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Review

Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies

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Abstract: Rare earth elements (REE) are widely used in high technologies, medical devices, and military defense systems, and are especially indispensable in emerging clean energy. Along with the growing market of green energy in the next decades, global demand for REE will increase continuously, which will put great pressure on the current REE supply chain. The global REE production is currently mainly concentrated in China and Australia; they respectively contributed 85% and 10% in 2016. However, there are 178 deposits widely distributed in the world, and reported REE resources as of 2017 totaled 478 megaton (Mt) rare earth oxides (REO); 58% of these deposits contained exceed 0.1 Mt REO; 59 deposits have been technically assessed. These resources could sustain the global REE production at the current pace for more than a hundred years. It is noted that REE demand from clean technologies will reach 51.9 thousand metric tons (kt) REO in 2030, Nd and Dy, respectively, comprising 75% and 9%, while these two elements comprise 15% and 0.52% of the global REE resources, respectively. This indicates that Nd and Dy will strongly influence the development of exploring new REE projects and clean technologies in the next decades.

Keywords: global rare earth resources; rare earth demand; clean technologies

1. Introduction

Rare earth elements (REE) were first discovered in 1788. However, global annual REE production and consumption was less than 5000 metric tons of rare earth oxides (REO) before the 1950s and, until the 1960s, they were even rarely used in our daily life [1]. Since the 1960s, rare earth applications gradually have expanded to everyday life, such as television screens, the petroleum industry, and computer systems; therefore, the global REE production and consumption have seen a significant increase in the following decades (Figure 1). REE are now widely used in auto- and fluid catalysts, metallurgy, medical systems, high technology, clean energy, and military defense systems, and they are especially indispensable in emerging clean technologies, such as wind power turbines, electric vehicles, energy-efficient lighting, and catalytic converters [2,3]. The total value of worldwide products containing REE is at least $1.5–2 trillion US dollars (US$), which comprised nearly 5% of the global total gross national product in 2009 [4]. A significant shift from traditional energy sources towards clean energy, such as electric vehicles, is occurring; wind turbines are becoming recognized on a global scale. This transition will lead to a continuous increase in demand for REE in the coming decades [2,5,6], and such an increasing demand puts forward a higher request for global production of REE, and requires a steady supply chain in the long run.

The International Union of Pure and Applied Chemistry defines REE as a group of 17 elements comprising the 15 elements in the lanthanide group, plus scandium and yttrium [7]. Based on the structure of electron shell, REE are typically subdivided into light rare earth elements (LREE) and heavy rare earth elements (HREE). However, there is no unified classification on which element is LREE or HREE. According to U.S. Geological Survey (USGS), lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, and gadolinium are LREEs, while terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium constitute HREEs [8,9]. Due to similar properties, scandium and yttrium are generally considered as REE, while yttrium is classified as a HREE since it shares similar properties with other elements belonging to HREEs. Scandium does not belong to LREE or HREE because it is not extracted from the same deposits as other REEs, and Pm is rarely found in nature; therefore, they will not be further discussed in this paper. In addition, a third classification is sometimes added into LREEs and HREEs: middle rare earth elements (MREEs) [10–12].

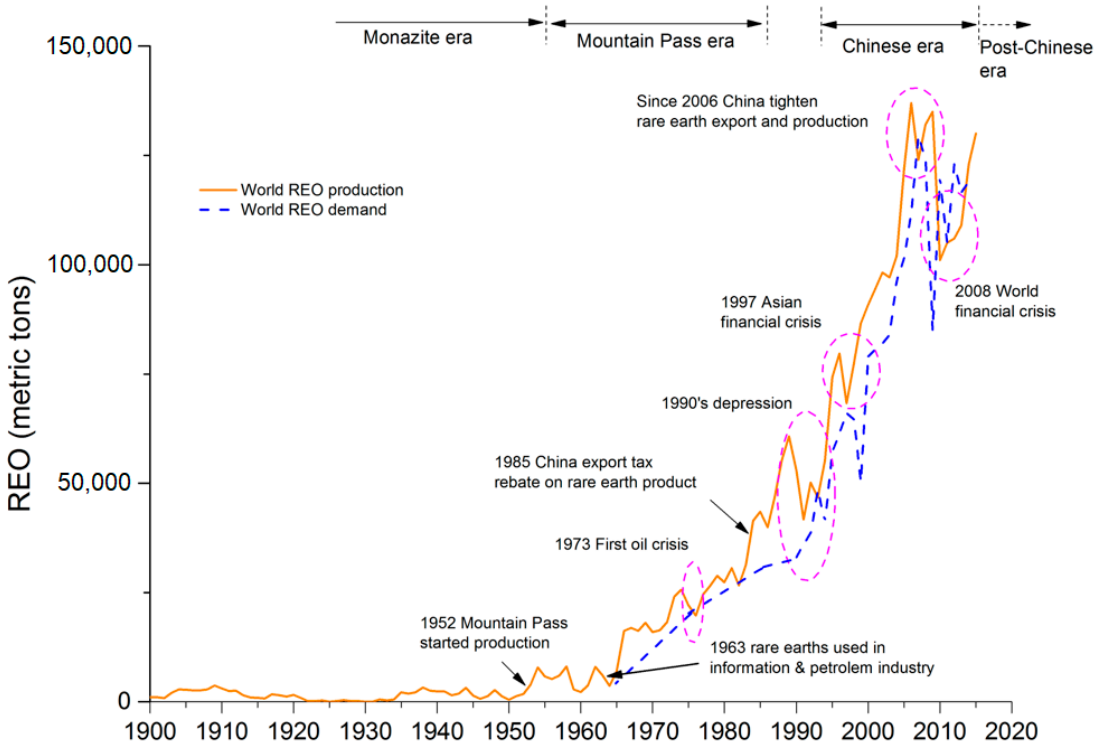

Figure 1. Global rare earth production and demand, the data obtained from [13–16].

REE are relatively abundant in the upper part of the Earth's crust; the crustal abundance of Ce and La are, respectively, 63 ppm and 31 ppm, which are the most abundant of the REEs and more abundant than the average crustal concentrations of Cu (28 ppm) and Pb (17 ppm), while Tm and Lu are, respectively, 0.30 ppm and 0.31 ppm, which are the rarest of the REEs, but still more abundant than precious metals Au (0.0015 ppm), Ag (0.053 ppm), and platinum group elements [17]. The total crustal abundance of REE is 169 ppm, and LREEs (La to Gd) are 137.8 ppm, far higher than HREEs (31.34 ppm). However, the abundance of a particular element in the geosphere does not always mean ease of exploitation. The feasibility of exploitation usually depends on the geology, grade, tonnage, available processing technologies, costs, and associated environmental issues. The REE are generally not concentrated in economic viable quantities, and having similar ionic radii make them difficult to extract and recover cost-effectively. In addition, the most trivalent REE have similar ionic radii to Ca^{2+}, Th^{4+}, and U^{4+}, and the REE minerals are, therefore, normally associated with Ca, Th, and U, making the exploitation of REE deposits full of environmental issues. Global REE production, thus, is mainly carried out in several countries.

The global production of REE was 126,000 metric tons of REO in 2016 (Figure 2), which was mainly comprised of China (85%) and Australia (10%), and the remainder distributed among Malaysia, Brazil, India, Russia, and Vietnam. In addition, considerable illegal production is carried out mainly in Southern China. Though no uniform pattern can be presented, the illegal production is estimated to reach 20% of the legal production in China [18]. Currently, more than 200 REE-bearing minerals have been identified [19,20]; however, most of the global REE production currently comes from four minerals: bastnäsite, monazite, xenotime, and loparite [9]. Bastnäsite in China constitutes the largest percentage of global REE production, followed by monazite in Australia and India, loparite in Russia, and xenotime in Malaysia. These rare earth-bearing minerals are mainly associated with igneous rock (alkaline rocks and carbonatites); additionally, other economically-viable REE minerals are also found in placer deposits, pegmatites, iron-oxide copper-gold (IOCG), marine phosphates, and residual deposits from deep weathering of igneous rock [21]. In these minerals, LREEs constitute the largest segment, while HREEs are currently mainly extracted from ion adsorption clay in Southern China, especially the illegal production, which is also mainly concentrated in this region.

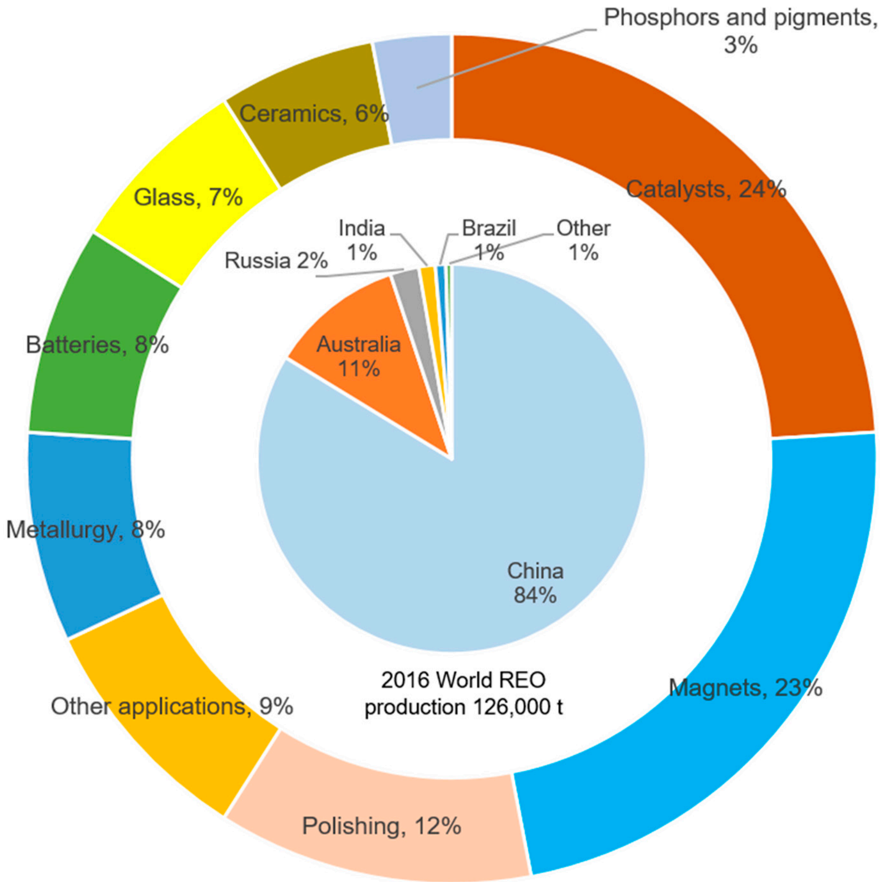

Figure 2. The distribution of global rare earth production and consumption in 2015, the consumption data obtained from [16], the production data adapted from [22].

REEs have excellent electronic, optic, catalytic, and magnetic properties that provide solutions for many challenges of modern technology, making them useful for a wide range of applications. Though there are no uniform classifications for rare earth applications, the REE markets are commonly divided into nine sectors: catalysts, polishing, glass, phosphors and pigments, metallurgy, batteries, magnets, ceramics, and others [23–26]. Global REE consumption was estimated at 119,650 metric tons of REO in 2015, with catalysts being the largest segment, followed by magnets, polishing, and others (Figure 2). The annual growth rate of global REE demand is expected to increase by 5% by 2020, and global demand for REE would continue to maintain growth for a long time along with the increasing growth market of clean energy [2]. Such increasing demand creates great pressure, as well as a challenge to the global supply chain of REE. This paper aims to evaluate the global potential of rare earth resources, highlight the economic value for current advanced rare earth projects, and analyze the global demand for REE from clean energy technologies in the mid and long term (2016–2030), thus providing a basis for the quantitative analysis of the opportunities, challenges, and constraints to the global REE supply chain and demand in the future.

2. Methodology

2.1. Identification of Global Rare Earth Resources

Currently, global REE are mainly extracted from deposits in China and Australia. The REE price hike and potential supply shortage have attracted wide concerns of global investors; many rare earth deposits worldwide, therefore, have got explored and/or assessed (presented in supplementary information Table S1). However, the success of these projects depends on many factors such as geological minerals, rare earth grade, individual REE distribution, and economic value of raw ore and related products.

Understanding the geological types of rare earth deposits is crucial for assessing the exploring deposits and determining the feasibility of mining operations, processing, and refining [27]. Existing rare earth mines, and potential future deposits, are situated where the geological processes have concentrated the REE grade significantly above the crustal average; enrichment of the REE may occur through two geological processes: primary processes, such as magmatic and hydrothermal, and secondary processes such as weathering and sedimentary transport. Rare earth deposits can, therefore, be divided into primary and secondary deposit types. Primary rare earth deposits are typically associated with alkaline-peralkaline igneous rocks and carbonatites. Erosion or weathering of primary types may produce deposits, such as placer and ion adsorption deposits [20]. In this paper, based on the USGS classification [21,28,29], we split rare earth deposit types into carbonatite, alkaline igneous rock, placer, ion adsorption, iron-oxide copper-gold (IOCG) deposits, and others. In general, rare earth deposits associated with alkaline igneous rocks are of rather low grade, but may exist in large tonnage and relatively enriched in the HREE, such as Lovozero in Russia (containing 6.6 megaton (Mt) REO at 1.12%) [30]. The carbonatite-associated deposits are currently the main sources of global REE production; Mountain Pass in California, USA, Mount Weld in Western Australia, Australia, and Bayan Obo in Inner Mongolia, China are typical carbonatite rare earth deposits, however, which are mainly dominated by LREE. Placer rare earth deposits usually form in rivers, beach and shallow marine environments, and typical placer production is currently proceeding in India and Malaysia; however, placer deposits are usually associated with high content of radioactive elements (e.g., Th, U). Ion adsorption deposits are mainly located in southern China, although they are low-grade, easily mined, and contain high content of the more valuable HREE. IOCG may contain REE enrichments, and it has the potential to produce REE as a by-product, but recovering REE from this deposit is very difficult and costly.

Except for identifying the deposit mineralogy, REE-distribution is critical to the economic value of REE-deposit. A wide range of parameters can be used to evaluate the potential feasibility of a rare earth project: tonnage (million metric tons), ore grade (%), individual REE distribution (%), ore value (US$/t), and basket price (US$/t). Tonnage is the most important parameter to evaluate the economic feasibility of an REE-deposit; in this paper, the tonnage above 0.1 million metric tons of REO is recognized a medium size deposit, which represents more than 20 years of continuous operations at a rate of 5000 metric tons per annum REO, while tonnage exceeding 1 megaton (Mt) REO is considered as a large size deposit, and the rare earth resources of current operation deposit almost all exceed 1 Mt REO. Ore grade means the total rare earth oxides (TREO) of one unit of ore, and high ore grade typically represents the high potential economic value of a deposit. An individual REE distribution is based on the individual REE as a fraction of TREE, expressed as REE/TREE-%. Ore value, meaning TREO-value per unit mass of mineral resource (US$/t), reflects the in situ value of the ore material, considering the ore grade but not the tonnage and the recovery of the ore. Basket price represents the potential price if the TREO is extracted from the ore, not considering the ore grade and the total recovery rates.

2.2. Rare Earths in Clean Technologies

REEs play an important role in emerging clean technologies, such as wind turbines, electric cars, energy-effective lighting, and rechargeable batteries; with the transformation of global energy system towards a more sustainable and renewable one, these clean technologies are predicted to grow significantly in the next decades. However, given the different development tendency in these technologies, individual REE demand differs in these sectors; combining this with the disequilibrium of different REE distribution in natural resources, there is an urgent need to project the tendency for different sector and REE demand for these technologies.

According to U.S. Department of Energy, these sectors include electric vehicles, wind turbines, batteries, and energy-saving lighting. In addition, catalytic converters are also considered as a clean technology in our study. Average rare earth volume for individual sectors is mainly based on the information published by the U.S. Department of Energy [2], and it will be described in the following text. We have developed four different future demand scenarios for these above five fields; by elaborating scenarios for these sectors, rare earth demand from clean energies are analyzed on four horizons: 2016, 2020, 2025, and 2030.

In order to estimate the requirement of REE using this present state of four technologies in 2016/2020/2025/2030 situation, eight market scenarios regarding five technologies markets are predicted, including wind power, linear fluorescent lamps (LFLs), compact fluorescent lamps (CFLs), light-emitting diode (LED), electric vehicles (EV), electric bicycles, NiMH batteries, and catalytic converter. The annual installation wind power is expected to increase from 63,360 MW in 2015 to 107,488 WM in 2030 at the moderate scenario, and offshore wind turbines were installed at about 3400 MW in 2015, accounting for 5.3% of the total wind turbines [31] (we have assumed that the market share of offshore wind turbines will increase 5% every 5 years along with the recent drop in offshore price, and 40% of offshore and 50% of onshore wind turbines will use the permanent magnets [2]). The annual new installation for LFL, CFL, and LED is, respectively, expected to be 2142, 2903, and 2675 million cps in 2016 [32]. While the LFL and CFL will decrease to 1447 and 1604 million cps in 2020, the LED will increase to 4828 million cps in 2020 [32]. According to above historic data, we have assumed that LFL and CFL will respectively decease at 22% and 7% per annual rate, and the LED will increase at 4% per annual rate until 2030. Electric bicycles sales were about 35 million units in 2016, and this is projected to grow at a 0.4% compound annual growth rate between 2016 and 2025 [33]. The registration of new electric cars was over 750 thousand in 2016, and a collective aspirational goal is set, which is that the EV market share of all EV members will reach 30% by 2030 [34]; we have assumed that the electric cars will increase at least 30% per annul until 2030, and 100% of electric cars and 70% of electric bicycles will use permanent magnets. The market share of NiMH batteries in hybrid electric vehicle (HEV) will decrease from 85% in 2016 to 65% in 2020 and to 10% in 2025 [35], and HEV accounted for about 90% of total electric cars in 2016; we have assumed that the market share of NiMH batteries in HEV will also be 10% in 2030. The international automobile production was 99 million in 2016, and it will increase to 100 million in 2020, and 108 million in 2023 [36]; we have assumed that it will increase to 112 million in 2025 and 117 million in 2030. Table 1 presents an overview.

Table 1. Overview of global clean technologies demand at 2016/20/25/30.

Year	Wind Power (MW)	Lighting			Electric Vehicles		Batteries	Catalytic Converter
		LFL	CFL	LED	Electric Cars	Electric Bicycles	NiMH Batteries	
		(Million Cps)			(Car)		(Battery)	(Million Cars)
2016	63,350	2142	2903	2675	750,000	35,000,000	580,125	95
2020	79,005	1604	1491	4828	2,140,0000	35,500,000	1,251,900	100
2025	76,810	1116	662	5874	7,953,375	36,200,000	715,803	111
2030	107,488	776	294	7146	29,530,323	37,000,000	2,657,729	117

3. Results and Discussion

3.1. Global Potential of Rare Earth Resources

The steps involved in developing a REE deposit can divided into three main stages: from the discovery of the resource, through exploration, and, finally, to a production mine. There are about 851 rare earth deposits all over the world that have been discovered or reported, but most of them remain at the first step: the discovery of the occurrence of the resource, while the tonnage and ore grade of these deposits have not been identified; only a small part of these deposits have sufficient geology exploration, and just several deposits have gone into the production stage [28]. The rare earth supply disruption in 2010 promoted companies and governments to explore the global rare earth resources and, consequently, many new deposits have been discovered and explored in this process. As of 2017, 178 deposits and occurrences containing REE have been identified and developed, and 59 REE projects have conducted feasibility studies to the advanced stage or gone into production. Some of these deposits could become new REE suppliers in the future, alleviating the REE supply and demand, which is contradictory.

Based on published and reported data, the total amount of global REE resources is 478 Mt REO, located in China (164 Mt), Brazil (55 Mt), Australia (49 Mt), Russia (48 Mt), and Greenland (43 Mt), with the remaining 119 Mt spread in Canada, Sweden, USA, Vietnam, and others (Figure 3). These resources could supply the global REE at the current production rate (130 kt REO) over hundred years. Global REE resources are mainly concentrated in some large size REE deposits or regions, such as Bayan Obo in China, Morro dos Seis Lagos in Brazil, Tanbreez in Greenland, and Lovozero in Russia. In terms of principle deposit types, the majority of the current global REE resources are dominated by carbonatite, which contains 297.6 Mt REO within 66 deposits, constituting 62% of the total resources. In addition, a further 76.9, 74.1, 22.9, and 2.9 Mt REO are hosted by alkaline igneous, IOCG, placer, and ion adsorption types, with an additional 3.7 Mt in other types. In contrast to major deposit types, major REE mineralogy in these deposits is lacking sufficient data to identify, since most of these deposits usually consist of more than one REE mineral, and further exploitation of these deposits has not been started. Additionally, it should be noted that REE resources, as opposed to REE reserves, have not have demonstrated economic viability. Reserves could be economically extracted or produced at the time of determination, while resources are merely an indication of potential economic feasibility, and the global REE resources, therefore, are substantially higher than figures published by the USGS [22] (126 Mt REO).

About 27% of these deposits have REO ore grades <0.2%; 55% of projects have REO ore grades <1%, and only 5% of deposits have REO concentrations >10%. While almost all of the current REE deposits in production have REO ore grades >1%, such as 8.8% in the Mount Weld central lanthanide deposit (CLD), 5% in Bayan Obo, and 1.12% in Levozero, about 42% of these deposits are below the medium size, and 76% contain <1 Mt REO. While 5% contain >10 Mt REO, these giant deposits need to be further exploited and developed in the future. Cumulative frequency curves for ore grade (%) and REE tonnages are presented in Figures 4 and 5. In terms of these two factors, global REE resources are currently dominated by low grade (<1%) and low size (<0.1 Mt) carbonatite deposits, which, therefore, mainly consist of LREE; this is the main challenge of the future global REE supply chain. In addition, hazardous impurities in these deposits also deserve serious consideration when exploited as an REE deposit.

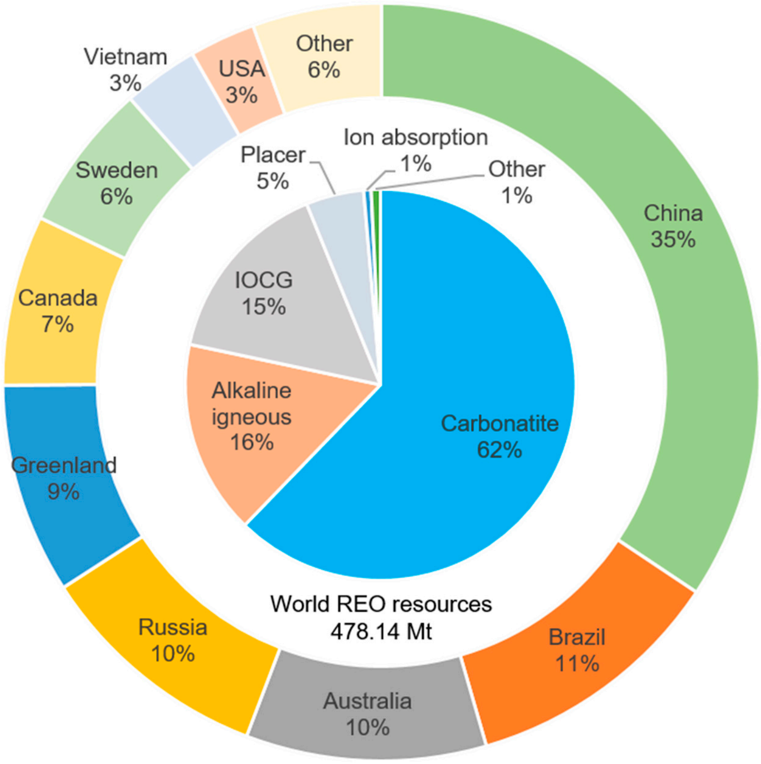

Figure 3. The distribution of global rare earth resources by principle deposit type and country.

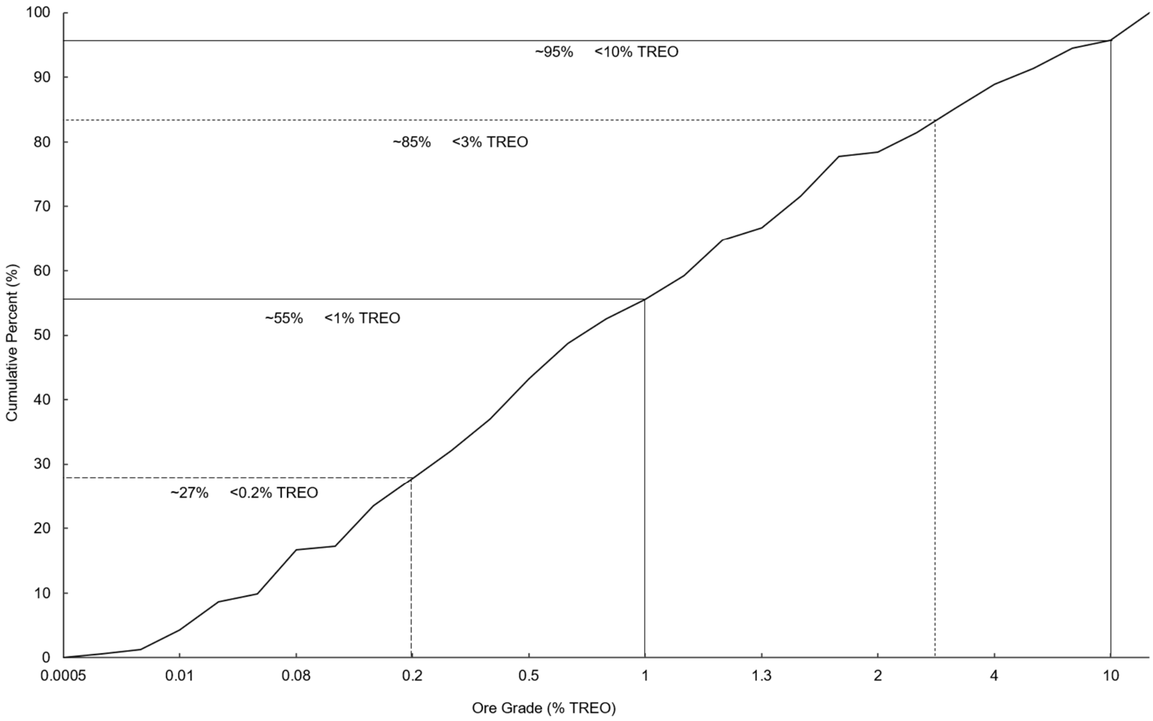

Figure 4. Cumulative frequency curves for the ore grade.

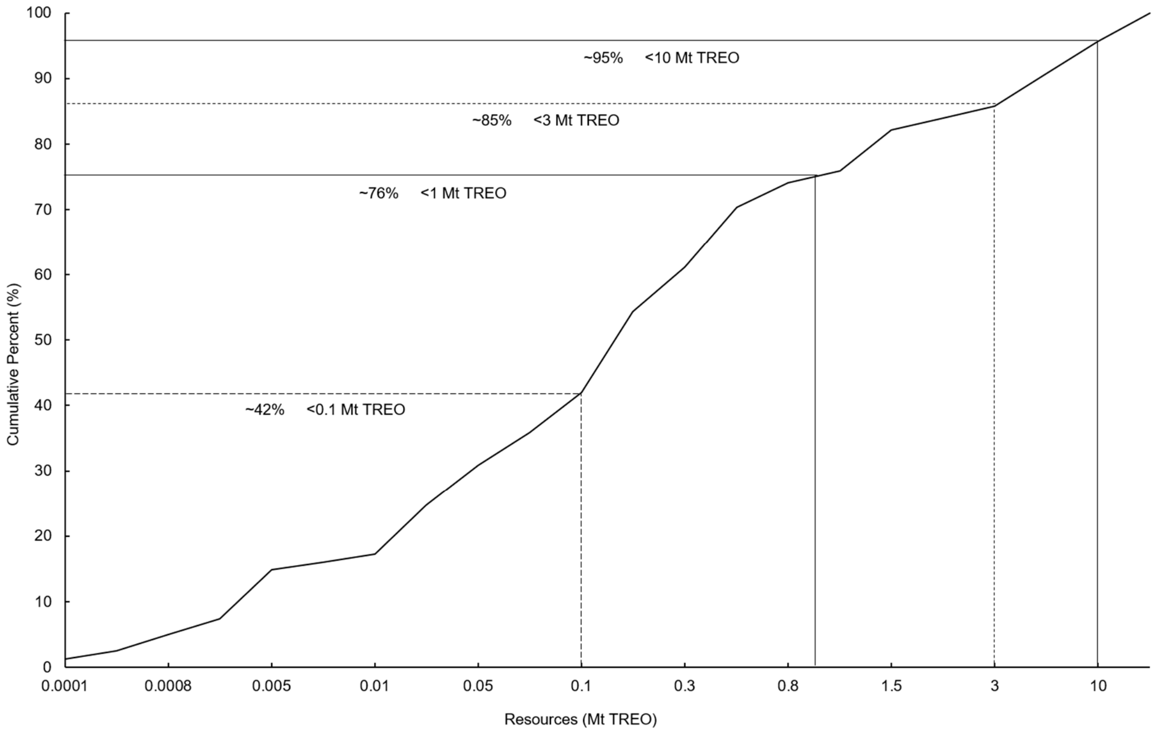

Figure 5. Cumulative frequency curves for the contained total rare earth elements (REE) resources.

At present, since most of these deposits remain in the first stage, the individual REE concentration data, therefore, are not available for all of these deposits. However, 59 REE deposits out of the 178 deposits have reached an advanced stage (being explored or being technically and/or economically assessed), and their REE distribution have been reported in the literatures to date, of which 10 projects have been in operation. The code-compliant resources of the 59 REE deposits is 276 Mt REO, accounting for 58% of the total resources of 178 deposits (Figure 6). Ce is the most abundant REE (~130 Mt), followed by La (~68 Mt), Nd (~43 Mt), Pr (~13 Mt), and Y (~9 Mt). The LREE are more abundant than HREE overall, and the ratio of LREE to HREE is 18:1, besides, the volume of Y constitutes of 62% of the entire HREE resources, further indicating the nature of the scarcity of HREE like Dy, Tb, Eu, and Lu. In terms of market value, the total REO value of these 59 projects is about $3.24 trillion US dollars (22.35 trillion CNY). Based on REO market prices in China in December 2016, the market value of LREE and HREE, respectively, constitutes 62.5% and 37.5% of the total. In the LREE resources, Pr and Nd are the most two precious, and their value constitutes 77% of the total LREE market value. For the HREE resources, Dy, Yb, and Y are the three most prevalent, and their value contributes to 96.7% of the total HREE market value; although the volume of Y constitutes the largest segment of HREE resources, its market value just contributes to 23.4% of the total HREE market value. Dy is the most valuable element in all REEs.

The ore grade and tonnage of advanced stage REE-deposits have shown in Figure 7. In terms of these two factors, most of current REE deposits in production stage have a relative higher ore grade (1–10%) and tonnage (>1 Mt) of TREO; this in turn indicates that about half of the advanced REE deposits could not go into the last stage-production mine. However, ore grade and tonnage are not the only decisive factors for the success of an REE project. Although containing low grade and tonnage, REE deposits abundant in HREE still have high economic value to exploit (Figure 8), such as Longnan, Xinfeng, and Xunwu in Southern China; they have a higher basket price than about 80% of total deposits even though their ore value is low. The ore grade, tonnage, REO-basket value, and REO-ore value are the most important considerations in the exploration or development of a new REE project, directly determining the success or failure of an REE project to a certain extent.

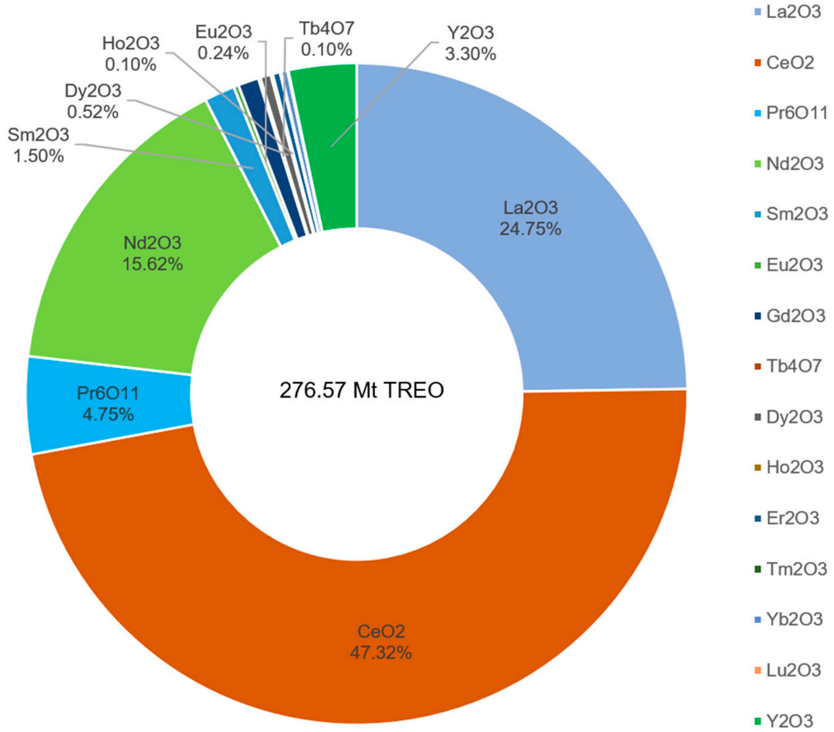

Figure 6. Code-compliant rare earth resources for 59 advanced-stage REE deposits (as of January 2017).

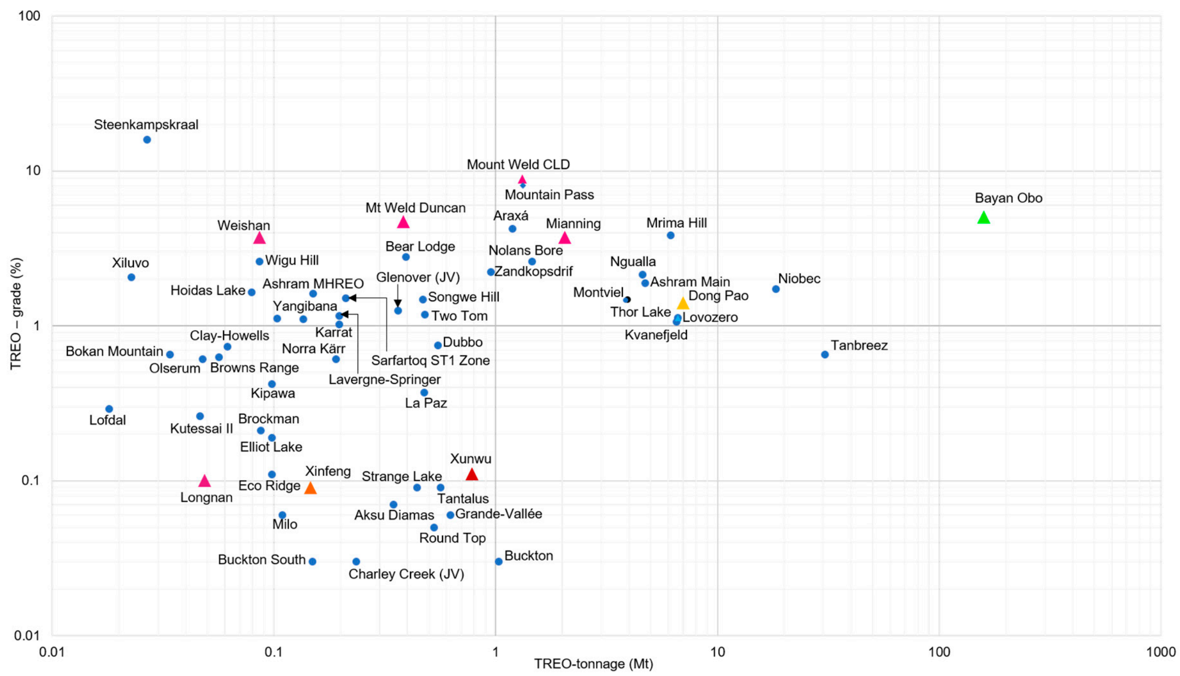

Figure 7. The ore grade and tonnage for advanced stage REE deposits.

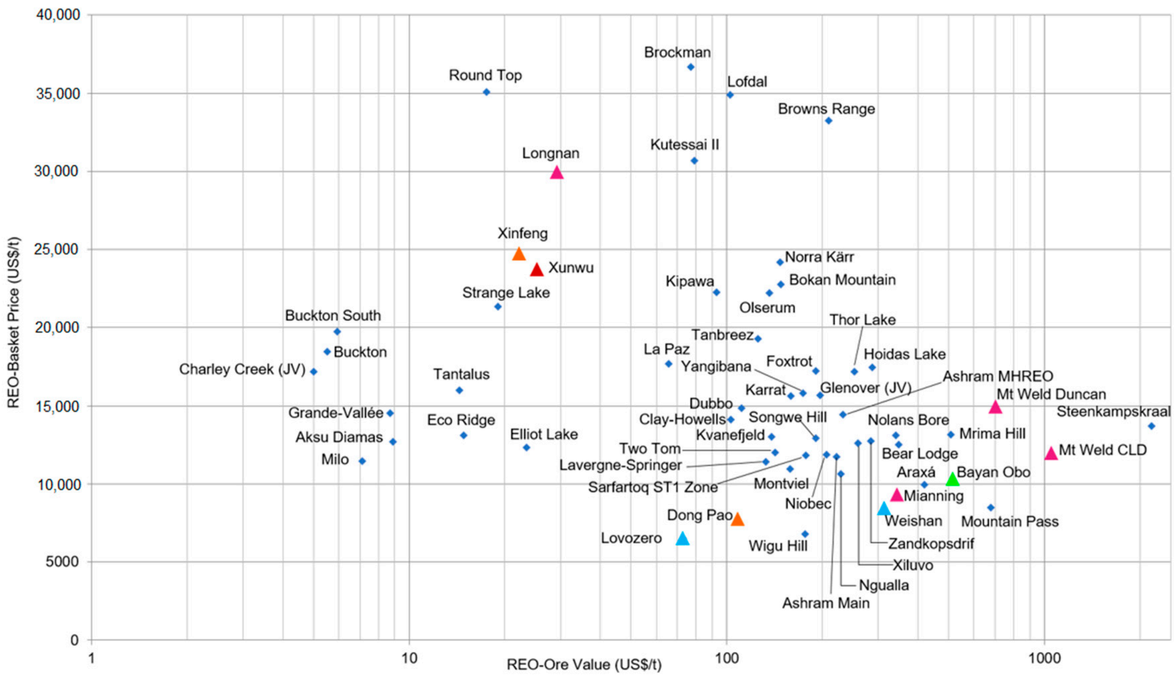

Figure 8. The ore value and basket price for advanced stage REE deposits.

For polymetallic deposits containing REE, the situation will become more complicated. Except for the factors mentioned, the value of diversity of co- and by-product elements (e.g., Fe, Nb, Hf, and Ta) associated with REE deposits and available economic recovery methods also plays an important role in the success of developing polymetallic deposits. For example, REE are extracted as an important by-product of iron production in Bayan Obo and niobium production in Lovozero at present, while REE were not extracted from the Olympic Dam deposits, even though it contains a large amount of REO and iron production is underway.

3.2. Rare Earth Demand from Clean Technologies

The growth of global primary energy will increase to an average of 1.3% per annum by 2035; fossil fuels remain the dominant source of energy, accounting for more than three-quarters of total energy supplies in 2035, and renewable energy is the fastest growing source of energy; its share in primary energy will increase to ~10% by 2035 [37]. Along with the growing demand for green power generation and energy saving technologies, REE applications used in permanent magnets in wind turbines and energy-efficient lighting are important applications of REE in the coming years. Meanwhile, electric vehicles, NiMH batteries, and catalytic converters will contribute to limiting climate-changing greenhouse gas emissions; the REE demand, therefore, will continuously increase with the growing market of these clean energies. However, the demand will not grow uniformly for every individual REE. The average volume of individual REE used in every application is shown in Table 2, and the global demand for REE from clean technologies is shown in Figure 9.

Table 2. The average volume of individual REE for clean technologies.

Application	La (kg)	Ce (kg)	Nd (kg)	Eu (kg)	Tb (kg)	Dy (kg)	Y (kg)
Wind turbines (/WM)			120			12	
Electric vehicles (/motor)			0.45			0.075	
Electric bicycles (/motor)			0.038			0.031	
NiMH battery (/battery)	0.61	0.86	0.255				
CFL (/bulb)	0.0000765	0.00018		0.0000405	0.000045		0.000558
LFL (/bulb)	0.000462	0.000137		0.0000945	0.000105		0.0013
LED (/bulb)				0.0000004			0.000005
Catalytic converter (/auto)		0.02					

Sources: US DOE [2], Ku et al. [38].

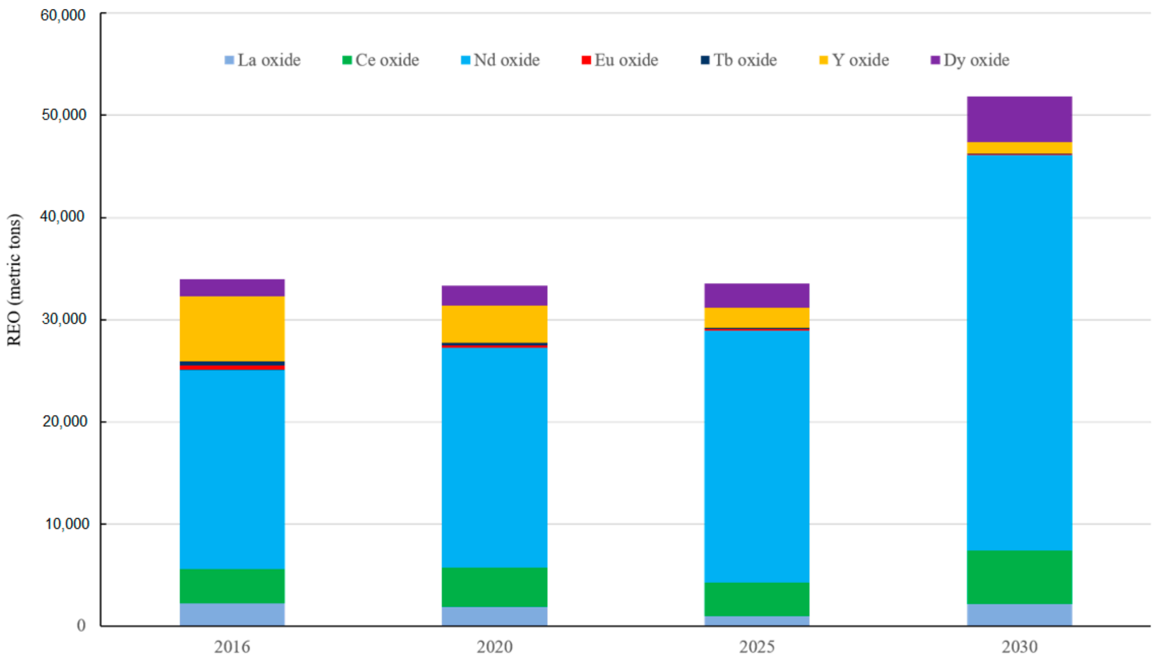

Figure 9. Global demand for REO from clean technologies in 2016, 2020, 2025, and 2030.

REE demand for clean technologies in 2016, 2020, 2025, and 2030 is expected to reach 33.9, 33.3, 33.6, and 51.9 kt REO, respectively. With the growing market for LED, CFL and LFL lighting will lose market share over the next decade; thus, REE demand for CFL and LFL will decrease correspondingly. The share of REO demand from lighting in totally clean markets is expected to decrease from 29.2% in 2016 to 3.2% in 2030, and the demand for Eu, Tb, and Y oxides for lighting in 2030 will decrease to 16.6%, 16.4%, and 17.2% of 2016 level, respectively. By contrast, the market for wind power, electric vehicles, NiMH batteries, and catalytic converters will face continuous growth to a different degree. The share of REO demand from wind power, electric vehicles, and NiMH batteries in total clean technologies is expected to increase from 11.6%, 50.1%, and 3.4% in 2016 to 13.4%, 68.5%, and 10.3% in 2030, but the demand for Nd and Dy oxides from these three fields in 2030 will increase to 199.2% and 268.3% of 2016 level. This indicates that Nd and Dy oxides will play an increasingly more important role in the development of clean energy in the future, while the importance of Eu and Tb oxides will decrease (this could relieve the current crisis of HREE resource scarcity to a certain degree).

In order to predict future trends in REE production and demand, two primary scenarios were used in our study: (1) a conservative scenario of 3% annual growth rate for REE production [27]; and (2) an optimistic scenario of 5% annual growth rate for REE production [26]. Both 3% and 5% growth scenarios for REE production are presented in Table 3. Nd is the most important raw material for permanent magnets, and this element will not meet the growing demand from clean technologies under the conservative scenario, but it could meet the demand under the optimistic scenario. Eu, Tb, and Y will be in surplus over the next decades, even under the conservative scenario. However, Dy will be in deficit in both of two scenarios: the production of this element could, respectively, supply about 50% to 70% of demand from clean technologies in 2030 under two different scenarios. Nd and Dy will be the critical materials for clean technologies during the next decades, and they will largely decide the success of the exploration of a new REE project, while for the REE market, the unequal supply and demand for individual REE will be clearer in the next decades.

Table 3. Global REE production at 3% and 5% annual growth rate.

Scenario	Year	Nd	Eu	Tb	Dy	TREO
Current	2012	21,669	367	348	1362	131,100
3% annual growth rate	2020	27,449	464	440	1725	166,073
	2025	31,821	538	511	2000	192,524
	2030	36,890	624	592	2318	223,189
5% annual growth rate	2020	32,014	542	514	2012	193,694
	2025	40,860	692	656	2568	247,208
	2030	52,149	883	837	3277	315,507

Sources: REE production data in 2012 from EC [39].

4. Conclusions

Global REE mineral resources, totaling 478 Mt REO, mainly are represented in carbonatite and distributed in China, Brazil, Australia, and Canada, in which 42% of REE deposits are from medium-sized mines (resources <0.1 Mt REO), although 85% of REE deposits have REO concentrations <3%. The REE resources already produced and technically assessed are 276 Mt REO, with an average of LREE (La to Gd) to HREE (Tb to Lu) ratio of 18:1; however, the market value of LREE and HREE, respectively, constitute 62.5% and 37.5% of the total REE market value. The data presented in this paper indicate that current total REE resources are sufficient to meet the global REE production at a current rate over hundred years. The REE demand for clean technologies will descend first and then ascend. REE demand from clean technologies will reach 50 kt REO in 2030; however, it will decrease from 33 kt in 2016 to 32 kt in 2020, then increase to 34 kt in 2025. The REE demand from the lighting market is expected to decrease continuously, while the REE demand from wind turbines, electric vehicles, and NiMH batteries is expected to continue to increase. For individual REE, Eu, Tb, and Y will be in surplus with the global lighting market shrinking during the next decade, and Nd and Dy will face critical supply conditions (especially, Dy will be in shortage even under the optimistic scenario (5% annual growth rate of production)).

The unequal demand for individual REE puts uncertainties and constraints on the exploration of new REE projects, since the distribution of individual REE are not consistent with the demand for individual REE. Although Nd and Dy are expected to be in shortage, the other REE are expected to be in surplus; this indicates that the prices of most of REE will decrease; the exploration of new REE deposits is not profitable in the long run. In this sense, how to solve the unbalanced demand and supply for individual REE will be the key factor in the success of new global REE projects and the development of clean technologies. Developing REE recycling techniques from end-of-life products and substitution technologies in critical REE is likely to be an effective method in solving this imbalance problem.

Supplementary Materials: Additional information on global rare earth deposits is available online at www.mdpi.com/2075-163X/7/11/203/s1, Table S1: Global rare earth deposits.

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