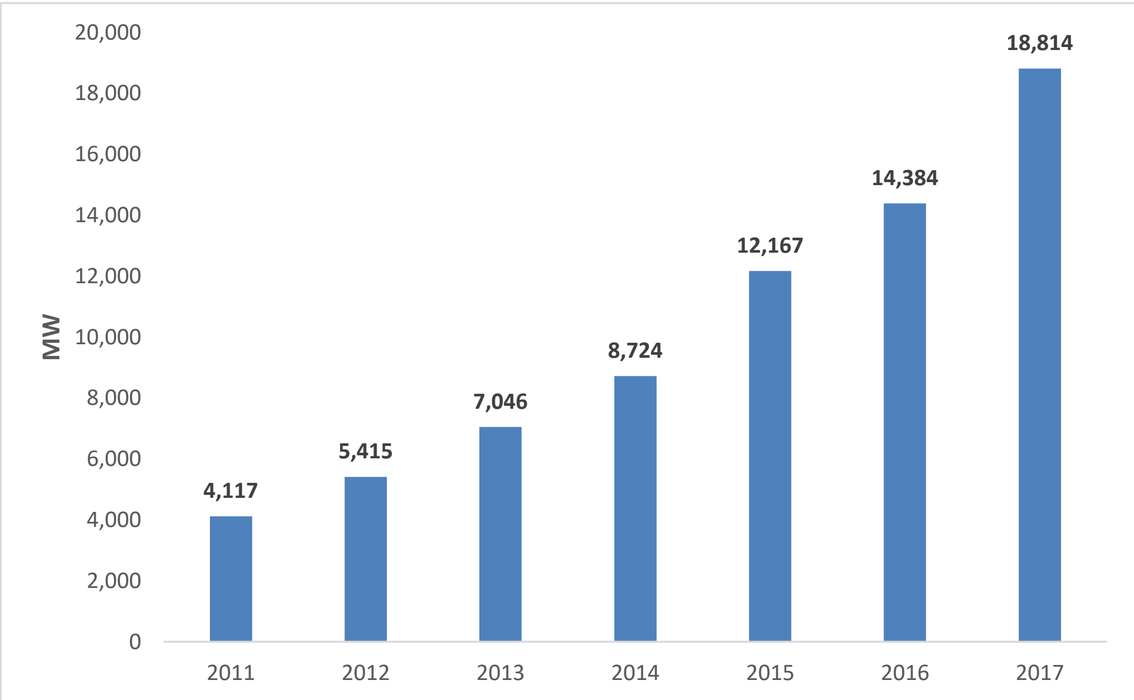

Figure 6-9: Increasing offshore wind capacity from 2011 to 2017 (modified after GWEC, 2017)

Concurrent to offshore growth, onshore wind generation is also expected to increase at about 25% per year until 2025 (International Energy Agency, 2018). Alternatively, GWEC, (2019) suggest that onshore wind capacity will grow at 50 GW per year until 2025. At current levels of capacity estimated at 568 GW, the onshore capacity in 2025 is expected to be at 918 GW. However, more long-term forecasts expected onshore generation to reach a saturation point in the next 20 years whereas offshore wind generation will continue to grow (IPCC, 2011).

The information detailed above formed the basis for a demand forecast of Nd and Dy. Additionally, several extra assumptions have been made regarding the turbine market in the future:

- Even split between turbine size and speed to benchmark turbine capacity;
    - Average of 5.1 MW per turbine (Table 6-3).
- Two scenarios;
    - 100% of all turbines make use of NdFeB magnets.
    - 40% of offshore and 50% of onshore utilise NdFeB magnets.
- No advancement in technology, which reduces the required amounts of REEs.

Table 6-3: Average capacity (MW) and mass of NdFeB magnets in wind turbines

Speed	kg NdFeB/magnet/MW	Capacity (MW)	kg NdFeB per turbine
Slow	650	5.00	3,250
Medium	80	5.12	410
Fast	160	5.00	800
Average	**297**	**5.12**	1,520

Sources: Pavel, et al., 2017, Zhou et al., 2017, Clean Energy Ministerial, 2019

Based on the assumptions above, the total requirement of NdFeB magnet material was calculated. To get the quantity of Nd and Dy, a ratio of its known mass was worked out relative to the mass of each magnet. The following scenarios are presented in Table 6-4.

Based on Scenario 1, the expected demand of permanent magnets for onshore and offshore wind turbines will be 53,160 and 4,053 tonnes respectively, totalling approximately 57,213 tonnes. This equates to a requirement of 23,922 and 1,824 tonnes of REEs for onshore and offshore respectively totalling 25,746 tonnes.

Scenario 2 indicates the demand for onshore and offshore magnets (40% of offshore and 50% of onshore utilise NdFeB magnets) will be 26,580 and 1,621 tonnes of NdFeB magnets respectively (total of 28,201 tonnes). The REEs for onshore and offshore will constitute about 11,961 and 0.729 tonnes respectively, equating to 12,690 tonnes REEs. Thus, depending on the outcome of turbine design, a range of between 9,303 and 16,635 tonnes of REEs will be required in 2025 to keep up with demand.

Table 6-4: Expected demand for Nd and Dy based on forecasts of wind energy in 2025,

Turbine	Estimate 2025 Wind Capacity (MW)	Turbines Qty (Total MW/Average Capacity)	Scenario 1 (100% of turbines use NdFeB Magnets		Scenario 2 (50% onshore; 40% offshore)	
			NdFeB (tonnes)	REE (tonnes)	NdFeB (tonnes)	REE (tonnes)
Offshore	70,000	13,664	4,054	1,824	1,621	730
Onshore	918,000	179,192	53,160	23,922	26,580	11,961
Total	988,000	192,856	**57,214**	**25,746**	**28,202**	**12,691**

Sources: Zhou et al., 2017; IEA, 2018; GWEC, 2019

6.3.1.2 **Alternative Energy Vehicles**

Global EV sales reached about 545,000 in 2015 (Pavel, et al., 2017). At the end of 2017, more than one million EVs had been sold around the world for the first time, making up just over a 1% share of the light vehicles sold in the same time period. Despite the growing trend, the total number of EVs as a percentage of all vehicles worldwide is still low, approximately 0.1%. Based on this increasing trend, it is expected by some researchers that EVs will sell four times that amount by 2020 and make up 5% of all light vehicles on the road (Hertzke, et al., 2018) whereas some estimates put EV sales at 25% of all light vehicles by 2025 which would require about 130,000 tonnes of REEs (Dickson, 2018), although this is on the higher end of EV forecasts.

In 2015, assuming that all EVs sold during that time utilised NdFeB magnets, approximately 1,100 tonnes of NdFeB magnets would have been needed to meet demand, which equates to 1% of the NdFeB market in that year. Of these magnets, Nd and/or Pr comprise about 30% and Dy and/or Tb about 1 % of the weight. This means that in 2015, approximately 367 tonnes of REE was used to manufacture the magnets for EVs.

An average of 0.675 kg of REEs are used in EV motors, depending on the type of EV, the size of the motor and the manufacturer. The total REE requirement ranges from between 0.45 to 0.75 kg Nd and uses about 0.075 kg Dy. For this report, demand forecasts of 100 million EVs by 2030 was used, as the EV30@30 campaign is considered highly ambitious. However, it may result in a conservative forecast. An estimate of 50 million EVs will be on the road by 2025 at a rate 7.2 million vehicles per year. This would result in a requirement of a cumulative total of 33,750 tonnes of REEs to be produced from now until then, with an average of 6,750 tonnes of REEs per year (Table 6-5).

Table 6-5: Expected EV growth from 2015 to 2025, and corresponding Nd-Dy requirements

Year	Quantity of EVs	Nd per unit	Dy per unit	Nd (tonnes)	Dy (tonnes)	Total REE tonnes
2015	545,000	0.6	0.075	327	41	368
2017	1,200,000	0.6	0.075	720	90	810
2019	8,400,000	0.6	0.075	5,040	630	5,670
2020	15,600,000	0.6	0.075	9,360	1,170	10,530
2025	51,600,000	0.6	0.075	30,960	3,870	34,830

Sources: Pavel, et al., 2017, Zhou et al., 2017, Clean Energy Ministerial, 2019

Like EVs, e-bikes use varying amounts of NdFeB magnets, ranging from 60 to 360 g according to Shaw and Constantinides, (2012), 300 g according to Habib and Wenzel, (2014) and an average of 100 g according to Zepf (2013) cited in Schulze, (2015). If an average of 150 g NdFeB is assumed, then amount of Nd and Dy is approximately 50 g and 6 g respectively per magnet as Dy can make up 4% of the magnet by weight (Hoenderdaal, et al., 2013).

According to Pavel, et al. (2017), e-bike sales reached upwards of 40 million units in 2013 and expected to grow at a rate of 4% per annum beyond 2019, despite sales being slower during the period from 2014-2015 (Figure 6-10).

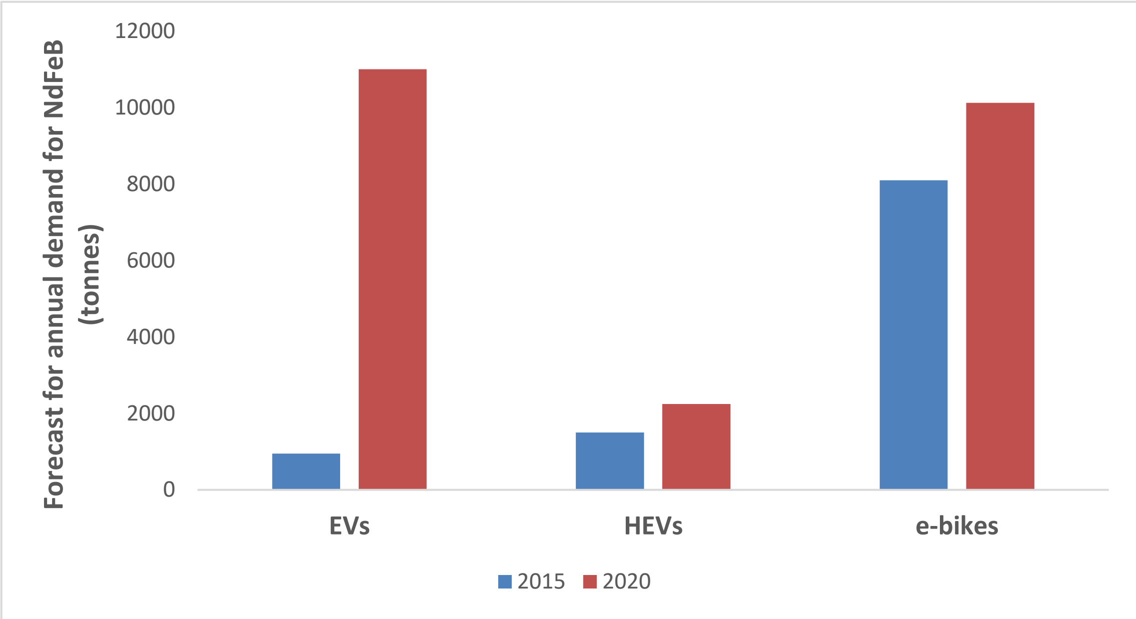

Figure 6-10: Estimated demand for NdFeB batteries for use in EV, HEV and e-bikes (after Pavel et al. 2017)

Overall, this annual growth is much slower than that expected for the EV market, largely due to the already higher market penetration. Estimates of 50 million e-bikes will enter the market by 2020. With these estimates, the resultant demand for NdFeB magnets will be approximately 10,000 tonnes which translates to an estimated 2,800 tonnes of REEs. By 2025, about 3,500 tonnes of REEs will be required (Table 6-6) to satisfy the production of almost 61 million e-bikes, using the annual growth rate of 4%.

Table 6-6: Expected e-bike growth from 2015 to 2025, and corresponding Nd-Dy requirements

Year	e-bikes	Nd per unit	Dy per unit	Nd (tonnes)	Dy (tonnes)	Total REE tonnes
2015	35 000 000	0.05	0.006	1 750	210	1 960
2016	40 000 000	0.05	0.006	2 000	240	2 240
2017	45 000 000	0.05	0.006	2 250	270	2 520
2018	47 500 000	0.05	0.006	2 375	285	2 660
2019	48 000 000	0.05	0.006	2 400	288	2 688
2020	50 000 000	0.05	0.006	2 500	300	2 800
2025	60 832 645	0.05	0.006	3 042	365	3 407

Sources: Schulze, 2015 and Pavel, et al., 2017

6.3.2 Batteries

Besides the use of permanent magnets in EVs, Nickel-Metal Hydride (NiMH) batteries are also used in BEVs which contain REEs. Each battery contains approximately 1.725 kg per REEs, of which Nd comprises about 0.255 kg. However, the use of batteries comprising REEs is likely to dwindle (Binnemans et al., 2018), as more efficient and cheaper batteries have been increasingly used in the EV space, particularly Li-ion batteries. Zhou, et al. (2017) has forecasted a total EV market to consist of 10 to 20% NiMH batteries by 2025. If 10% of EVs still retain the use of NiMH batteries by 2025 (i.e. 5 million vehicles), then an estimated 8,600 tonnes of REEs La, Ce and Nd will be required to meet the NiMH battery demand, where Nd will make up 1,275 tonnes.

6.3.3 Catalysts

Ce is currently used in catalytic converters on almost all internal combustion engine (ICE) motor vehicles. To ascertain the future Ce demand for this application, the number of ICE vehicles need to be estimated. From 2000 to 2018, there has been an increase from 58 million to 95 million vehicles produced each year (Statista, 2018). This is an average annual increase of 3.5% in vehicle production. If the same average is extrapolated to 2025, then, it is estimated that the vehicle production will be a little more than 120 million. Approximately 0.02 kg of Ce is used in each vehicle that has a catalytic converter, resulting in a demand of 2,424 tonnes of Ce in 2025 (Table 6-7).

Table 6-7: Growth in Ce demand for use in auto-catalysts (modified after Statista, 2018)

Year	Quantity of Vehicles (million)	Ce per unit (kg)	Total Ce (tonnes)
2018	95.00	0.02	1.90
2019	98.33	0.02	1.97
2020	101.77	0.02	2.04
2021	105.33	0.02	2.11
2022	109.01	0.02	2.18
2023	112.83	0.02	2.26
2024	116.78	0.02	2.34
2025	120.87	0.02	2.42

6.3.4 Phosphors

According to the U.S. Department of Energy, (2011), the LED market is expected to grow whereas the CFL and LFL markets are expected to decrease in the future (McKinsey and Company, 2012). The phosphor market is more well understood due to it being more established, therefore growth rate predictions are considered more reliable. Table 6-8 shows the percentage change in new installations for the number CFLs, LFLs and LEDs which has been projected to 2025. By 2025, the CFL, LFL and LED markets will contain 613, 397 and 10,853 million units. About half of Y demand globally is due to phosphors in clean energy (Zhang, et al., 2017).

Table 6-8: Percentage change for new installations in lighting market (modified after McKinsey and Company, 2012)

New Light Sources	Units	2016	2020	2025	% change per annum
CFL	million units	1,170	852	613	-6.8
LFL	million units	645	511	397	-5.2
LED	million units	1,587	3,285	10,853	26.8

Based on these projections, the lighting market will need a total of 1,443 tonnes of REEs, a combination of La, Ce, Eu, and Y, to satisfy the demand in 2025 (Table 6-9).

Table 6-9 shows the expected mass of specific REEs that are currently being used for clean technology applications. These quantities are used for quantifying the future demand of REEs. Some elements are not represented for specific applications, such as Pr and Tb for magnets. Instead magnets are represented by Nd and Dy. The growth of Pr and Tb in magnet technology is expected to increase.

It is also important to note that the forecasted demand for 2025, presented in Table 6-9, provides an estimate for elements used exclusively in clean technology. In addition, their estimated demand is based only on this technology. Other applications in other sectors where elements such as La, Ce, Eu, Nd, and HREEs are used falls outside the scope of this research, although some of their markets are still expected to grow.

Table 6-9: Simplified quantity of REEs required for each clean technology application (Modified after Zhou, et al., 2017) and a summary of critical REE demand for 2025 for the respective use, based on benchmark averages from the literature

Source	Application	Expected Units (2025)	La (kg)	Ce (kg)	Nd (kg)	Eu (kg)	Tb (kg)	Dy (kg)	Y (kg)	Comments/Assumptions	REE required per unit (kg)	Total REEs required per application in 2025 (tonnes)
Zhou et al., 2017; IEA, 2018; GWEC, 2019, GWEC, 2016	Wind Turbines	192,856	-	-	100	-	-	33.5	-	Higher of 2 scenarios used	133.5	25,745.85
Zhou et al., 2017; Binnemans, et al., 2018	NiMH Batteries	5,000,000	0.61	0.86	0.26	-	-	-	-	Assume 10% of current demand in 2025	1.73	8,625.00
Clean Energy Ministerial, 2019; Pavel, et al., 2017; Zhou et al., 2017)	Electric Vehicles	7,200,000 – 8,330,000 (50,000,000 total)	-	-	0.60	-	-	0.08	-	50% of target achieved by 2025 (i.e. 50 million EVs)	0.68	6,750.00
Schulze, 2015; Pavel, et al., 2017	e-bike	60,832,645	-	-	0.05	-	-	0.01	-	4% growth per annum	0.06	3,406.63
Zhou et., 2017; Statista, 2018; Binnemans, et al., 2018	Catalytic Converter	121,193,891	-	0.02	-	-	-	-	-	La not included as Ce is the main component in auto-catalysts	0.02	2,423.88
U.S. Department of Energy, 2011; McKinsey and Company, 2012	CFL Bulb	613,173,435	0.0000765	0.00018	-	0.0000405	0.000045	-	0.000558	Declining market	0.0009	551.86
	LFL Bulb	396,590,403	0.000462	0.000137	-	0.0000945	0.000105	-	0.0013	Declining market	0.0020985	832.24
	LED Bulb	10,853,104,350	-	-	-	0.0000004	-	-	0.000005	Growing market	0.0000054	58.61
Total REEs required for clean energy applications												**48,394.07**

6.4 Market Pricing

In simplest terms, commodity price represents the point where supply and demand meet, and according to Tilton and Guzmán (2016) indicates the amount someone will pay for the product and what the seller is willing to accept. However, this is only the case if the market is fair and competitive. Commodity markets are hardly fair and truly competitive. The rare earth market is a classic example of an unfair market and the price fluctuations in recent years have demonstrated this.

REE pricing is complicated and information is difficult to source. However, this is because China has significant control over REE pricing, due to its near monopolistic hold on supply. During the REE crisis of 2010, freight on board (FOB) price variations for the rest of the world were, for the most part, much higher than within China which demonstrates the variability throughout the rest of the world relative to China (Table 6-10).

Table 6-10: Average REE oxide price increases for the Rest of World versus China between 2009 and 2011 (Chen and Zheng, 2019)

2009-2011 REE oxide price (FOB China)	Price Increase (average)	
	Rest of World (%)	China (%)
La-oxide	2,133	531
Ce-oxide	2,629	919
Nd-oxide	1,226	1,133
Pr oxide	1,095	919
Sm-oxide	3,041	578
Dy-oxide	1,253	1,239
Eu-oxide	576	576
Tb-oxide	645	630

Currently, REE prices are critical in the decision-making of where to focus efforts for supply, either through developing exploration projects outside of China or importing from China (Chen and Zheng, 2019). However, establishing accurate and reliable pricing models is difficult, and to date has not been done with any confidence, due to the complexities of the market (Barakos, 2017; Fernandez, 2017).

The reason for price data being difficult to source is largely due to REEs being sold on contract, at a pre-negotiated price, especially within China. Contracts should result in increased price stability as they are held for longer periods of time between producers and consumers (Chen and Zheng, 2019). According to Barakos, (2017), pre-negotiated contracts are important for long-term outlook of producers and consumers alike, and lack of such contracts may result in previously feasible projects becoming too risky if exposed to spot REE prices. Conversely, producers who do not sell on contract, need to accurately establish their REE basket price, which is an average price based on the rare earth assemblage. This basket represents the price for the recovered REEs, relative to the which REEs are present (Garcia, et al., 2017). If it is La and Ce dominated, the basket price will be lower than if it were composed of more HREEs (Suli, et al., 2017).

Price volatility in the past was exaggerated because of Chinese supply on pre-negotiated contracts between Chinese producers and consumers outside China. To illustrate this, rare earth prices are shown from 2008 to 2016 (Figure 6-11). The average LREE price was approximately US$15/kg in January 2011 which increased to an average of USD$120/kg in July 2011. The same trend is observed for HREEs, although an order of magnitude higher. Eu approached USD$4,500/kg at its peak, up from USD$400/kg a few months earlier. However, despite these relatively, short-term increases, deflated REE prices since 1970 for both LREEs and HREEs indicate there has been an overall price decrease (Fernandez, 2017). The price correction that followed the Chinese supply debacle was caused partly by the WTO’s decision to impose penalties on China should they continue restricting supply, which was only finalised in 2015, but also the commissioning of Mt. Weld. Mt Weld is a large producer which came online in 2013, which helped to alleviate some of the price concerns. If supply can be secured from projects in development, the REE prices will likely remain subdued for the foreseeable future, as the associated political risk will decline.

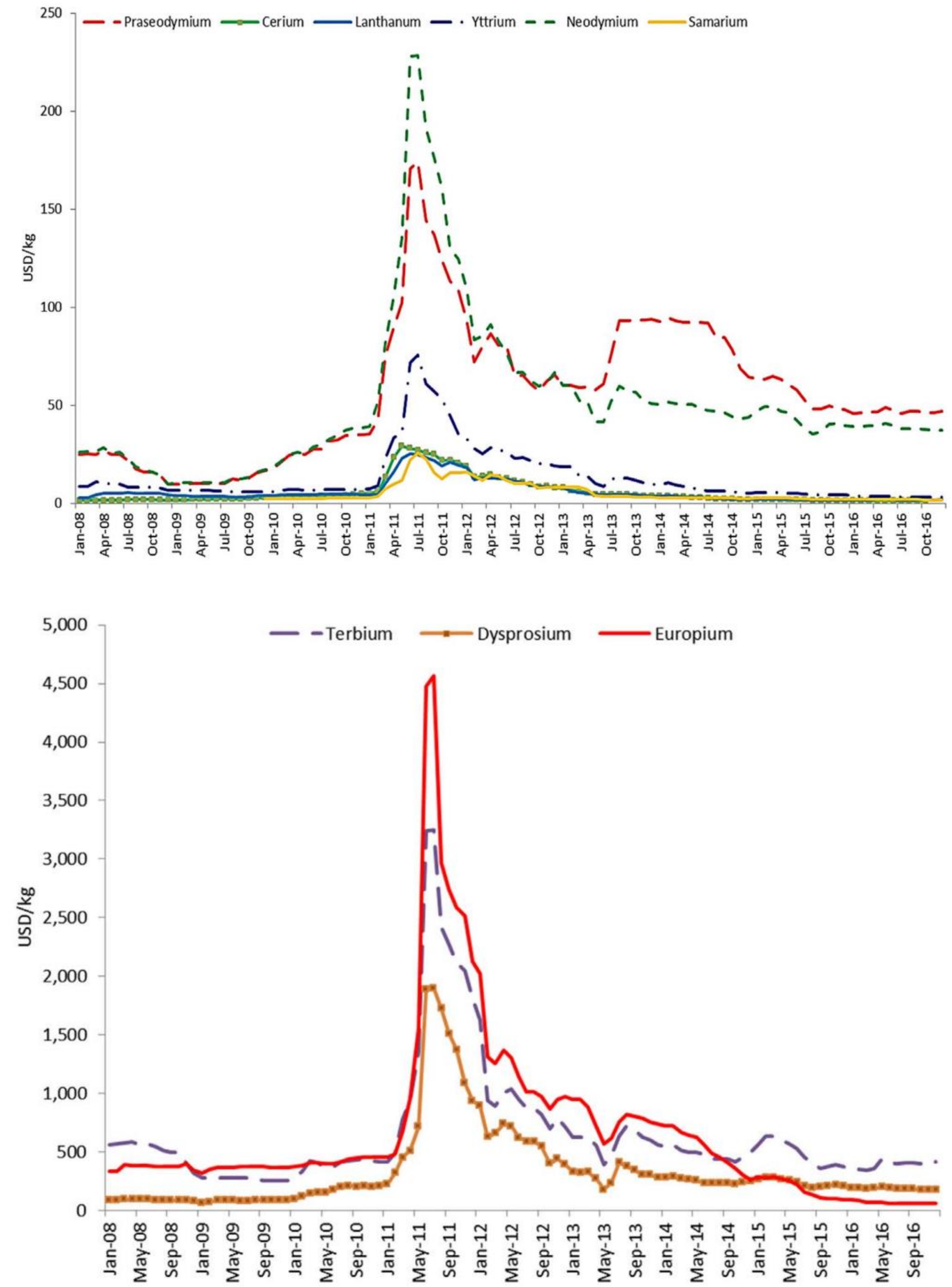

Figure 6-11: LREE and HREE prices from 2008-2016 (after Fernandez, 2017)

There are different set prices for REEs, namely 1) domestic prices, 2) cost, insurance and freight (CIF) for Europe, and 3) freight on board (FOB) in China (Barakos, 2017). In Europe for example, trading of oxides is more common, as oxides are more often required for the downstream processing than metals. Therefore, pricing for REOs is more commonly reported, but metal prices are provided. Pricing for REOs is reported in USD$/kg and the prices vary between LREOs and HREOs. HREOs (i.e. Dy-, Tb-oxide) are less common and therefore fetch a higher price, typically between 350-500 USD$/kg, whereas LREEs (i.e. Nd-, Pr-oxide) range from 60-100 USD/kg. La-, Ce-, Y- and Sm-oxide, commonly in oversupply, fetch much lower rates, usually not more than USD$10/kg (Garcia, et al., 2017).

According to Barakos, (2017), when assessing project viability, chosen REE prices typically reflect Chinese FOB prices. With forecasting, it is best practice to avoid cycle peaks and select an average price that represents reality (Barakos, 2017). Having several REEs within a single deposit can affect the marketability of the product that producers/marketers want to sell, either negatively or positively. Therefore, it is important for each deposit to characterise the REE assemblage, proportions and determine whether an appropriate product can be sold in an open market, or perhaps on contract.

6.5 Chapter Summary

REEs have many commercial uses, but currently their strategic importance is within their uses in clean technologies and hi-tech industries. This research has focused on several clean technology applications such as:

- The use of Nd, Pr, Dy and Tb in high strength permanent magnets which are commonly used in electric vehicles and wind turbines;
- The use of La, Ce and Nd in NiMH batteries to power electric vehicles;
- The use of Ce in catalysts in internal combustion engines; and
- The use of several REEs in low energy lighting such as LEDs.

An investigation of the historical and current demand of REEs for the abovementioned applications highlights that growth in demand has resulted in more REEs being required. Looking forward, forecasted demand based on projected growth of each application indicates that several REEs such as La, Ce, Nd, Dy and Y are going to be required in larger quantities to meet global requirements of clean energy as a result of ongoing efforts to reduce carbon emissions. As a result, Nd, Dy (Pr and Tb) are forecast to be the most sought after REEs due to their use in magnet technology which is expected to grow rapidly over the next few years and even possibly the next two to three decades. Due to this projected growth of magnet technology and thus, an increase in demand for several REEs, it is imperative to analyse the relationship between supply and demand of these elements to determine if supply will keep up with demand, and as a result, how this balance will impact the price. Price surges of the last REE bubble were a direct result of a supply shortage, due to jurisdictional scarcity.

7 SUPPLY AND DEMAND BALANCE

In response to the higher demand, REE production is expected to rise, through capacity expansion of existing operations and the introduction of several new mining projects across the globe. Historically, this has already been observed with the commissioning of Mt Weld and Browns Range REE deposits in Australia. As a result, China's grip on REE supply is likely to decrease but to what extent is currently unknown (U.S. Department of Energy, 2017; Roskill, 2018). Despite key REEs (i.e. Nd, Pr, Dy) entering a period of growth and increasing demand, due to permanent magnet technology, the REE industry has entered a period of uncertainty. This uncertainty is mostly caused by two issues. Firstly, mining operations and REE refineries have to abide by increasingly stricter environmental protocols, and secondly, higher tariffs between the U.S. and China on REEs and their end use products as a result of the incessant trade war (Roskill, 2018).

There are two issues at hand regarding REE supply, namely jurisdictional scarcity and geological scarcity, which are interlinked. Going forward, most REE supply will be enough to meet the growing demand. However, constraints by China could result in jurisdictional scarcity and it is unlikely that the world will be able to keep up with demand for the clean technology applications. To avoid this, China must maintain its supply channels to the rest of the world and active project development is required outside of China to ensure a reliable supply. A steady supply from the rest of the world will likely balance the price of critical REEs (Nd, Dy, Pr and Tb) as geological supply concerns diminish and dependence on China decreases. Another risk is that the projects outside of China are not developed fast enough, and China is unable to meet global demand on its own. With China cracking down on illegal mining of REEs and implementing environmental regulation on all operations, domestic production has not been as high as it could have been, particularly in the elements it was forced to import in 2018.

Kalvig and Machacek (2018) indicate that there will be approximately 25,000 tonnes of Nd produced by projects currently in development assuming they all began producing by 2025, which is plausible but highly unlikely. This amount is still not adequate to meet the demand forecasted for Nd reported in this research. Thus, in the event that China limits or cuts the rest of the world off from REEs, there will be a supply deficit for critical REEs needed for clean technology applications.

As such, it is imperative that rare earth deposits are developed within China and outside of China in order to contribute to global supply. Several roadblocks exist in doing this, which has resulted in the failure of many REE projects in the past, such as:

- Expensive capital expenditure (CAPEX) required to develop rare earth deposits. These can range between $500 and $1,000 billion USD (Sykes, 2013);
- Complicated mineralogy and assortment of REEs within REE-bearing mineralogy; and
- Inconsistent quantities of specific REEs resulting in oversupply of non-critical elements and variable supply of highly desired elements.

Figure 7-1 illustrates the historical balance between supply and demand. The image depicts how demand exceeded supply in recent years due to Chinese control over the market.

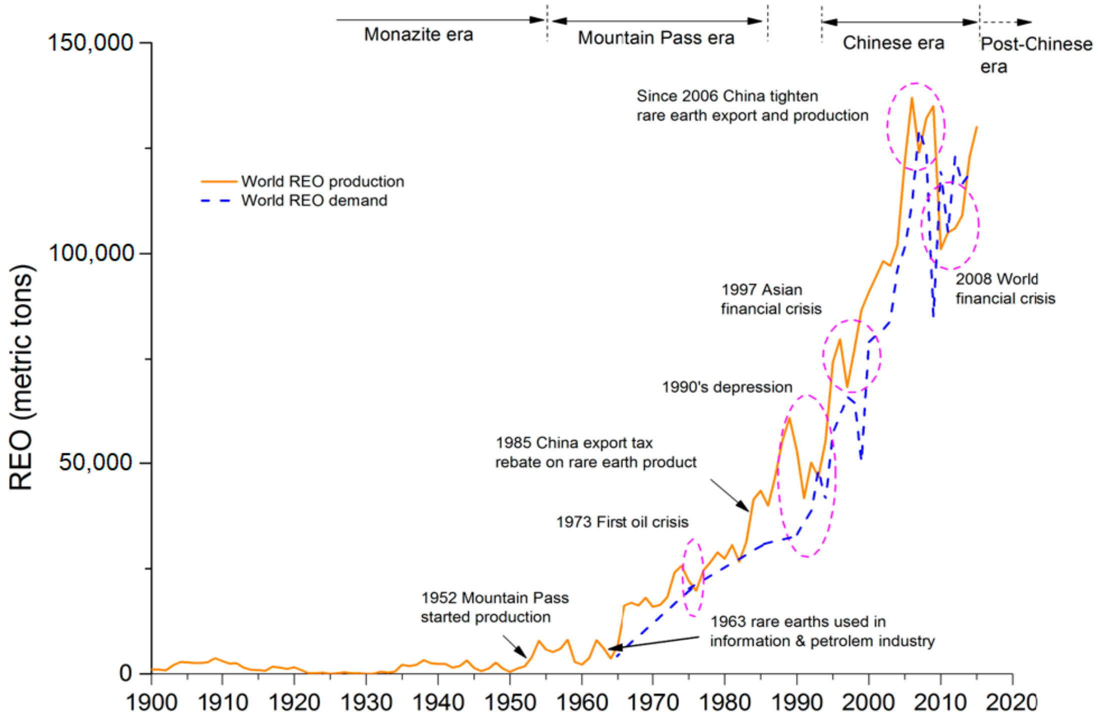

Figure 7-1: Supply versus demand of REOs (after Zhou, et al., 2017)

7.1 REE Imbalance Scenarios

As discussed earlier in this report, Nd, Pr, Eu, Tb and Dy are expected to increase in demand the most, due to their use in permanent magnets and phosphors required for clean energy initiatives and low carbon technology. As a result, these REEs are considered critical due to their risk in supply. La and Ce however, are not considered critical as they are commonly overproduced during mining as their cumulative production is more than 50% of all REEs produced annually (Borra, et al., 2018). Therefore, production is currently dominated by La and Ce whereas most of the demand is for Nd and Dy. This commonly results in oversupply of La and Ce and a possible shortfall from primary production for Nd and Dy (Jowitt, et al., 2018). However, despite the surplus of La and Ce, their market is still expected to grow at reasonable rates (~5% per annum) due to the constant supply of Ce and La for use phosphors in mobile phones, TVs and computers and the use of Ce in catalytic converters (Alonso , et al., 2012; Borra, et al., 2018).

Several scenarios exist and the outcome will dictate whether supply will exceed demand or vice versa. From the literature, production of REEs is expected to grow on average by 5% per annum (Alonso, et al., 2012; Goodenough, et al., 2017). This is considered relatively conservative for Nd, La, Ce, Y, Dy, Tb and Eu as demand for their primary applications is expected to exceed this (Alonso, et al., 2012). Nevertheless, three scenarios are presented below to gauge which elements are most sensitive to supply. Average annual growth rates of 3%, 5% and 10% were used and compared to the forecasted demand, shown in Figure 7-2.

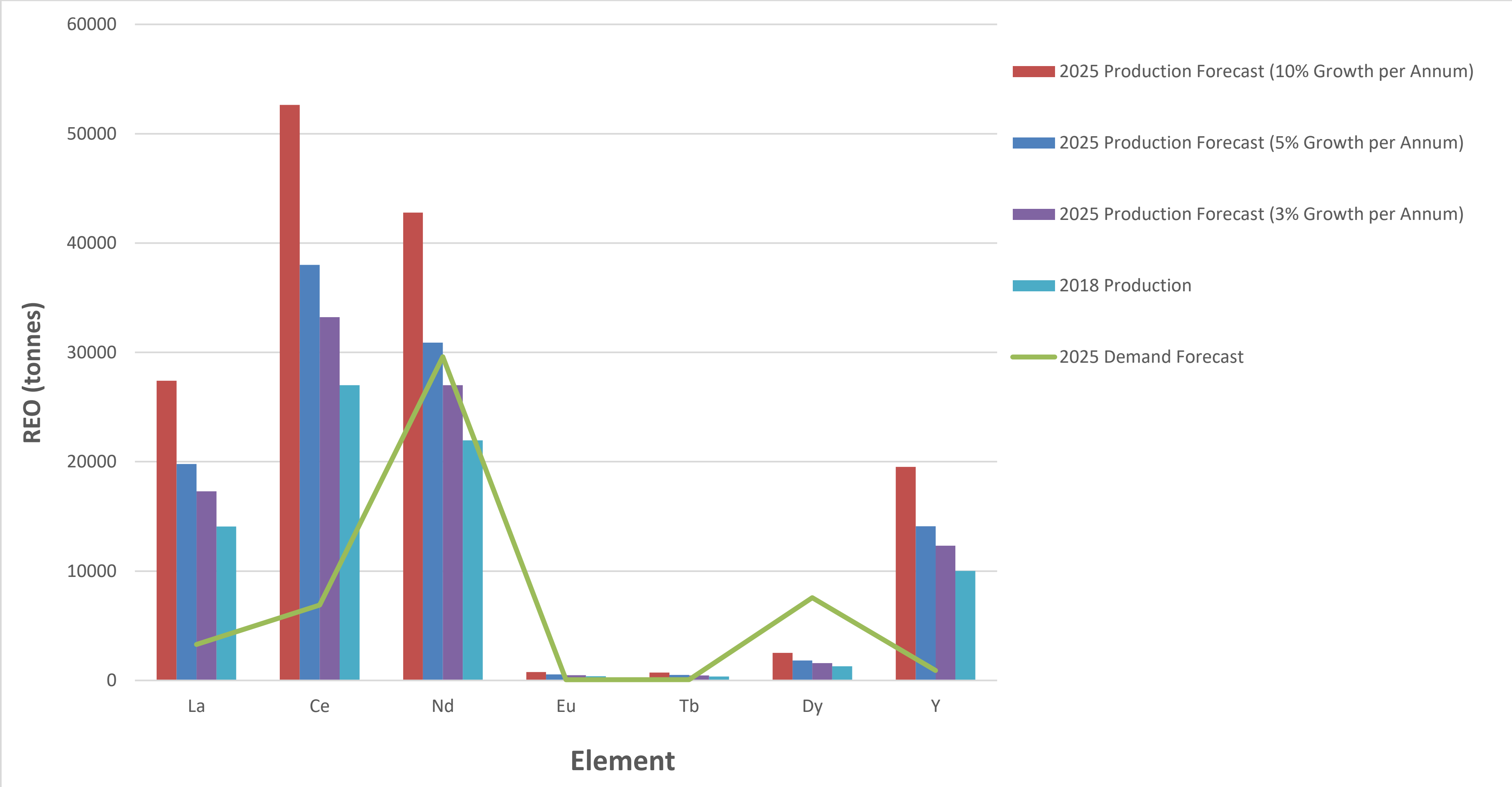

Figure 7-2: Forecast of production at 3%, 5% and 10% growth per annum versus demand for 2025, relative to current production (source Zhou, et al., 2017; Kalvig and Machacek, 2018)

All three scenarios show a similar outcome, except Scenario 1 (3% production increase) where both Nd and Dy are in short supply, instead of just Dy. Supply for La, Ce, Eu, Tb and Y will exceed demand. As mentioned, La and Ce are commonly produced and often in oversupply. Eu will be in oversupply but not to the same extent as the LREEs. Binnemans, et al. (2018) suggest that Eu demand will decrease in the coming years due to the decline of CFLs, further exacerbating the extra supply. In addition, recycling of REE-rich phosphors is expected to increase. Therefore Eu will likely no longer be measured as critical. Tb, like most HREEs is rare and mostly produced in China. In 2025, Tb will also be in oversupply. Besides phosphors, Tb is mostly used in NdFeB magnets. There is expected to be a large oversupply of Y in conjunction with a waning demand. Its primary use in phosphors is declining. It is used in phosphors markets that are expected to grow, i.e. LEDs, however in such small abundances. Binnemans, et al. (2018) note that Y is not likely to succumb to jurisdictional scarcity as a few REE deposits are outside of China that maintain the supply.

Scenario 1, a conservative 3% growth rate suggests that supply of Nd and Dy will not match demand. The estimated shortfall for Nd and Dy will be 2,600 tonnes of Nd and 5,900 tonnes respectively. At 5%, Nd supply can satisfy demand with an expected surplus of 700 kg. However, a 5,700-tonne deficit of Dy will be realised. At 10%, there will be a surplus of approximately 13,000 tonnes and a deficit of 5,000 tonnes Dy. Magnets are the fastest growing application for REEs and is increasing its market share in terms of application year on year. If scenario 1 prevailed, and there are insufficient quantities of Nd and no readily available substitutes, the Nd price will likely surge rapidly forcing many development projects to come online in order to alleviate the demand or alternative, less efficient and possibly more expensive magnets, such as SmCo magnets may be more commonly used again. Very little Nd is currently entering the market due to recycling. This may increase going forward, but unlikely anywhere near the rate required to meet demand by 2025 as by then not many magnets will be available for recycling. Scenario 2 and 3, where Nd supply exceeds demand, is considered more likely from the present moment till 2025. With the growing Nd demand, and enough resources available in 2025 to meet this demand, it is more at risk due to geopolitical, trade and production capacity constraints. Russia for example, is a candidate nation, that can significantly increase the LREE output, including Nd, due its large reserves.

Dy, is likely to be in short supply sooner than 2025 based on the large deficit observed. Dy is geologically scarce, due it being a less commonly occurring HREE. It is also at risk in terms of origins of supply, as it, alongside other HREEs like Tb, is currently only produced in ion-adsorption clay deposits in China (Binnemans, et al., 2018). Dy is observed to be the only REE under real threat in terms of supply and other solutions will be required to increase the said supply or replace it with another element. It may be possible to use excess Tb to supplement the short supply of Dy in magnet manufacturing. The possibility of bringing new Tb online comes from recycling of Tb-rich lamps (Jowitt, et al., 2018). Although Dy is an important component in magnet technology, the process can be complete without it. As a result of the supply shortage, there will be an urgent need to replace Dy as much as possible and as such the market will look for substitutes or alternative technology. In fact, wind turbines that employ a cooling system to allow the NdFeB magnet to function optimally, without the use of Dy have already been developed (Binnemans, et al., 2018).

A second approach was investigated, to determine whether supply of Nd and Dy would meet demand in 2025. The forecast for Chinese production and the rest of the world is determined by Kalvig and Machacek (2018) which assumes a 5% increase per annum for China, and all projects currently being developed, becoming producers, excluding China. As before, Figure 7-3, shows that supply will exceed demand for Nd and there will be a significant shortfall of Dy. Interestingly, demand for Nd cannot be met without China, even after the commissioning of 34 new mines. Cumulative production from China and the rest of the world will still result in a deficit of between 3,000 and 5,000 tonnes Dy. However, it is questionable whether the rest of the world will begin producing REEs at this scale by 2025.

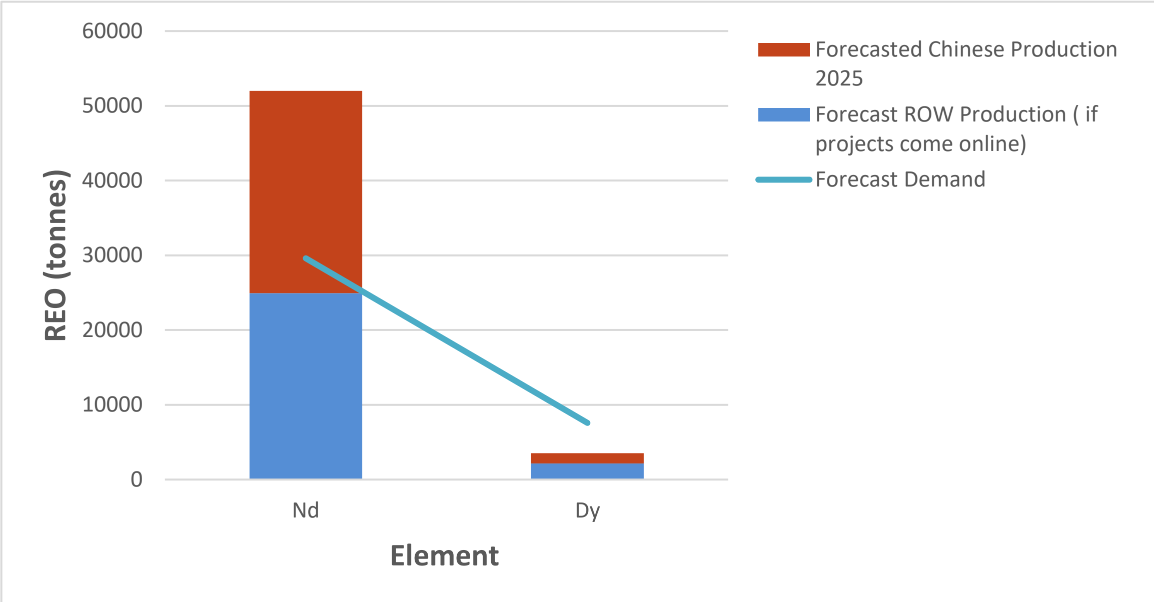

Figure 7-3: Forecast production for critical REEs (modified after Kalvig and Machacek, 2018) versus expected demand

7.2 Chapter Summary

Historically, periods of increased demand in REEs have been due to global economic crises, such as the oil crisis in 1970s and the Global Financial Crisis (GFC) in 2008. However, in some scenarios, demand for Nd and Dy will likely exceed supply by 2025 due to increased demand for clean technology and a global desire to combat climate change. It may be possible to offset the lack of supply somewhat, but in order to prevent the imbalance, project development needs to be prioritised and more mining operations need to come online. With the expected price surge for Nd and Dy, should demand exceed supply, it is probable that deposits previously deemed uneconomic may come online. In addition, technological advancement may assist in improving metallurgical and environmental factors that are currently the reason for many uneconomic deposits. The impending imbalance of Nd and Dy is largely caused due to their uses in clean technology, lack of viable projects to increase supply and China's monopoly over their supply.

8 DRIVERS OF DEMAND

REEs are largely used for high-tech and clean energy applications for properties including illumination luminescence, magnetism and strength imparted to alloys (Tse, 2011). Clean energy applications are a major driver for rare earth demand. Coupled with this global plan to reduce greenhouse gases, the demand is expected to increase rapidly particularly for the elements used in specifically in clean technologies. The same trends will likely be seen for other clean commodities, such as battery metals i.e. lithium, cobalt, nickel and manganese.

Demand for a commodity can differ from country to country but is often consistent on a global scale. Such demand can be related to several factors, including population size and growth, economic growth rate, the stage of a country’s development and its legal framework/regulation that may incentivise the use of specific commodities to achieve a nation’s national agenda.

This section will assess the potential for REE market growth by investigating population and economic growth trends in developed and developing nations. The current and future demand for REEs will be discussed, paying attention to demand drivers such as new policies that are driving clean technology and how this is likely to affect the growing demand.

In order to assess the current and future demand for REEs, it is necessary to understand the drivers of demand. Some of the main drivers addressed in this research are:

- Economic and population growth;
- Policies to promote clean energy applications as an alternative source of energy; and
- Chinese control of supply.

8.1 Economic and Population Growth

In order to assess the potential demand that a commodity may reach, it is useful to relate its applications to economic growth. Economic growth commonly refers to Gross Domestic Product (GDP) and is the international measure of a countries economic position, especially when calculated per capita. GDP is loosely defined as the value generated within a country, through goods and services in a one-year period. A country's need for commodities often plays a role in the commodity super cycles, particularly in times of economic growth, thus according to Cuddington and Jerrett (2008), these super cycles mimic global GDP. As of 2018, the world's three largest economies included the U.S., China and Japan (Figure 8-1) (Smith R. , 2018).

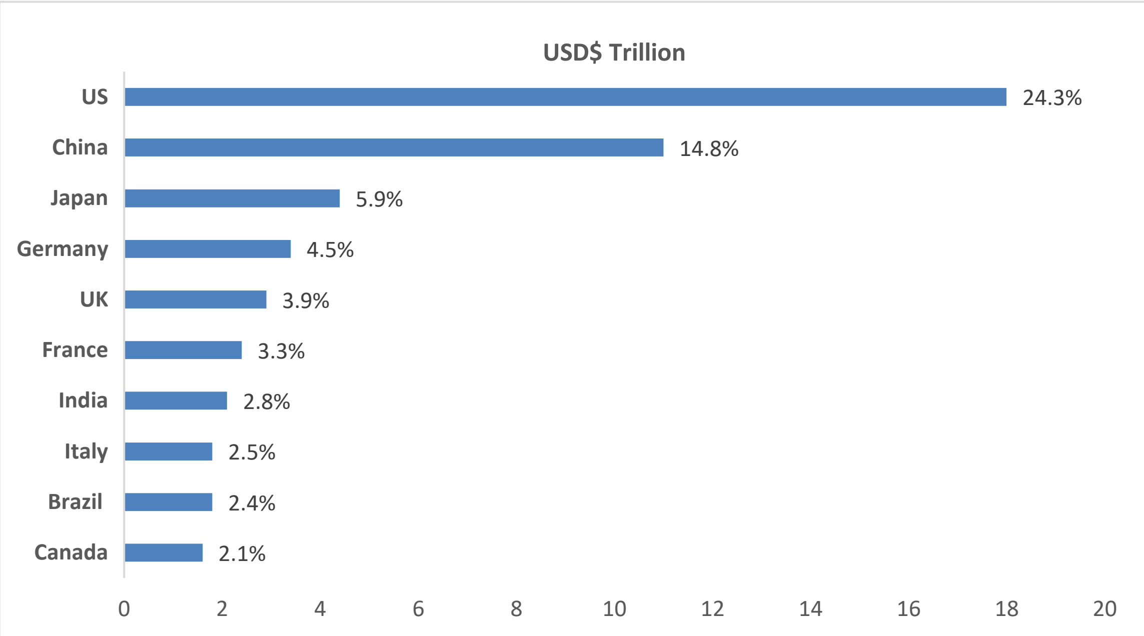

Figure 8-1: Worlds' largest economies, measured in USD$ Trillions (modified after World Population Review, 2020)

Over the last two decades, China's economy has increased more than any other, at a rapid pace. This resulted in China securing the position for the second largest economy in the world. Comparably, the U.S. economy has developed at a stable, increasing growth rate year on year, allowing it to maintain its position as the world's richest economy. However, during this time, due to China's rapid rate of development, global economic growth resulted. China's economic growth was spurred by its large-scale industrialisation over a relatively short timeframe and was the main driver for the last commodity super cycle which came to an end in 2008 at the onset of the global financial crisis (GFC) (Erten and Ocampo, 2013), and again in 2012. The commodity slump in 2012 was largely caused by a slow-down in Chinese economic growth, which has directly impacted global economic growth, particularly in the last two years (United Nations, 2018). From 2010 to 2015, there was a general decline in the growth of developing economies, despite accounting for most of the global economic growth. During this period advanced economies also began to recover more year on year.

Three economic shifts, described below, have dictated global economic shifts, and are major controls of the international economic position:

- China's markets remaining subdued, as it shifts toward services-based economy, would seriously undermine global economic growth. China's economy slowed down to about 6% from about 9% prior to the 2012 commodity slump;
- Lower commodity prices; and
- Increasingly strict monetary policies (International Monetary Fund, 2016). In order to achieve economic growth going forward, particularly in developing nations, macroeconomic stability is required to ensure sustainable growth of up and coming markets and developing economies (The World Bank, 2019).

According to the International Monetary Fund (2016) and The World Bank (2019), economic growth in advanced economies, was a reasonable 2.5% for the U.S. and a meagre 0.2% for Japan. Conversely, economic growth in developing economies was about 4.5%. As a result of China's lower growth rate, the Indian economy was able to grow more, achieving growth rates of more than 7.5%. Going forward, economic growth is forecast to increase by 4.6% across emerging economies in regions including Southeast Asia, Central America, Eastern Europe, the Middle East, the Pacific as well as sub-Saharan Africa. In comparison, the developed nations such as Australia, Japan, the U.S., UK and parts of Europe are forecast to have much lower rates of economic growth, with an average of 1.5% over the next three years (World Bank, 2019).

Despite all this, economic growth in terms of GDP is not exclusively considered accurate when determining the wealth of a nation. This is due to population dynamics. A more accurate analysis of a nation's development status is therefore GDP per capita, which considers population dynamics such as population growth. The theory of intensity of use is based on GDP per capita to determine raw material consumption and assess the level of a nation's economic development.

The link between commodity usage and economic growth per capita was originally conceived in the early 1970s by the World Iron and Steel Institute. The theory was further developed by Malenbaum (1978), Auty (1985) and Tilton (1985) who suggested that the association between the economic development of a country and its use of commodities will follow a specific curve, shaped like an inverted "U". This curve is termed the Material Kuznets Curve (MKC) and was put forward by Focacci (2005) due to its similarities with the original Kuznet Curve which was developed to represent fluctuations of income inequality and increasing GDP (Kuznet, 1955) but also shows the path of greenhouse emissions over GDP.

The theory is based on the premise that as an economy begins to industrialise, by shifting away from a primarily subsistence, agrarian base, it demands increasing amounts of raw materials to develop infrastructure capable of supporting a more developed economy (Figure 8-2).

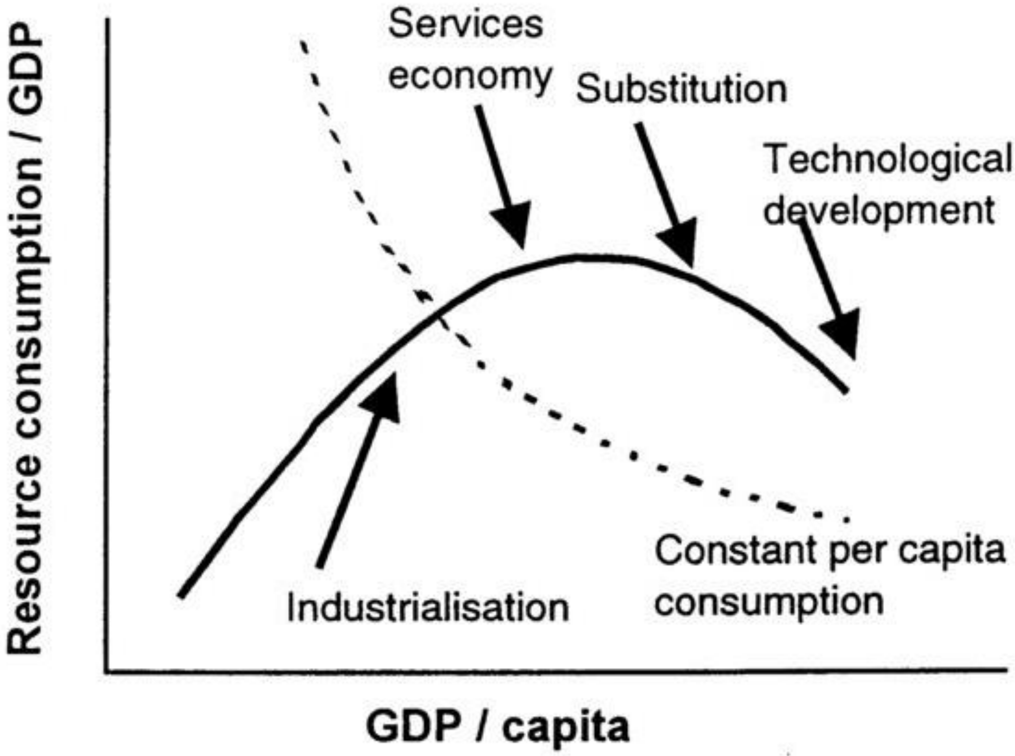

Figure 8-2: Simplified, idealised curve illustrating different stages of economic development and resource consumption (after Van Vuuren, et al., 1999)

As the economy develops further, people begin to demand more sophisticated products as a result of higher income, such as vehicles, mobile phones and appliances. Furthermore, at peak development, the consumer sophistication changes once again to more goods and services-based, such as finance, technology and education. Once an economy reaches this point, it typically decreases its need for raw materials, causing a sharp decrease in the intensity of use of commodities (Tilton and Guzmán, Mineral Economics and Policy, 2016). Consumer sophistication is explained to a degree by Roberts (1992), with the concept of material composition of products (MCP). Roberts (1992) discusses how changes in MCP is largely based on profitability, which in turn determines rates of a products diffusion in the market. However, substitution of materials often results in a new material being more profitable. To date, this does not apply to most applications that use REEs due to their unique properties, both chemical and physical as discussed above. As a result, their profitability in MCP is determined by its current market penetration. This aligns with the idea that specialised metals, used in advanced technology, does not fit the intensity of use curve, causing it to shift (Tilton and Guzmán, 2016). REEs do not necessarily fit the intensity of use curve and going forward, they are likely going to be required by both developing and developed economies. This is because the intensity at which these metals are consumed is not necessarily related to income per capita or relate to industrialisation.

The intensity of use model was used throughout the 1970s and 1980s as a method of forecasting the demand for specific metals and is still considered useful as a baseline assessment of a metals demand. However, more recent thinking, is that more elaborate assessments should be done such as the identification of consumers and the variety of applications. In order to contextualise the REE markets, it is necessary to quantify economic and population growth on a global scale which is critical to estimating consumption of products (Roberts, 1992).

According to the United Nations (UN), the global population in mid-2017 was 7.6 billion people. The global population is estimated to be as high as 9.8 billion people by 2050 and over 11 billion people by 2100, which is a rapid growth rate. Currently, China and India remain the top two most populated countries with 1.4 billion and 1.3 billion people respectively. A large proportion of the balance are from other parts of Asia and Africa, which are mostly made up of developing countries. The least developed countries in the world, comprising 47 nations, are estimated to contribute the largest amount to the global population by 2030, with an increase of over 30% and almost 2 billion people by 2050 (UNDESA, 2017).

Although the forecast increases appear high, it is relatively lower than historic growth rates for the same countries. This is due to the increase in economic development and education as a result, a relative decrease in population growth

(UNDESA, 2017). As such, it must be mentioned that forecasts are based on assumptions that may never be realised. These forecasts become increasingly inaccurate for increasing periods of time and are often presented as ranges of estimates.

Soile (2013) argues that the intensity of use theory is flawed and cannot necessarily assume that countries with comparable GDPs will have the same intensities of use for certain raw materials. This is largely dependent on which industrial activities a nation undertakes in order to develop economically. In the research undertaken by Soile (2013), the intensity of use for copper was analysed for South Korea, Singapore and Vietnam. These three countries are at different stages of their development. The key findings suggest that (1) the relationship between intensity of use and per capita GDP is too restrictive, and fails to consider a country's primary economic activity; (2) intensity of use for copper and similar metals is greater in developing countries as opposed to services-based economies, and (3) there is low intensity of use for metals in services-based economies.

REEs are an arguable exception, with higher consumption in more developed countries. During a country's development phase, short to medium run consumption of REEs is dependent on two factors:

Firstly, the rate of economic growth. Due to the specific clean energy and high tech applications of REEs, it is unlikely undeveloped economies, particularly in Africa and parts of Asia, will require any significant amounts of REEs during immediately after its attempt to industrialise and will therefore consume materials suited for infrastructure development such as copper and iron ore. Many of these countries also do not yet necessarily have access to the technology, skills and capital to implement green technology over fossil fuels and this will be a large driver for demand of REEs in the future as they develop economically and grow per capita. Population growth and economic development ultimately leads the point where developing nations shift from agrarian to industrialised economies, and during this shift, developing countries will require more clean technologies, thus a greater demand for REEs (Alonso, et al., 2012; MIT, 2016).

In addition, REEs are rather versatile because of their uses in different sectors. For example, smartphones utilise varying amounts of almost all REEs (Rohrig, 2015) but mainly consist of Nd, Pr, Ce and La. This wave of mobile phones is a continuously growing market across the globe, particularly in developing nations, as manufacturers release relatively inexpensive devices aimed specifically at low-income earners. Coupled with a smartphone market which was expected to grow by four times between 2010 and 2015 (Laurent, 2014), the developing world is expected to be large consumer in this regard. Thus, in order to understand developing nations future demand of REEs, it is important to understand the economic development of various regions and what can be done to develop their respective economies more rapidly. It is also important to understand that new applications, suitable for developing nations may shift the macroeconomic dynamics and that consumer sophistication is increasing in many ways beyond the level of economic development.

The second factor impacting the short to medium run consumption of REEs is the rate of reduction of global fossil fuel use. A major constraint at present for developing nations, which is expected to intensify in the future, is the external pressure from the developed world to reduce fossil fuel consumption in order to reduce greenhouse gas emissions. There is currently a higher demand in developed nations for sources of clean energy, as fossil fuels are still considerably cheaper than establishing wind farms and other sources of renewable energy..

There is a possibility that REE consumption continues to increase, due to a lack of effective and widespread substitutes or alternative technologies being developed (Figure 8-3). This will potentially affect both developed and developing nations, particularly at the end of their development cycle.

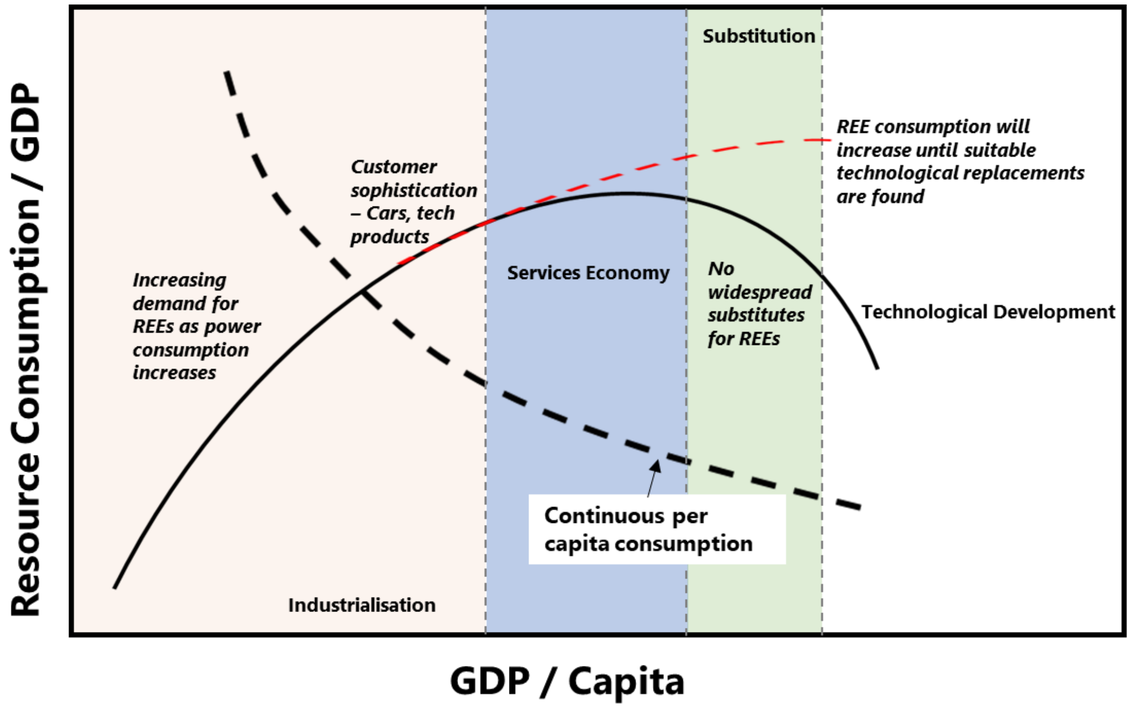

Figure 8-3: Possible scenario for REE consumption during economic growth and in the event of no widespread substitutes (modified after Van Vuuren, et al., 1999)

8.2 Government Policy and Clean Energy Initiatives

As previously mentioned, there is a global agenda to reduce carbon emissions despite economic development and population growth of many nations. According to the International Energy Agency (IEA), current energy requirements across the globe are estimated to be 13,000 to 14,000 million tonnes of oil equivalent (Mtoe) (International Energy Agency, 2019). Energy consumption has increased rapidly across regions such as the Middle East, Asia and Africa. This increase in consumption is mainly driven by population growth, economic development and easier access to market. Consumption growth rates have exceeded 20% per region in the last ten years. Despite high growth rates from Africa and the Middle East, more energy was consumed in Asia in 2016 as shown in Table 8-1.

Table 8-1: Percentage of global energy consumption in emerging markets and developing economies in 2016 (modified after Kahan, 2019)

Region	Percentage of Global Consumption
Asia and Oceania	42
Middle East	6
Africa	3

In comparison, slower growth was recorded for developed nations such as the U.S. with only a 1% increase in consumption between 2010 and 2016. During this time, the EU economies declined their consumption by 5% (Kahan, 2019). Most of the fuel used in the energy industry is still largely hydrocarbons, such as petroleum. Coal powered energy is also used but is in decline on a global scale and is mostly a predominant energy source in regions that produce a lot of coal (Kahan, 2019) i.e. Australia, China, South Africa.

The major negative aspect associated with fossil fuel-powered energy is the resultant greenhouse gas emissions. Greenhouse gas emissions have historically been viewed as a burden on modern society and industrialising nations. However, these emissions progressively compromise the earth's atmosphere and ultimately result in climate change and global warming. More than 65% of the greenhouse gas emissions is a result of the global energy sector (Espa and Rolland, 2015). Many nations, despite still using large amounts of fossil fuels, are also including the use of nuclear and renewable energy. Renewable energy, such as wind and solar, is still the least common energy source and is more common in developed nations, mainly because of incentivising policies, political will and economic status.

Demand for primary energy is estimated to be 20,000 Mtoe by 2040, which is an increase of 1.4% per year (Zhou, et al., 2017). By this point, the world will likely not keep up with energy requirements from traditional fossil fuels alone, and renewable energy is likely to make up between 10 and 20 % of primary energy. The increase in renewable energy is also expected to be spurred on by increasing global pressure to minimise greenhouse gas emissions, both developing and developed countries will be forced to use greater amounts renewable energy sources. However, the burning of fossil fuels is currently still cheaper than implementing renewable energy programs, but policy changes, and government intervention, is causing a rapid change especially in North America, and Europe (Espa and Rolland, 2015). Irrespective, more and more of this energy requirement will have to be met by renewable and clean energy sources if climate change is expected to be thwarted. The Paris Agreement, under the United Nations Framework Convention on Climate Change (UNFCCC), is aimed at global active participation in the reduction of carbon dioxide (CO_2) and other greenhouse gas emissions. A concerted effort from developed nations to assist developing nations to reduce their emissions is also expected as part of the agreement (United Nations Climate Change, 2018).

As developing nations become increasingly populated they will likely require growing amounts of energy. Concurrent to this, a conscience decision has been made to move away from fossil fuels for power generation and vehicle fuel. This suggests there will be large growth in demand for permanent magnets. Policies, for road transport from nations and cities around the globe are also aimed at reducing carbon emissions and promoting a green future through the implementation of EVs.

The push for increased EVs is because internal combustion engines (ICE) comprise up to 30% of global carbon emissions (Transport and Environment, 2018). This commitment in ICE vehicle reduction will thus increase the need for electric vehicles (Burch and Gilchrist, 2018) for which REEs are required. Countries making such commitments include India, China, Ireland and the UK and cities like Paris and Mexico City. India, a highly populous developing nation, is a good example of this. They have committed to clean energy policies at a national level and plan to reach

EV penetration of 30% of all vehicles on their roads by 2030, which equates to approximately 84 million EVs (Department of Heavy Industry, 2012). The original target was to replace the entire nations vehicles with EVs by 2032 but was scaled back significantly shortly after the announcement on a global platform (Sharma, 2018). Policies created by government may indicate intent to commit to the reduction of greenhouse gases, however, it is often questionable whether developing nations can afford to meet these commitments.

EV's market penetration is expected to increase rapidly over the course of the next few years, which will be driven by government policy, cheaper costs of manufacturing, and better ranges of a single charge are making them more accessible and desirable for consumers. According to Hertzke, et al. (2018) in a report for McKinsey and Co, BEVs comprise over 65% of global EV market share and are selling at a faster rate than PHEVs. It is noted that although this is a global average, different jurisdictions might sell more PHEVs based on government regulation/policy, availability, and customer preference. Some nations namely, China, France, UK, Netherlands, Sweden, Denmark and Norway have already managed to reach up to 5% market penetration in their respective jurisdictions because of policy shift, effective government regulation (International Energy Agency, 2016) and consumer sophistication. As far as countries and regions responsible for selling the most EVs, China is the global leader, mainly in BEVs, and is followed by the U.S and the EU. China's market is currently larger than the joint sales of both the U.S. and Europe (Hertzke, et al., 2018).

Fishman et al. (2018), through the process of Monte Carlo simulation, forecast that there will be a progressive shift from one AEV technology to another from now until 2050, resulting in the staggered incline of sales at the expense of an outdated technology. HEV sales are predicted to decrease from 2030 onwards, followed by PHEV sales in 2040 and finally BEV and FCV are expected to grow steadily until

2050. In summary the AEV market is set to grow going forward and with this the demand for REE.

Going forward, the IEA, together with the Electric Vehicles Initiative (EVI), which comprises policy makers from 16 nations, aim to average yearly sales of EVs of up to 7.2 million units by 2020, with more than three times that amount in stocks. This target is ambitious but is in line with their 100 million EV plan by 2030 which was an outcome of the Paris declaration (International Energy Agency, 2016). Assuming the plan to meet over seven million in annual sales by 2020 is realised, and all EVs used NdFeB magnets, approximately 10,000 tonnes of NdFeB magnets would be required (Pavel, et al., 2017).

Subsequently, the EV30@30 campaign, also established by the EVI, aims to further accelerate the sales of EVs where they will comprise 30% of new vehicles sold in 2030 (Clean Energy Ministerial, 2019). Figure 8-4 illustrates the difference in EV quantities based on the 100 million target and the EV30@30 campaign, which aims to bring in about 220 million EVs by 2030.

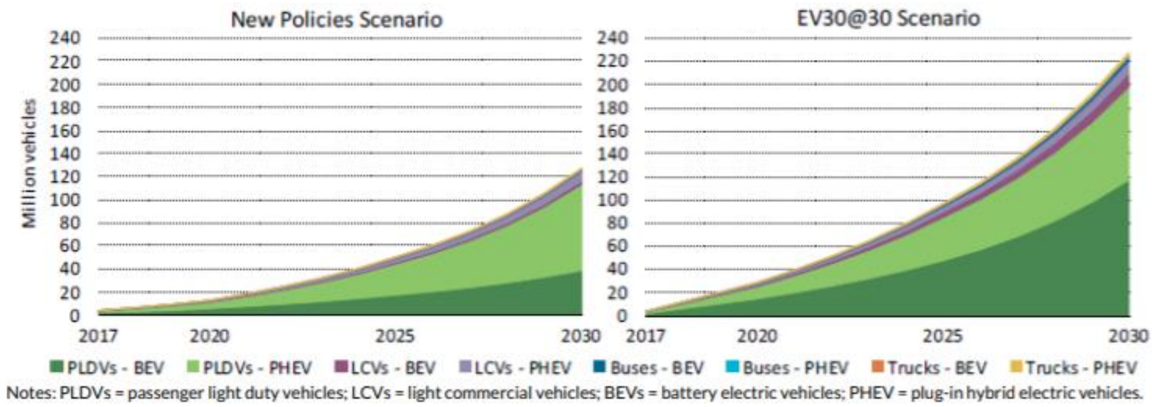

Figure 8-4: New Policies Scenario (left) versus EV30@30 Scenario (right) (after Clean Energy Ministerial, 2019)

Several developing nations possess REE resources and as a result have an opportunity to develop their mining industry based around these resources and consequentially add to the global supply and develop their economies. Currently, several African, Asian and South American countries have significant rare earth resources. Should the resources be successfully exploited, can lead to increased revenues which can be added to the national fiscus of a nation through taxes, royalties and mineral rents. This extra income at a national level, could be harnessed to stimulate economic growth and promote industrialisation and in turn, an increasing demand for REEs which they can supply (The World Bank, 2017). Additionally, REE producing countries can also outline a plan to develop downstream processes to reduce global dependence on China for end-use applications. These processes can also develop much needed skills and capacity which may be very useful during the integration of clean energy. Interestingly, African countries have been the focus of a study that outlines the strategic importance for countries like the U.S. and UK to form partnerships and facilitate development of the resources. This is due to the increasing demand, but also concern for supply (Becker, 2011). If such collaboration was undertaken, it would have to carefully managed in order to ensure the appropriate skills development, capacity building and wealth was distributed to the host nation and ultimately mutually beneficial.

8.3 Impact of Chinese Control of Supply and Pricing

A major and currently topical issue in the rare earth space is an ongoing trade war between the U.S. and China. Historically, during the prior REE crisis, prices increased dramatically due to China's curtailed supply to the global market. However, somewhat surprisingly, the current REE prices are unaffected in comparison (Figure 8-5).

Figure 8-5: Historical to present price chart for Nd (modified after Trading Economics, 2019)

The Nd price is represented as it is considered one of the most critical REEs. Elements such as Pr and Tb have similar price profiles. Conversely, prices for Eu, La and Ce declined post 2015 and have remained relatively low, mainly due to their oversupply in mining operations across the world. Prices have also remained relatively more stable due to the WTO intervention in 2014 as previously mentioned, but also due to China's control of the pricing (Williams, 2019). Short term price fluctuations do exist and cannot always be blamed on the current trade war. For example, in 2018, a short-term price increase was noted for Nd, Dy and Tb. Prices for these elements were comparatively low prior to the surge, and as a result, several processing plants in China held onto their stock until prices increased. This lack of supply into the market caused the prices to rise temporarily (Backeberg, 2019).

At present, there is no supply restrictions, as REOs are excluded from the $200 billion tariff list that the U.S. government has imposed on China, showing an appreciation for the China's ongoing supply dominance as well as the U.S.

dependence on said supply (Backeberg, 2019; Williams, 2019). Conversely, China has included a 25% tariff on rare earth trade as part of its tariff list, once again showing its dominance in REE supply (Backeberg, 2019).

The trade war was not specifically caused by REEs, but it has become a very large component as China is using its control of supply as leverage to win the dispute. As a result, supply concern is once again widespread amongst REE consumers. Owing to China also having the most developed downstream processes in the value chain, end-use applications are also at risk. This conflict will be a major driver for demand if it continues, creating jurisdictional scarcity as seen in 2009, or until enough global supply can be secured outside of China. It is almost certain that REE prices will begin to surge rapidly if the U.S. decides to impose tariffs on either REOs, processed materials or manufactured products as this will result in further supply curtailments.

8.4 Impacts of Recycling and Substitution on Demand

The possibility to substitute REEs has not been very successful to date. Until such a time, where viable and cost-effective substitutes are discovered, the producing REE mines and projects in development are going to become increasingly important in order to meet growing global demand. Dy and to some extent, Nd are at the most risk in terms of supply and both with rapidly growing demand. This demand, without adequate substitution will likely result in more capital expenditure for exploration in order to develop a promising project pipeline and aim to bring previously deemed uneconomic projects online (Haxel, et al., 2002).

Alternatively, if element substitution is not viable for the same application, new technology/application may be a better solution. It is worth considering that even new technology may experience supply constraints. Nevertheless, new technology could vastly reduce the dependency on highly constrained REEs in the future. The high temperature superconductor (HTS) is a good example of potential replacement technology for permanent magnets and may become a significant contender in the wind energy space. HTS technology is still in research phase but initial testing indicates it has the potential to perform better than permanent magnets, be more lightweight and cost less to produce.

If the research holds up, commercial application of HTS would alleviate the constraints of Nd and Dy supply. HTS technology incorporates Y which is not considered critical in terms of supply but is known to have clean energy applications. There is potential for HTS to encroach on permanent magnet market share, which would result in an increase in demand for Y (Zhang, et al., 2017). Additionally, much lower REE requirements are needed for HTS, with estimates of 2kg per MW, where Y will comprise between up to 0.8 kg (Wuppertal, 2014 cited in Pavel et al., 2017). According to Buchert (2011) cited in Pavel et al. (2017), if necessary, Y could be replaced by La or Ce, both of which are in oversupply.

8.5 Chapter Summary

The main drivers of demand for clean technology applications and the REEs that are required, include economic and population growth, government policy and initiatives, the impact of Chinese control of the supply chain and finally the impact of recycling and substitution. As economic growth, facilitated by population growth, occurs in developing nations, the principle of intensity of use will likely be followed. REEs are expected to play a significant role in these nation's development. REEs will be needed for power generation, motor transport and everyday product applications such as mobile phones and computers. It is expected that REEs will continue to be needed even after economic development has peaked in current developing nations. This expected, continuous demand REEs is partly due to global climate change initiatives brought about by the Paris Agreement. This responsibility will fall onto developed and developing countries alike if the agreement is to succeed. These initiatives and policies, which often revolve around increasing clean technology and reducing carbon emissions, are being implemented at city, state and national level in many countries around the world.

Current trade conflict between the USA and China is also considered a driver of demand due to uncertainty within the market. The trade war could result in a repeat of the REE supply crisis that occurred a decade ago, which will result at best in limited supply of REEs and their products to the res.t of the world.

Finally, substitution and recycling are arguably both potential opportunities to reduce global dependence on primary REEs. However, to date, substitution has not been very effective, and recycling is not expected to have a meaningful impact on supply in the short to medium run. This lack of supply, further intensifies the need for primary REEs, thus having a continuous effect on the global demand.

9 CONCLUSIONS AND RECOMMENDATIONS

Despite the name, rare earth elements are not rare. However, in geological environment, economic concentrations are rare and unevenly distributed around the globe.

The rare earth market has been plagued by issues of supply, resulting in record high prices between 2010 and 2013, as demand peaked. Economic and jurisdictional scarcity was brought on as a result of international political plays between China, Japan, the U.S. and Europe, which provoked China to reduce its supply to the rest of the world in 2009. China, effectively having a monopoly on the rare earth market, across the entire value chain, was on track for a total ban on REO exports, if it were not for the intervention of the WTO. Rare earths have become increasingly more important in high-tech applications, such as La, Ce, Nd, Eu, Dy, Y, for their use in high-powered magnets, phosphors, catalytic converters and batteries, used in clean technology and technology in general. This is considered important for ongoing environmental sustainability in most first world nations and in some developing nations. As a result, many countries have classified REEs as critical metals. By and large, the magnet technology market is expected to grow at much quicker rates than any other clean technology market, and as a result, rapidly growing for Nd and Dy. At this rate, the world may be in short supply of Dy and by 2025, with a possibility for the same outcome for Nd.

Demand for REEs in clean technology is mostly driven by two factors. Firstly, population growth and economic development of developing countries. Developing countries will still require large quantities of fossil fuels to develop, as it is substantially cheaper than renewable energy. However, in doing so will continuously be adding to the problem of greenhouse gas emissions. It is inevitable that they too will have to incorporate renewable alternatives in their energy mix, which will require growing amounts of REEs. Additionally, developed and developing countries alike are being put under increasing pressure from each other to reduce their carbon footprints and go green. This process has been spearheaded largely by developed nations, particularly in North America, Europe and Japan. Policies and initiatives developed in international settings, such as the Paris Agreement, as well as strategies outlined by individual countries, typically involve meeting specific targets in greenhouse gas reduction. This involves ambitious plans of EV deployment and establishing renewable energy programmes. Going forward, it is likely that developing nations will be among some of the largest contributors to clean energy due to their increasing population size but also may be some of the future producers of much needed REE supply, from deposits yet to be exploited. Figure 9-1 summarises the major drivers and constraints of the REE market.

This research was based on a broad market with many aspects. As part of the recommendations, future work could include a more detailed look at other clean technologies and their effects on individual REEs. It would also be valuable to address the same questions in future work, or part of an ongoing assignment in order to compare and to continuously update.

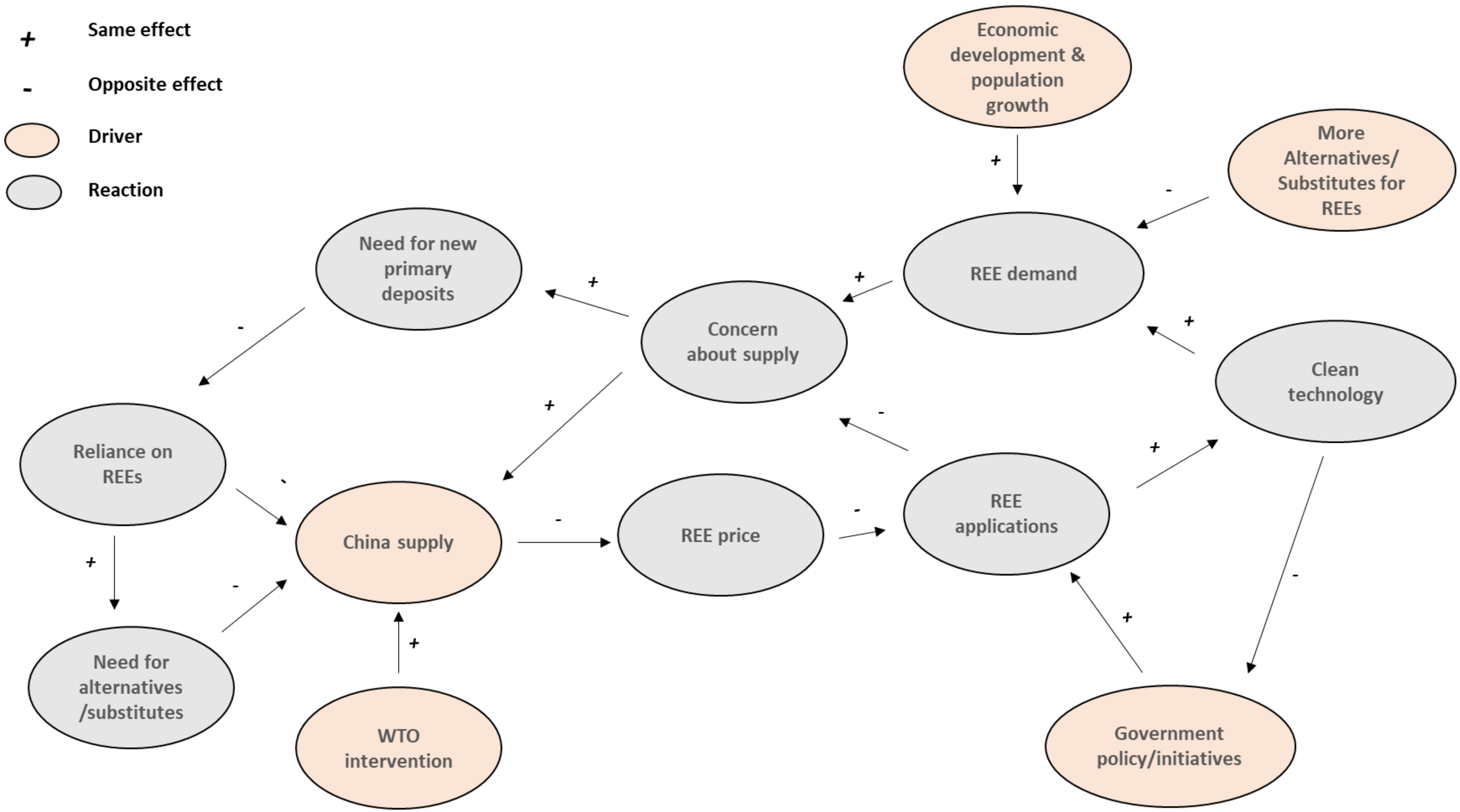

Figure 9-1: Simplified feedback model summarising the drivers and reactions of the REE market

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Appendix 1

Compilation of Resource data for current REE mines and projects in development

Company Name	Project Name	Country	Deposit Type	Status	Total Resources M+I (Million tonnes)	TREO M+I (%)	Contained TREO M+I (Mill tonnes)	Total Resources Inferred (Million tonnes)	TREO Inferred (%)	Contained TREO Inferred (Mill tonnes)
Pensana Metals	Longonjo	Angola	Carbonatite	Resource	-	-	-	240.00	1.60	3.85
Lynas Corporation	Mt Weld	Australia	Carbonatite	Mine	29.50	7.00	2.06	25.90	3.60	0.93
Northern Minerals	Browns	Australia	Hydrothermal Breccia	Mine	4.69	0.70	0.03	4.28	0.56	0.02
Alkane Resources	Dubbo	Australia	Carbonatite	Resource	42.81	0.74	-	32.37	0.74	-
Arafura Resources Ltd	Nolans	Australia	Carbonatite	Resource	34.90	3.00	-	21.00	2.30	-
Hastings Tech Metals Ltd	Yangibana	Australia	Carbonatite	Resource	12.50	1.20	-	8.40	1.09	-
Serra Verde	Serra Verde	Brazil	Ion-adsorption-clay type	Resource	390.00	0.16	-	521.00	0.10	-
MBAC Fertilizer Corp	Araxá	Brazil	Carbonatite	Mine	6.34	5.01	-	21.94	3.99	-
Rainbow Rare Earths	Gakara	Burundi	Vein	Mine	-	57.00	0.05	-	-	-
Commerce Resources Corp	Ashram	Canada	Carbonatite	Resource	29.60	1.85	-	220.00	1.88	-
Avalon Advanced Materials	Nechalacho	Canada	Alkali Igneous Rock	Resource	65.83	1.57	-	3.67	0.75	0.03
GeoMega	Montviel	Canada	Carbonatite	Resource	82.40	1.51	0.27	184.20	1.43	0.59
Canada Rare Earth Corporation	Red Wine Complex - Two Tom Deposit	Canada	Alkali Igneous Rock	Resource			-	40.64	1.25	-
Search Minerals	Foxtrot	Canada	Alkali Igneous Rock	Resource	7.39	1.09	-	1.96	1.17	-
Quest Rare Minerals Ltd	Strange Lake	Canada	Alkali Igneous Rock	Resource	278.00	0.93	-	214.00	0.85	-
Defence Metals Corp	Wicheeda	Canada	Carbonatite	Resource	-	-	-	11.37	1.96	-
MGX MINERALS INC.	Ren	Canada	Carbonatite	Resource	-	-	-	-	-	-

Bio Lantanidos	Bio Lantanides	Chile	Ion-adsorption-clay type	Resource	22.00	0.06	0.01	121.00	-	-
Greenland minerals and Energy Ltd	Kvanefjeld	Greenland	Carbonatite	Resource	451.00	1.40	5.14	559.00	1.07	6.00
Tanbreez	Tanbreez	Greenland	Alkali Igneous Rock	Resource	28.00	0.65		4000.00	0.65	30.55
Cortec Mining Limited/Pacific Wildcat Resources	Mrima ill	Kenya	Carbonatite	Resource	48.70	4.40	2.15	110.70	3.61	4.00
Tantalus Rare Earths AG	Tantalus	Madagascar	Ion-adsorption-clay type	Resource	197.70	0.19	0.18	430.00	0.09	0.38
Minbos Resources Limited	Ambato	Madagascar	Carbonatite	Resource	-	-	-	-	-	-
Mkango Resources	Songwe Hill	Malawi	Carbonatite	Resource	21.03	1.41	0.30	27.54	1.33	0.37
Lindian Resources Ltd	Kangankunde	Malawi	Carbonatite	Resource	-	-	-	2.53	4.24	0.11
Promac	Xiluvo	Mozambique	Carbonatite	Resource	1.11	2.05	0.02	-	-	0.00
Namibia Critical Metals Inc	Lofdal	Namibia	Carbonatite	Resource	2.88	0.32	0.01	3.28	0.27	0.01
Fen	Fen	Norway	Carbonatite	Resource	-	-	-	84.00	1.08	-
Acron	Veliky Novgorod	Russia	Alkali Igneous Rock	Mine	-	-	-	-	-	-
ICT Group/Rostec	Tomtor	Russia	Carbonatite	Resource	-	-	-	154.00	9.50	18.00
Solikamsk Magnesium Works	Karnasurt	Russia	Carbonatite	Mine	23.00	1.35	0.00	-	-	-
Steenkampskraal Holdings Ltd	Steenkampskraal	South Africa	Alkali Igneous Rock	Resource	0.61	14.40	0.09	0.06	10.50	0.01
Frontier Rare Earths	Zandkopsdrift	South Africa	Carbonatite	Resource	22.90	2.32	0.53	20.80	1.99	0.42
Galileo Resources Plc	Glenover	South Africa	Carbonatite	Resource	7.41	2.20	0.16	2.96	2.00	0.06
Tasman Metals	Norra Kärr	Sweden	Alkali Igneous Rock	Resource	31.11	0.61	-	-	-	-
Peak Resources	Ngualla Hill	Tanzania	Carbonatite	Resource	40.00	4.10	1.69	1.70	3.56	0.06
Montero Mining	Wigu Hill	Tanzania	Carbonatite	Resource	2.40	3.98	0.08	1.10	1.83	0.02

Rwenzori Rare Metals	Makutu	Uganda	Ion-adsorption-clay type	Resource	-	-	-	321.00	0.08	-
Rare Element Resources Ltd	Bear Lodge	USA	Carbonatite	Resource	16.30	3.05	0.50	28.90	2.58	0.74
Texas Mineral Resources	Round Top	USA	Rhyolite	Resource	0.30	0.05	0.48	0.22	0.05	0.34
MP Materials	Mountain Pass	USA	Carbonatite	Mine	16.71	0.08	1.33	-	-	-
Ucore Rare Metals	Bokan Mountain	USA	Vein	Resource	4.79	0.60	0.03	1.05	0.60	0.01
Total					**1921.91**		**15.11**	**7180.56**		**62.64**

Sources: The MSA Group (2010); AMEC (2011); Daigle (2012); Avalon Rare Metals Inc (2013); Clay and Ackroyd (2013); Hulse et al. (2013); Pollard and Mapleson (2013); Dahlberg (2014); Mineracao Serra Verde (2015); Short et al. (2015); Acron, (2016); Harmer and Nex (2016); Masun et al. (2016); The MSA Group (2016); Alkane Resources Ltd (2017); Arafura Resources Limited (2017); Commerce Resources Corp (2017); Zhou et al. (2017); BioLantanidos Minera (2018); Hastings Technology Metals Ltd (2018); Lynascorp (2018); Morelli (2018); Roskill (2018); Steenkampskraal Holdings Ltd (2018); GeoMega Rare Earths (2019); Minbos Resources Limited (2019); Namibia Critical Metals Inc (2019); Northern Minerals (2019); Pensana Metals (2019); The MSA Group, (2019); Opaxe (2020)