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Rare Earth Elements: dynamics in the global market

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Introduction

The rare earth elements are a particular type of minerals that over the years have assumed an extremely important strategic and economic importance. They are used in various fields of application, from the most advanced technologies such as hybrid cars and permanent magnets to the mobile phones we use every day. Their importance has increased by leaps and bounds since major political players have decided to follow a green economy globally. In fact, these particular materials are used for example in essential applications for clean energy production such as wind turbines.

However, contrary to what their name may imply, rare earths are not so rare. According to some estimates, gold is much more difficult to find on the market compared to these minerals. What makes them so valuable is their concentration because their presence must be sufficient to justify the extraction costs.

In addition, the environmental burden resulting from the extraction of these minerals must be taken into account. The impact that these mostly polluting procedures have is to be counted among the costs. For this reason, in Western countries such as Europe these practices are no longer considered feasible, thus leaving room for China to impose itself as the world's largest exporter to the point of creating almost a monopolistic market. This has obviously had repercussions not only in the economic sphere but also in the diplomatic one, since China, willing to live with the costs and negative impact of extractions, uses this predominant position against other countries. By directly controlling prices, the Asian giant has the opportunity to manage and preserve its reserves.

This aspect has stimulated the search for alternative ways such as recycling and the replacement of used materials by countries such as the USA, Europe and Japan, which are trying to counter the Chinese monopoly by looking for a way to become independent.

This thesis therefore wants to analyse the birth and evolution of the rare earth market, with a focus on their main applications. Specifically, the Chinese market and the relations with its major competitors and consumers, including the United States, Japan and

European Union, will be assessed. The issue of the balance problem, i.e. the relationship between demand and unbalanced supply, will therefore be dealt with, also considering the alternative paths that certain countries are trying to follow, such as recycling. Finally, a space will be dedicated to the analysis of the environmental impact that extraction practices have.

1. Rare Earth Overview

1.1 Rare Earth Element definition

According to the definition proposed by the International Union of Pure and Applied Chemistry (IUPAC), the "rare earth" nomenclature identifies a specific group of 17 chemical elements belonging to the periodic table which includes the lanthanides, scandium (Sc) and yttrium (Y). The latter two elements are considered part of the rare earth group since they are in the same deposits and share some of the chemical characteristics of the other elements (Balaram, 2019). The list of Lanthanides includes 15 elements with atomic numbers between 57 and 71: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu) (UNCTAD, 2014). Conventionally all elements are called Rare Earth Elements (REEs).

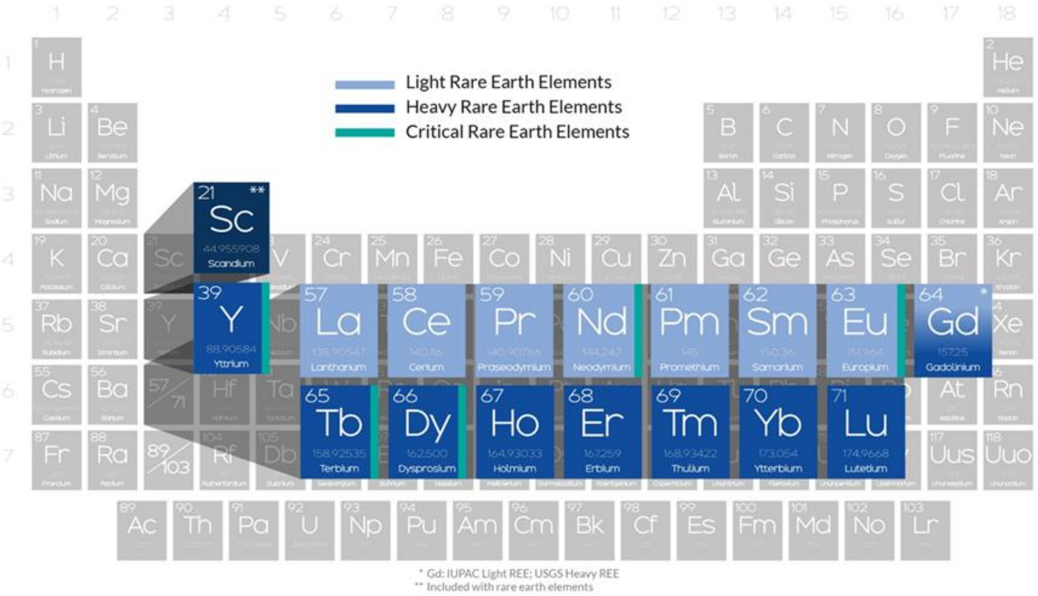
REEs are not found in their purest form but are bound to other minerals, the most frequent of which are bastnaesite and monazite. The first is more difficult to find and is made up of REEs as opposed to the second which is found in deposits of other minerals. In the last case then the REES are the result of a refining process that is more difficult to put into practice and therefore also much more expensive (Hurst, 2010; Giancani, 2020). The first deposits to be discovered were those of monazite in different parts of the world including India, Brazil, Malaysia but also China and Australia. While, the first reserves of bastnaesite were discovered in China and the United States later, in the 1950s (Goldman, 2014). One of the most prolific and well-known bastnaesite sites is the one located in Mountain Pass, California.

REEs are generally divided into two macro-groups: light rare earths (LREEs) and heavy rare earths (HREEs). The chemical elements ranging from atomic number 57 to 62 (lanthanum, cerium, praseodymium, neodymium, promethium, samarium) belong to the first group, while those ranging from 67 to 71 (holmium, erbium, thulium, ytterbium, lutetium) together with yttrium are among the heavy ones (Ganguli et. al, 2018).

According to an alternative classification, mainly used in China, REEs can be divided into three groups, namely light, medium and heavy REEs, but in general contemporary scientific literature considers the division into two groups to be the most relevant (Stratfor Team, 2019).

As stated by Oddo-Harkins rule, elements with even atomic numbers are available in larger quantities than elements with odd atomic numbers (Haxel et al., 2002). The general rule is that elements with the highest atomic number are less abundant in nature. Therefore, the world-wide availability of LREEs is the most abundant, while that of medium-heavy rare earths is the most limited. The main REE of the first group is cerium while of the HREE is yttrium (Binnemans, 2015).

Figure 1.1 REEs: Periodic Table



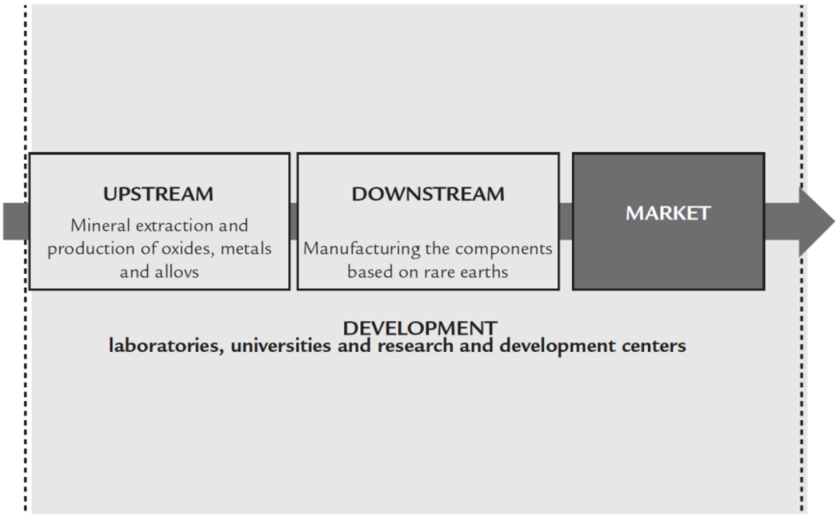
Source: National Energy Technology Laboratory (accessed 01/10/2020)

Figure 1.1 shows on the periodic table all the chemical elements that can be defined as REEs, grouped in the two different macro-groups; moreover, the subjects that are considered critical to date are highlighted.

The definition "rare earths" is not exactly correct since these elements are distributed over almost the entire earth's crust. For example, thulium and lutetium, the two less abundant REEs, are at least 200 times more available than gold (Haxel et al., 2002). What makes REEs so difficult to obtain is the fact that they are not readily available for exaction but are found in a variety of minerals and coal-based resources. By definition, total annual production is expressed in tons of rare earth oxides, REOs (Ali, 2014). Moreover, the available deposits are concentrated in certain areas of the world, which is why their supply is ensured by a limited number of sources. Instead, they are called earth element because in the 19th century in French, the vehicular language of the time, an oxide of an element was called "earth". In the same way in German, the second most used language in science and academia, the oxide of an element was called "Erde", i.e. earth, of an element (Voncken, 2016).

The most complicated aspect is therefore to extract the single metal from the ore in which it is embedded. The production steps can be grouped into two macro-phases: upstream and downstream production as shown in Figure 1.2 (Ortiz et al., 2014).

Figure 1.2 REE’s manufacturing phases



Source: Ortiz et al. (2014), page 362

The process is different, costly and more complicated from the extraction of other mineral elements, especially since the different elements share very similar chemical properties (Kalantzakos, 2018). The first step consists of extracting the ore from the ground and isolating the REOs from other minerals by crushing the rock in which they are contained, also using solvents. The result must be a powdered compound that can be separated through the use of tanks in which the REEs will float. At this stage of the process an agent is added which causes the air bubbles created at the base of the tank to rise to the surface with the ore attached (Hurst, 2010). The next step is to render the oxides into the form of pure metals through the process of electrolysis. At this point the result is a metal concentrate that must be fired in suitable ovens and dissolved in acid. The reaction results in radioactive waste consisting of thorium and uranium waste. Waste and hazardous materials will be separated and stored for disposal (Bourzac, 2011; Ortiz et al., 2014). It was precisely this toxic waste that makes processing dangerous, especially from an environmental point of view, and that decreed the end of the largest non-Chinese deposit. Molybdenum Corporation (MolyCorp.), one of the most influential companies in the REEs refining market, was no longer able to manage the accumulated waste, so it was forced to close down.

The second phase, known as downstream, involves the use of REEs to create components that are then used in the final products. The materials resulting from the first step can be further processed and used to create REEs alloys that can then be assembled into various applications and components. The whole process can takes at least 10 days (Hurst, 2010; Ortiz et al., 2014).

1.2 Historical backgrounds

1.2.1 From 1787 to 1960: an overview

Although the importance of REEs was clear from the outset, at first the information available was not complete. It took several years to discover and develop all the powers of these materials. The development and history of how the REEs market was born and grew is the result of an interweaving of political and diplomatic relations as well as economic aspects. Without considering these elements it is not possible to draw a clear picture of how the market of these commodities has developed to have a global impact.

To date, the importance of REEs in various industrial applications is so globally recognized that they are defined as "vitamins" in modern industries. The importance of REEs is not only for economic development but also for national security, technological advancement and the entire industrial and agricultural production sector (Klinger, 2015).

The first discovery took place in 1787 in a Swedish mine near the village of Ytterby. A black unclassified rock was found and was given the name Ytterbite, which a few years later was changed to Gadolinite. The turning point came almost ten years later, however, when a Finnish scholar Johan Gadolin isolated a new material from this rock that would be called Yttrium. Although the importance of this discovery was quite clear, it took several years for research to focus specifically on the analysis and study of these elements (Klinger, 2017). Over the years, thanks also to technological development and research, it has been possible to separate various chemical elements from this first component: terbium, erbium and ytterbium. Initially no scholar had realized that these new elements were like matryoshkas: from the discovery of one element many others could be separated (Metalpedia, accessed 20/10/2020).

The researchers of the time were therefore faced with a new epochal discovery. Since these elements had only been found in that mine, they were not thought to be spread over the rest of the earth's crust. For this reason, they were wrongly defined as rare.

The first application that sees REEs as a fundamental element for its success is the solution to one of the major problems of the nineteenth century: the lighting of all the areas that developed with industrial progress and that were facing the darkness of the night. This type of gas lighting used only 1% of the REE cerium, however for the time the production was so massive that a consequent problem emerged, namely the waste of REEs not separated (Klinger, 2015).

However, the large production has put the limited reserves to the test, and this has fueled the need to discover new deposits in order to be able to respond to global demand. It is precisely in this panorama that an entanglement of political and diplomatic relations develops, directing the search for new sources of REEs (Klinger, 2017). The success of these applications meant that interest in REEs was widely recognised, so that the REEs industry expanded beyond Europe's borders to the Americas, India and reaching, in 1947, places as remote and difficult to access as the Inner Mongolia Autonomous Region in Northern China. In order to gain a strategic advantage over Great Britain and France, it is precisely towards China that Germany will seek to expand through diplomatic relations aimed at securing an area rich in mineral resources (Klinger, 2015).

In the same way, even during the WWI, REEs played a fundamental role so that it was necessary to invest in the development of geological science and research in China as well. The Geological Society of China was the first scientific association to take root and operate in the Chinese Republic in the early 1900s (Gregory, 1923).

Over time, China has also opened up to international collaborations to exchange essential information for the advancement of research. The remaining global demand, which came mainly from Europe and North America, was satisfied by the exploitation of the reserves located in Brazil and India. The Russian Empire, on the other hand, was a market in its own right as it managed to satisfy the demand of its industrial system (Klinger, 2015).

The status of the REEs returns to emerge during the race for rearmament in the period before the WWII. This consolidated economic and diplomatic relations between the European and North American powers. The race for rearmament and the development of the atomic bomb has increased the need to obtain REEs to such an extent that the United States and Great Britain resorted to the exploitation of the reserves in the colonial territories. This ensured access to abundant reserves of REEs, thorium and uranium (Klinger, 2015).

The need to be able to draw on reserves of REEs became increasingly urgent. It should also be kept in mind that the Soviet Union was conducting several nuclear weapons tests in which REEs played a significant role. So, when India, from which the United States was supplied, decided not to export any more material and Brazil was unable to meet the demands, North America had to resort to domestic sources (Klinger, 2017). It was in this new phase that the REEs mine in California at the Mountain Pass was discovered, in 1949. In any case, the mine became operationally important only from 1953 when the first projects began (Kalantzakos, 2018). Among the overseas resources from which the United States could obtain raw materials, China had the potential to become the main source. Similarly, China recognised the United States as the best buyer to sell its reserves (Klinger, 2017).

With the industrial development induced also by the need to create increasingly technologically advanced weapons, it has been possible to discover new applications and characteristics of REEs such as the ability to remain stable even when subjected to high temperatures. Precisely for this reason China committed itself to this research and studies, becoming the most powerful nation in the REEs market in the mid-20th century (Klinger, 2015).

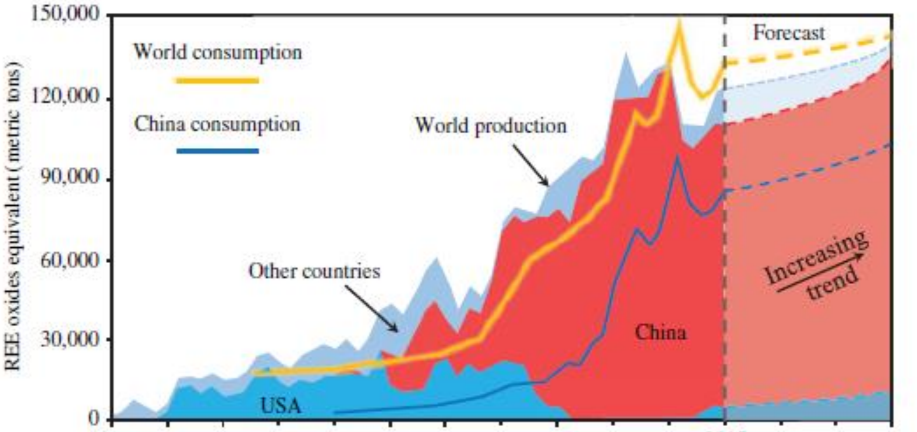
1.2.2 From 1960s and beyond: turning point

Since 1960s, China, with its discoveries and resources, has been making its way in the world with increasing boldness. If before Chinese production was limited to extracting raw materials and exporting them for processing and separation, after 1974, the scholar Xu Guangxian developed "the Theory of Countercurrent Extraction" which is the basis of the extraction methods used today (Chunhua et al., 2006), surpassing the US capabilities that until then had excelled. The Chinese scholar had focused his research on methods of extracting uranium isotopes but had the insight to use his findings in the field of REEs (Hurst, 2010). The innovation behind this avant-garde theory has made it possible to reduce production costs, making the Chinese model more competitive in the traditional panorama, and consequently also lowering the costs of the final products. In addition, this has made REEs a preeminent element in people's daily lives with the first colour televisions for example and other technological elements that now seem outdated (Klinger, 2015).

Thanks to this discovery and other improvements in production systems, China was able to reduce most of the costs of extraction and processing of raw materials such as for the case of europium used mainly in the production of colour televisions. In this way REEs, even if unconsciously, became a common element in people's everyday life. With the technological advancement REEs became a fundamental good and their applications increased immeasurably making them a critical material also from the political point of view. If before REEs were considered a necessary element specifically for niche industrial applications, they REEs soon became essential for everyone's life.

Figure 1.3 graphically summarizes the evolution of REEs production over time up to the early 2000s. In the graph the production data of United States, China, Other countries and World, are superimposed in order to underline the differences. The Chinese advance at the expense of American power is highlighted: in fact, China does not only exceed the United States but increases production by more than twice as much as its counterpart. The two lines show the consumption of REEs from both a global and a Chinese perspective. The last part shows a forecast of the levels that will be reached in the coming years. As can be seen, there will be an upward trend and it is assumed that global consumption may exceed production.

Figure 1.3 REEs production overview



Source: Huang et al. (2016), page 533

1.3 World's main deposits

As previously mentioned, REEs are widely distributed on the Earth's crust, as the Figure 1.4 shows, which is why the adjective rare with which they are defined can be misleading. Cerium, for example, is one of the most abundant elements on earth. The reason why they are so sought after is therefore not their abundance but their degree of concentration. Similarly, the same extraction practices that are often complicated and extremely expensive slow down the supply of REEs (Van Gosen et al., 2017).

Figure 1.4 Global reserves of REE

Source: Stratfor Team (2019)

The main Chinese mines are those located in Bayan Obo in the Autonomous Region of Inner Mongolia, which started its production in 1959, but also those in the Autonomous Prefecture of Liangshan in Sichuan and several southern provinces. In the lands of Mongolia and Sichuan the deposits are mainly related to LREE mining operations while the territories of southern China are rich in HREE (Wübbeke, 2013).

The second largest producer of REEs, the United States, began mining in 1885 from mines in the south of the State as for example the Carolina monazite belt, in Idaho, in the Bear Valley and in Florida. However, the most important source of REEs soon became the Mountain Pass mine in California. Due to Chinese competition and strict rules on respect for the environment, the mine was dismissed for the first time at the end of the 1990s, thus defining the end of the American era in the REEs market (Castor, 2008). The main mining activities in the San Bernardino County mine were conducted by the MolyCorp. company. Further exploration activities in the United States were conducted in Alaska, Arizona, Missouri, Nevada and Wyoming but never reached the extraction levels recorded in California (Van Gosen et al., 2017).

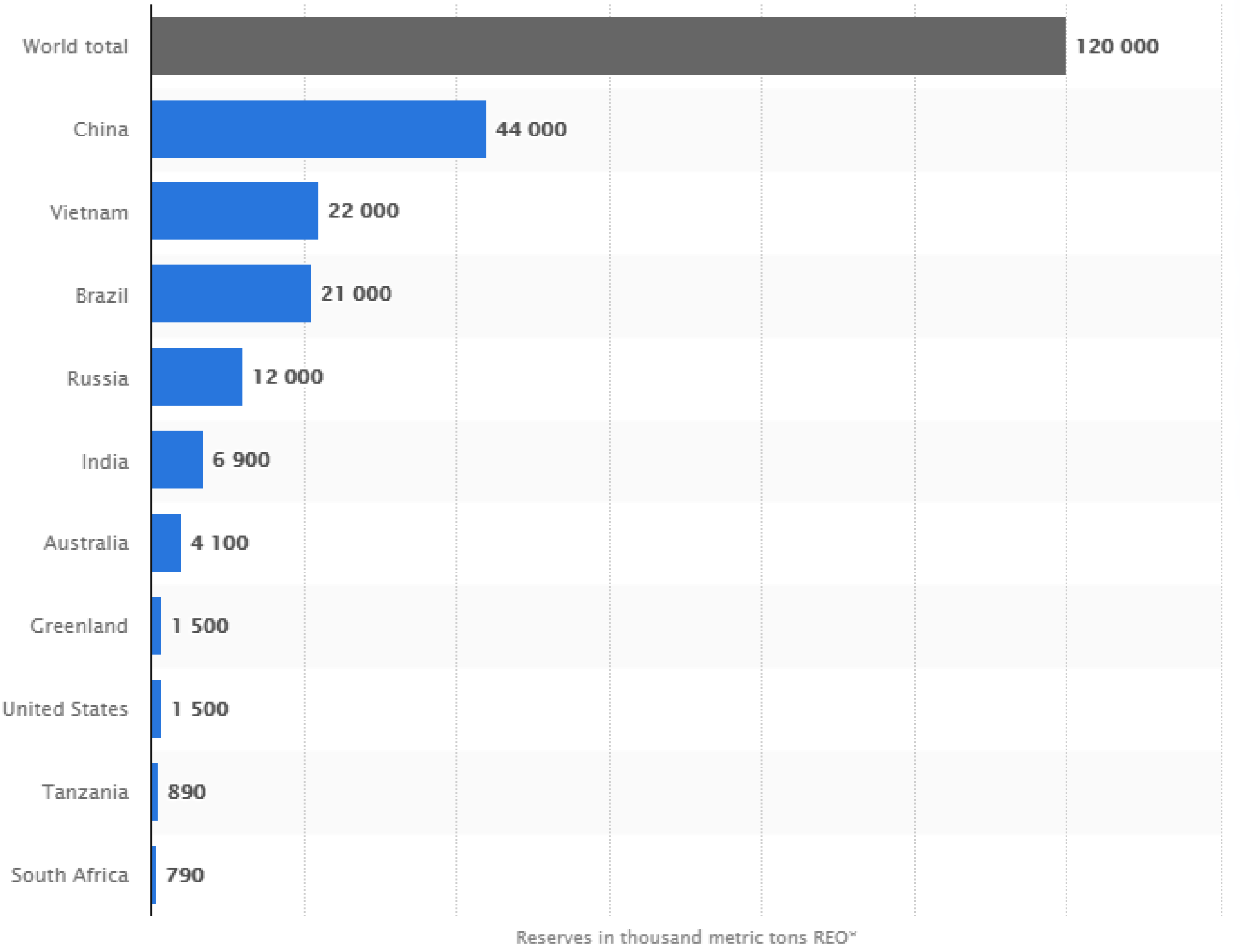
Other significant deposits have been found in other parts of the world, as mentioned above. These include Australia, where Lynas Corporation Ltd. (LynasCorp.) is the largest representative. We would also like to mention Malaysia and India, particularly the latter, where the two main producers are government companies. Finally, there are several mining sites in Russia, including the Lovozero mines in the Kola Peninsula and the Permskiy Kray mines (Van Gosen et al., 2017).

A number of new projects have also been developed in Scandinavia and Greenland to deal with the rampant Chinese monopoly. Specifically, the largest deposits are located in southern Greenland and the Baltic (Charles, 2013). However, the problem that companies will have to face in order to extract REEs in these territories is that a large part of the surface is covered by ice, making extraction work even more complicated and expensive. In spite of everything, in 2012, the European Union showed a strong interest in the Arctic territories and signed a cooperation agreement (Ungaro, 2013).

Japan has also played a key role in the REEs market, especially with the discovery in 2012 of a deposit near the island of Minami Torishima. At the beginning, time extraction practices were not efficient due to the depth of the deposit. Over time, however, the techniques have been perfected to the point of extracting over 16 million tons of REEs. For Japan, home to high-tech industries such as Toyota and Honda, which use the latest REEs products such as permanent magnets on a daily basis, this discovery is almost a breath of fresh air compared to China's strong monopoly grip. In fact, some researches in the seabed has shown that there would be enough dysprosium, an element used in the production of permanent magnets, to satisfy 730 years of use (La Repubblica Team, 2018).

Figure 1.5 shows the distribution of reserves globally in 1,000 metric tons REOs for each country. The main reserves are located in China, but Vietnam and Brazil follow soon after. It is important to remember that not all countries that have deposits are also able to work them. Very often, extracted materials are exported to China and processed there. This has allowed the Asian giant to tighten its grip on the market for these items more and more.

Figure 1.5 Worldwide reserves in 2020

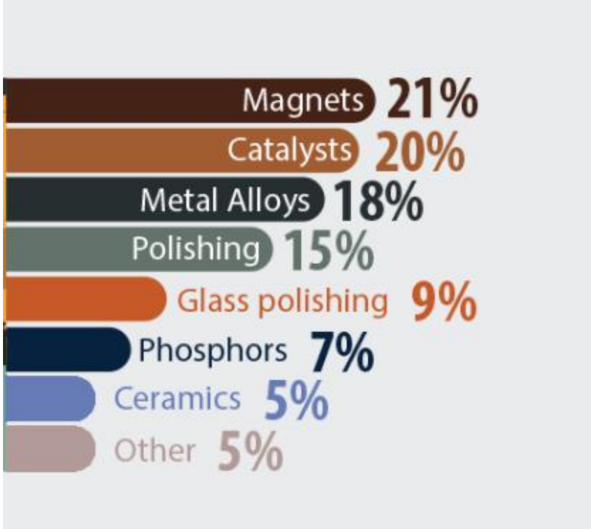


Source: Garside (2021a)

1.4 REEs main applications

With demographic and technological development, the use of REEs has increased exponentially. The fields of application of these elements are very diverse: from permanent magnets that in small dimensions enclose a considerable force of attraction to wind turbines that allow the production of renewable energy (Metalpedia, accessed 20/10/2020).

Figure 1.6 Uses in percentage of REEs in 2018



Source: Government of Canada (2020)

Due to their pyrophoric characteristics REEs are highly flammable materials, at the same time they are also used as catalysts. They are also phosphors able to produce natural luminescence if activated by particular radiations and for this reason they have been used in televisions but also in medical instruments (Giancani, 2020).

However, as you can see from Figure 1.6, in 2018 the main application which involved the use of REEs was permanent magnets essential for various end products including computers, smartphones and other components often used in the green economy.

Moreover, REEs play a central role in national defense as well. These minerals are used, for example, in equipment with GPS, night vision and other instruments used in defense (King, accessed 21/10/2020).

For example, in December 2020, the U.S. Army decided to collaborate with various extractive industries to implement new projects aimed at improving and making even more sophisticated the armament of the U.S. military. The use of these materials in such sensitive fields has made the need for supply a fundamental aspect for several governments (Hansen, 2020). A practical example is the U.S. case that, concerned about the possibility that China will suspend the supply of REEs, is looking for alternative sources where it can find the necessary material. Obviously, the almost obligatory choice to resort to other sources leads to significantly higher costs compared to the Chinese provisioning. The possibility of a Chinese embargo on the supply of REEs is worrying several nations, not only the United States. However, the difficulty of the United States is not only in obtaining resources but also in the extraction and processing of raw materials. This makes the Chinese monopoly even more stringent (Hansen, 2020).

2. The Supply Side

This chapter will analyse the supply side of the REEs market and leading producers with a specific focus on the evolution of Chinese production from the beginning to the creation of a quasi-monopoly with a particular attention to the 2010 supply crisis and its consequences.

The market of REEs, unlike other commodities, is not particularly large, for example, during 2019 its global value was about $1.15 billion (China Power, 2020a; Ortiz et al., 2014). The importance of this market therefore lies in products that use REEs such as smartphones, magnets, or colour screens, making the small REEs market an extremely profitable source of business. As mentioned earlier, REEs have been gaining more and more ground in the race for the most important commodities since the 1990s. Their various applications have made them fundamental in numerous sectors from the green economy, to the production of high-tech products and US military security. The most important global manufacturer is China, which reported 2019 production of 132,000 metric tons of REOs. However, these data do not include illegal production so it is assumed that the values may be higher than documented (U.S. Geological Survey, 2020). In 2019 Chinese exports were recorded for a total of 45,552 metric tons of REEs for a value of approximately $398.8 million (China Power Team, 2020b).

However, this has not always been the case, as has already been mentioned, China has only gained ground in recent years by establishing itself as the world leader in this market, but before its rise, the largest producer of REEs was the United States. Anyway, it is right to acknowledge China's ability to invest in research and fully exploit the resources present in the territory, even to the detriment of environmental standards.

2.1 Changes in the market

The strategic position of REEs on the international scene has been mentioned several times but it is important to underline the steps that have made them so. Several drivers have enabled China to become the benchmark in REEs production. Its extra gear has been to invest as much research as possible, thus improving year after year their extraction, refining and production techniques. China's foresight has enabled it to achieve the know-how needed to create a stable and profitable supply chain. Its goal was to obtain as much knowledge as possible both by developing domestic research projects and at the same time involving scholars from other countries through scholarships. Among these projects it is important to remember the Belt and Road Initiative which aims to create a bridge between China and the other powers of Eurasia and South America (Kong et al., 2019).

With the closure in 2002 of the largest non-Chinese mining site, the Mountain Pass mine in California, due to environmental problems, Chinese production, without a counterpart at its level, has taken control of the REEs market. The closure of a company like MolyCorp. not only has the effect of taking away earnings and jobs, but it also risks losing the technology and knowledge related to the production of the material (Kalantzakos, 2018). It was of little use trying to re-open the same American site several years later, in 2015, and China now controls a near-monopoly.

2.2 Production in China

China has been able to develop a manufacturing structure that has allowed it to establish itself in the international market as a primary source of REEs. To understand the factors that led to the rise of China as the largest producer of these commodities, it is important to take a step back and analyze what were the political and economic choices of the Chinese Government and those of its main competitors. In addition, only in the last years particular attention has been paid to environmental effects and resource conservation (Shen et al., 2020).

The main areas in which REEs deposits are present are three: Inner Mongolia, Sichuan and Jiangxi from which about 93% of the Chinese extraction quota has been extracted and produced in the period between 2007 and 2011 (UNCTAD, 2014). However, this almost monopoly has not always been the norm in fact the Chinese influence has only become predominant since 1975 (Shen et al., 2020).

At the beginning of 1970, in fact, the sector was not yet well developed, the companies that dealt with the extraction of minerals were a lot of small realities without, however, a valid organization that allowed them to evolve and create a stable production system (UNCTAD, 2014). In addition, as for other commodities, illegal mines had been shown to have a strong impact on the region's production landscape, making the monitoring of the country's production chain by central government particularly complicated (Shen et al., 2020).

With the beginning of the late 1990s and early 2000s, the Chinese government realized the underdeveloped potential and therefore tried to invest in the expansion of the production chain that until then was still in a rudimentary state (Nguyen et al., 2016).

To date, China continues to produce the majority of REEs resources globally but, in recent years, the other powers have realized the necessity to find an alternative to both Chinese production and the use of REEs where possible.

Surely it should be kept in mind that Chinese production data and reserves are not always accurate since official documents are not always translated into the vehicular language and illegal production not controlled by the government continues to have a prolific activity often not included in the reports (Shen et al., 2020).

2.2.1. Production before 2000s

At the beginning of the first half of 1900 China had not yet developed sufficient technology to allow it to extract and process rare earth minerals independently. It was only in the 1970s that some progress was made so far that some of this production was exported. However, the quantities were limited, in fact between 1973 and 1978 the production was around 150 tons of REOs (Shen et al., 2020). Extremely low levels if we compare them with those of today's production. The demand began to increase in 1980 when several nations used imports from China to meet their need for REEs. First of all, Japan imported between 1000 and 2000 tons of REOs and then partly also the United

States (Shen et al., 2020). As China's production increased, the central government showed interest in developing its nation's capabilities, and several research projects such as the China Rare Earth Information Center (CREIC) were established, involving nearly 3,000 engineers, scientists and scholars. In March 1986, a project to accelerate the country's development was approved by the Chinese President. The National High Technology Research and Development Program, also known as Program 863, focused on the improvement of several sectors, including biotechnology, energy and automation, where the use of REEs was crucial (Hurst, 2010). This was followed by a new project, called Program 973, which was implemented in March 1997. The investment involved $1.46 million and among the various fields of research in which the REEs were to be used was the study of a more accurate oil extraction process (Hurst, 2010). Collaborations with foreign bodies and industries were also encouraged because the central government had understood the need to attract foreign investment to stimulate its production sector, for example, through joint ventures (Goldman, 2014).

It was precisely in the face of this increase that the Chinese government decided to regulate the market that was consolidating in those years. In fact, the National Rare Earth Development and Application Leading Group was established, composed of several institutions headed by the same central government, with the task of regulating the production and exports of minerals (Shen et al., 2020).

The Chinese Government adopted the objective of developing the mining industry and to do so has focused on stimulating exports. The choices were mainly based on the refund of export taxes, which ranged from 13% to 17% (Shen et al., 2020). This has made it possible to improve production from 8500 tons REO to almost double that (Shen et al., 2020). In addition, during this period, several plants in different parts of the world have been closed to be reopened in China mainly to circumvent the rules of their national governments (Klinger, 2017). However, due to the different actors involved in the Chinese REEs market and the strong competition between them, finding a common regulation that allows the growth of the entire sector has not proved to be an obstacle-free path. Illegal production has affected prices by lowering them since the costs they incur are much lower and taxes are not paid. According to some statistics, in the early

2000s the weight of illegal production on the total has reached a level of 22-25% (Nguyen et al., 2016).

As Table 2.1 shows, the weight of illegal production of raw materials in China is significant. The staggering growth of irregular production over the years has reached 40-50% of total Chinese production. The consequences of this practice have an effect both on prices and production rates, but also in the form of environmental damage (Barakos et al., 2018).

Table 2.1 Illegal production in China in comparison with the Rest of the World (ROW)

	Illegal mining in tons of REOs	**ROW production in tons of REOs**
2013	25-35,000	12,000
2014	40-50,000	15,000
2015	70-90,000	19,000
2016	80-100,000	24,000

Source: Barakos et al. (2018), page 88

This has awakened the attention and strategic importance of these materials. It was no longer possible to extract and export REEs without any kind of control since this had direct consequences on the domestic production sector (Nguyen et al., 2016). The Chinese government decided in 1991 to suspend the licenses for the extraction of REEs and to limit foreign investments (Shen et al., 2020). Moreover, as an attempt to limit illegal production, China decided to give priority and aid to state-supervised and state-controlled enterprises. Private companies, on the other hand, could not operate in the sector (Shen et al., 2020).

The results of these regulations were not as satisfactory as hoped, so much so that illegal production continued to operate, and waste and environmental damage remained a problem. However, there has been recorded a general improvement in production such an extent that the annual growth rate has reached 22% and the market share 85% (Shen et al., 2020) This is because the companies enjoyed state aid such as the aforementioned export reimbursements as well as subsidized loans. Already in the 80's the production of REEs in the United States, headed by the mine in Mountain Pass, and that of China differed only by 10,000 tons of REOs, thus sanctioning a real passage of witness from the American power to the Chinese one (Vekasi, 2018). In 1995 Chinese production reached 60% of world production (UNCTAD, 2014). Foreign companies, in order to avoid being excluded from the supply of REEs, preferred to transfer some manufacturing units in the Chinese territory.

2.2.2. Production between 2000 and 2010

With the growth of the sector, other problems emerged and a compromise between economic progress and its environmental and resource impact was needed. The objectives of the Chinese government have therefore become increasingly focused on finding a solution or at least a way towards sustainability. Moreover, among the forces at stake, the role of local governments has become more and more marked. Their intent was to make their areas economically richer and often this did not coincide with the central government's decisions (Shen et al., 2020).

The choices of the Chinese government have focused on the use of various economic instruments aimed at preserving and facilitating the development of domestic sector such as production and export quotas but also export taxes and tight controls on foreign investments (Vekasi, 2018; Shen et al., 2020). China has demonstrated remarkable accuracy in protecting its REEs reserves with specific laws and restrictions. This was aimed at helping the growth of local industries that had the advantage of access to raw resources at lower prices and higher quantities. In addition, the foreign companies' decision to relocate their facilities to China to secure a supply became increasingly urgent. The feeling that was spreading among foreign companies was that if it was not possible to secure direct access to the source of raw materials, several production sectors could be damaged (Vekasi, 2018).

Unlike the other nations involved in the REEs market, China was the only one to exploit its internal resources by investing in internal research but also in those coming from outside its borders; in fact, the opening of foreign manufacturing plants in Chinese territories has allowed the Asian power to benefit not only economically but also by acquiring specific know-how. The use of these restrictive policies is due to several factors, the most important of which are the pursuit of generalized growth and maximizing returns. China has had the ability to make the most of the resources of its territory, even if paying an equally high price in terms of environmental damage, by assisting the economic and political choices (Fernandez, 2017)

Contrary to what it may seem, the deposits are not only located in Chinese territories. In fact, there are different possible sites available which are located in various countries globally. However, what is holding back other players from exploiting their deposits is the high and unavoidable costs involved in production processes and the environmental impact this has. To this must be added the long technical time needed to design a project and make it active, in some cases it may even take a decade (Leone, 2020). The final Chinese goal, however, was not only to become the largest exporter, but to be able to produce REEs and consequently end products independently, without necessarily resorting to intervention and exploiting the capabilities and technologies of other nations (Kalantzakos, 2019).

Chinese production therefore benefited from these preventive measures imposed by its central government; in fact, a peak was recorded in the years just before the 2010 crisis. Table 2.2 shows the values of Chinese production and reserves in terms of tons of REOs. What is noticeable is a considerable increase between 1999 and 2009, reaching 120,000 tons of REOs which may be due to regulations introduced to protect domestic production.

Table 2.2 Chinese mining production from 1998 to 2014

	Mine production in tons of REOs	Reserves in tons of REOs
1998-1999	65,000	43,000,000
2008 - 2009	120,000	36,000,000
2013 - 2014	95,000	55,000,000

Source: U.S. Geological Survey (2000), page 135; U.S. Geological Survey (2010), page 129; U.S. Geological Survey (2015), page 129

2.3 The 2010 supply crisis

The early years of 2000s thus states the Chinese quasi-monopoly which, after the closure of the largest US mine, had few other competitors to its credit (Vekasi, 2018). Moreover, in this period the Chinese giant was concentrating on the knowledge necessary to become autonomous also in the production of the final products in which REEs are used (Barakos et al., 2016), such as the electronic components that were previously composed in Japan. China's position of supremacy is sanctioned when China decides to establish an embargo against Japan by blocking exports of REEs. The Chinese government's decision was the drastic consequence of a diplomatic dispute with Japan over the detention of a Chinese fishing vessel captain and a more formal motivation such as the exacerbation of the effects that this type of production has on the environment. With this move, the Asian giant blocked the supply of a crucial product to the Japanese economy for more or less one month (Bradsher, 2010; Klinger, 2017).

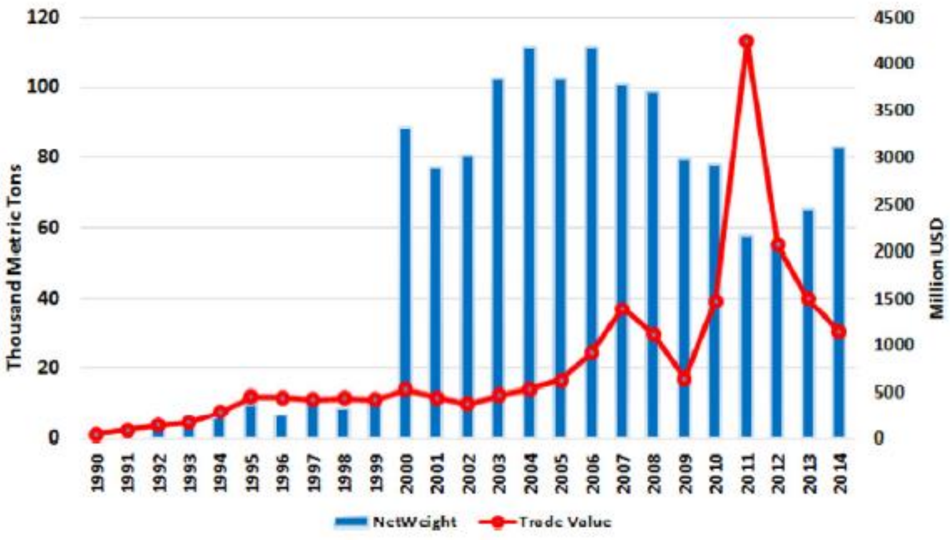
This stance has not only damaged Japan economically but has also had serious economic repercussions for the United States, Europe and other countries because China has decided to reduce its exports of critical minerals drastically (Shen et al., 2020). As already pointed out above, the fact that the export blockade caused a setback for Japanese industrial production (Vekasi, 2018) has also had an effect on the United States, which was also sourcing from the latter, especially for military procurement. This has prompted America to invest in the search for an alternative source within the United

States (Bradsher, 2010). However, they have not managed to become independent of Chinese resources.

The restrictions enforced on exports and the heavy taxation imposed on regular customers from China has damaged companies like Toyota and limited entire nations. This block has promoted a systematic search for new sources of supply and has made the exploitation of the commodities in question more efficient by reducing waste (Bradsher, 2013).

The nations most affected by the Chinese restrictions were certainly Japan and the United States, the latter in particular had already faced an embargo during its mining history imposed by the Indian government in 1946 (Goldman, 2014; Klinger, 2015). The impact of this decision, however, did not have the same disastrous consequences as in 2010, even though the reasons behind it were very similar, so much so that India had realized even before China the diplomatic potential of this critical material. It can be concluded that the American government did not learn anything from this event since, not even 60 years later, it found itself in a similar situation (Goldman, 2014).

Figure 2.3 Value and volume of exports between 1990 and 2014

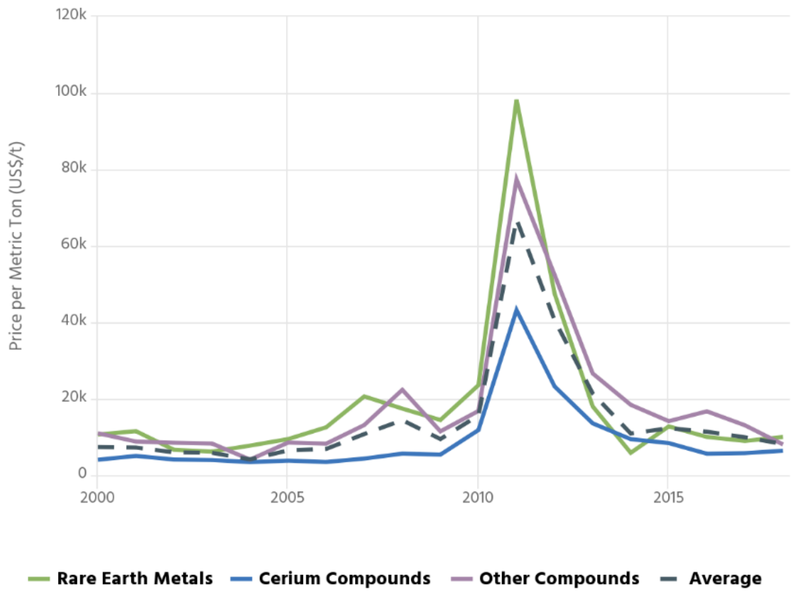


Source: Mancheri (2015), page 263

Figure 2.3 shows the gross value of global exports and their volume between 1990 and 2014. Before the 2000s China was not among the major exporters of REEs, but since then the graph shows that the volume of exports has undoubtedly reached a higher level. The second interesting fact is the evident decrease in the years of the crisis, 2011-2012, but at the same time, an important increase in the commercial value of REEs which shows the uncertainty that reigned in the market. In fact, when China imposed the restrictions it became more difficult and therefore more expensive to obtain these critical minerals (Mancheri, 2015). As a result of the reduction in exports, the demand for raw materials increased dramatically and the few reserves available were disputed by the various buyers, thereby also increasing the commercial value of the asset.

The effects on prices of REEs have been immediate and have increased exponentially. As shown in Figure 2.4, the tightening of export quotas resulted in import prices rising sharply from an average of $9.461 in 2009 to an average of around $66.957 in 2011 and then return to normal levels from 2014 onwards (China Power Team, 2020a).

Figure 2.4 Average global import prices in dollars



Source: China Power Team (2020a)

2.4 Dispute in the World Trade Organization (WTO)

The Chinese embargo has had devastating effects on the economies of countries that depended on their reserves. For this reason, the governments of these countries have mobilized themselves to re-establish a market as fair as possible by trying to restore a situation without protectionist measures. The matter was then submitted to the Dispute Settlement Body (DSB) of the World Trade Organization (WTO). In particular, United States, European Union and Japan have presented a concrete action against the People's Republic of China by joining forces for the first time in the history of international disputes (Kalantzakos, 2018). With these protectionist measures, China was in fact in violation of the laws of the international market and the agreements established by joining the International Trade Organization in 2001 (Kalantzakos, 2018).

China immediately tried to defend itself against the accusations made by its counterparts in the dispute. The Asian giant has tried to present reasons for its choices including the control of environmental damage that the practice of REEs mining causes but also limiting exports to safeguard the small reserves available (Dreyer, 2020). The Chinese government released in 2012 the first White Paper on policies regarding the REEs industry in which the resulting damage was thoroughly discussed (Bradsher, 2012). In this official document, China also pointed out that its REEs reserves were gradually decreasing and that they only accounted for 23% globally at the time (Bradsher, 2012). According to the Ministry of Industry and Information Technology, if regulations had not been introduced quickly to control the buying and selling of REEs, available reserves could have been exhausted within 20 years (Xinhua, 2012). This information was, however, denied by the United States Geological Survey, according to which China's reserves amounted to about one third of the world's reserves (Bradsher, 2012). Since the motivations of the parties involved were diametrically opposed, WTO intervention to resolve the dispute seemed to be necessary.

2.4.1 Position of the United States, European Union and Japan

As has already been mentioned, over the years China has acquired sufficient knowledge to become the world's leading exporter of REEs accounting for more 90% of global supply in 2014 (China Briefing, 2014). It is precisely for this reason that we speak of Chinese monopoly, or rather quasi-monopoly. From the 80s onwards China has in fact exploited the resources present in its territories to the maximum by exporting them at extremely competitive prices, an element due in part to the cost of the workforce much lower than that of the competition (UNCTAD, 2014). This was due also to the fact that China, unlike its counterpart, did not take into account the environmental issues involved in REEs processing. If in other countries, several mines have been closed due to difficulties in the disposal of radioactive thorium waste, in China this problem was not the priority (Klinger, 2017).

The first export quotas were introduced in 2011 for the following year. The restrictions and resulting price increases have made it more difficult for international consumers to access the reserves needed for their industries (Kalantzakos, 2018). In the face of this obvious disparity, the countries used to import critical minerals have realized the supremacy of China and they believed that the latter's choices were dictated by the desire to establish its monopoly at their expense. Moreover, in light of these developments, it was more convenient for foreign companies to move their plants in China in order to have constant access to critical raw materials. This, however, allowed China to be always updated on new research and discoveries in the technological field. The President of the United States at the time, Barack Obama, had reiterated that for American companies to be able to produce directly from the motherland they needed full access to key resources such as REEs (Doug et al, 2012).

Chinese restrictions hit international companies severely, which saw export quotas reduced to 54% in 2010. In this period the extremely limited supply could not meet the high levels of demand (European Commission, 2012). For the reasons just described, the three international actors have requested the intervention of the WTO Dispute Settlement Body in order to find a meeting point between the parties involved and at the same time engaged in tripartite projects to develop a strategy for recovery. Unfortunately, the decision to resort to the intervention of the WTO. was late, since the case was officially opened in 2012 but the technical time to handle a case like this varies from one year up to three (Kalantzakos, 2018)

2.4.2 Appellate Body Report and the consequences

At the end of the consultations in 2014 an Appellate Body report was published, which sanctioned the end of the dispute that had been going on for years. China was asked to remove all the various measures that prevented the creation of a fair and well-regulated market. The results were not instantaneous, China only effectively eliminated export quotas on May 1, 2015 and it took a couple of years to see the effects (Kalantzakos, 2018).

A few years after the crisis of 2010, the situation began to re-establish a semblance of normality in this atypical market. For example, dysprosium, a material considered extremely critical, in 2011 was sold at $1.903 per kilogram but already in 2012, the price dropped first to $627 per kilogram in February and $400 per kilogram in December (Kalantzakos, 2018). Moreover, the legacy that this litigation has left is that China's domestic policy has the power to influence international industrial production not only at the level of raw materials but also all sectors dealing with the end products in which these materials are used, thus having a potential disastrous effect on a global scale (Mancheri, 2015).

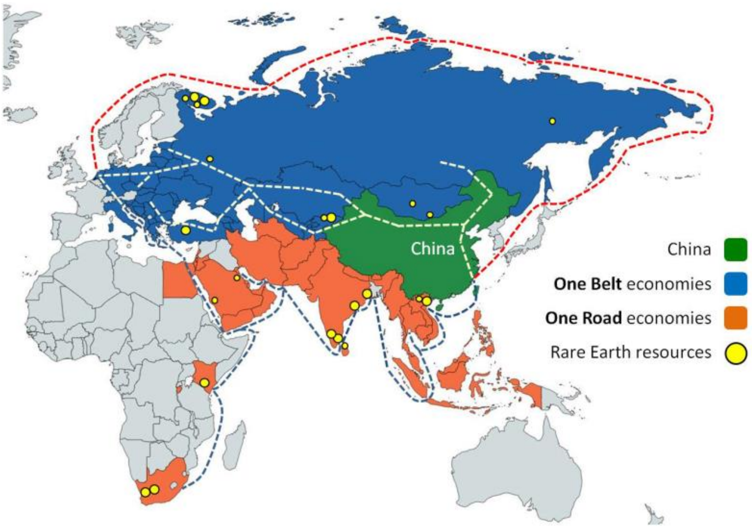
China never stopped defending itself by stressing the attempt to safeguard its reserves and territories. Moreover, it was also pointed out that no recourse had ever been made to WTO when REEs prices had reached extremely low levels (Kalantzakos, 2018). With this crises, the other international powers have realized the potential of REEs to be used as a weapon not only political but above all economic able to reveal all the flaws of a market still in strong imbalance. The 2010 crisis not only caused an increase in raw material prices but also damaged scientific collaboration and increased the gap between the Western powers and China.

2.5 Current Chinese production levels and the Belt and Road Initiative (BRI)

Over the years, China has not only focused on the development of the REES production and extraction system itself, but also the sectors concerning their different uses, redefining entire supply chains such as transportation, health and safety. At the expense of its counterparts, China has shown the foresight to invest in research and study of both the production of REESs and their uses. This constant flow of information and know-how has done nothing but consolidate Asian hegemony also on the final products that involve the use of REEs such as the high-tech sector.

To ensure its dominance, improve production efficiency and limit mining damage, China has engaged in the development of important strategies and projects among which the Belt and Road Initiative (BRI), launched in 2013 (Kong et al., 2019). In recent years China has focused on improving connectivity between different sources and the different territories where these can be found. This has increased its control worldwide and has in practice succeeded in creating a continuous thread with other powers, thus ensuring direct access to material considered crucial. This is precisely why China has promoted the BRI whose aim is to connect the developing world including Asia, Africa, Russia and Europe as can be seen from the Figure 2.5 (Barakos et al., 2018).

Figure 2.5 Belt and Road directions and REE deposits



Source: Barakos et al. (2018), page 86

This major global investment has mainly involved the transport and energy sectors and therefore the REEs industry. The innovative Chinese strategy is to tighten productive commercial partnerships by creating a solid network of contacts and breaking the patterns already designed by the old economic powers (Kong et al., 2019). At the same time, the Chinese giant is attempting to forge educational partnerships in addition to the commercial ones already mentioned. This would provide an opportunity for the countries involved to share a wealth of knowledge necessary to launch projects for the exploration of new REEs mining sites in an attempt to bridge the unstable supply-demand relationship in this market. As shown in Table 2.6, the countries involved in the BRI have potential resources useful to China in expanding its available sources of REEs (Barakos et al., 2018).

Table 2.6 Relevant resources of countries involved in the BRI

	Reserves in metric tons of REOs
India	5,97
Kenya	6,15
Russia	48,16
South Africa	2,06
Vietnam	15,44

Source: Barakos et al. (2018), page 89

China has not only focused on personal growth but has also thought of actively involving other new players and this has awakened the interest and concern of the old economic and political powers. This opens up the possibility in the coming years of a confrontation not only between the USA and China. As underlined during the Forum held in Beijing in May 2017, the aim of the BRI is to promote an integrated development plan and an exchange of know-how in various sectors (Xinhua, 2017). In a globalised way such as the current one, it is important to explore solutions for different sectors that are now interconnected and fundamental, such as transport, green energy and high-tech. In fact, BRI's main investment is in the field of transportation (27%) and energy (38%), both sectors that rely on the supply of REEs to develop (Kalantzakos, 2019). The possibility of reducing customs clearance times, increasing investment in the search for a state-of-the-art trading system must be central themes according to the Chinese government (Xinhua, 2017).

This openness and willingness to enter into commercial agreements and partnerships, especially with regard to products such as REEs, which are crucial for the medical and security sectors, has made China a growing power on the one hand, and on the other has highlighted the shortcomings of other nations that are concerned about the Asian giant. Fear is not therefore linked to China's continued growth, which for some years now has been almost inevitable and unstoppable but is even more so the desire to embrace the world that China has shown since the BRI (Kalantzakos, 2019). These economic and political choices have enabled China to improve its production level as we can see from Table 2.7 (U.S. Geological Survey, 2020).

Table 2.7 Reserves and Mine Production in metric tons of REOs at global level in 2019

	Mine Production in metric tons of REOs	**Reserves in metric tons of REOs**
Australia	21,000	3,300,000
Brazil	1,000	22,00,00
China	132,000	44,000,000
Greenland	Zero	1,500,000
India	3,000	6,900,000
Myanmar	22,000	Not Available
Russia	2,700	12,000,000
United States	26,000	1,400,00
Vietnam	900	22,000,000
World total (rounded)	210,000	120,000,000

Source: U.S. Geological Survey (2020), page 133

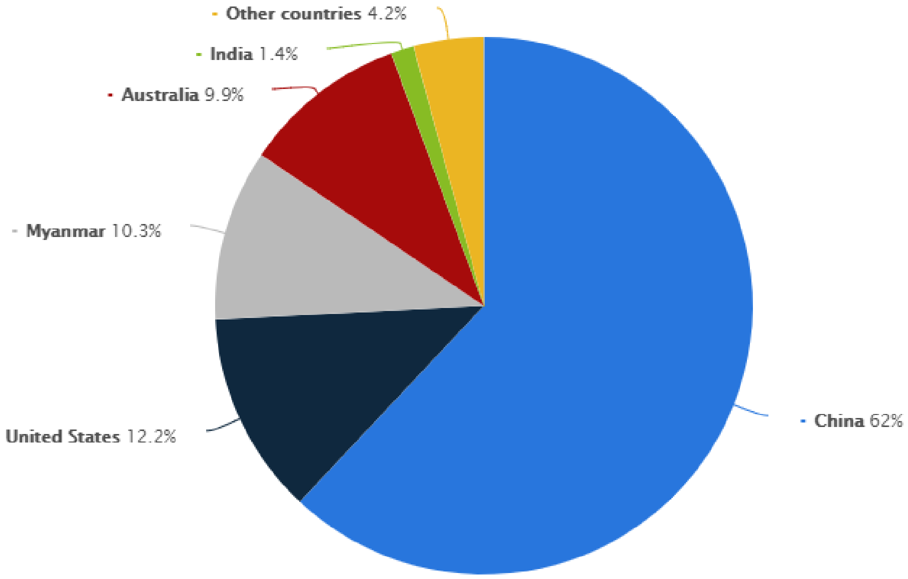
In accordance with the annual report released by the U.S. Geological Survey in 2020, Table 2.7 shows the production levels divided into the main sites and their respective deposits, both expressed in tons of REOs. It is clear that the largest producer is China with 132,000 and estimated reserves of 44,000,000 tons of REOs. Contrary to what one might think, China's biggest antagonist, the United States, has a limited production of REOs 26,000, well below its Chinese competitor. This is because, as explained in the previous section, in recent years the American colossus has had to give way to its Asian counterpart also because of the closure of the most important American mine in California, MolyCorp. Apparently the most profitable sites besides China are those located in Brazil, Vietnam and Russia with 22,000,000 and 12,000,000 tons of REOs respectively (U.S. Geological Survey, 2020), although in these territories it is often difficult to make the transition from the discovery of deposits to the actual production of REEs, which is most often managed by foreign companies.

In conclusion, what has allowed China to excel in the global REEs market is a combination of several factors including low labor costs, state-backed investment, and weak environmental laws. One of the capabilities that China has demonstrated is to internally control all stages of REEs production. Therefore, it has not needed to join with other industries outside its territories to sub-process these minerals, as has been the case with some of its competitors. This aspect makes it a complete and extremely powerful source, as the entire production process is controlled in-house. As has already been explained, this also allowed China to attract foreign experts, who allowed it to improve its production techniques.

2.6 Alternatives to Chinese production

Although China holds control of the REEs market, there are other manufacturers that are worth analysing. As shown in Figure 2.8, even though of minor importance, there are alternative sources to Chinese reserves. According to recent estimates, the largest producers outside of China are United States 12.2%, Myanmar 10.3%, Australia 9.9% (Garside, 2021c). Chinese competition, characterised by extremely low and difficult to reach prices, has made and still makes race tough even though some sites are currently being exploited. The search for REEs sources as an alternative to China's for many economies has become so fundamental that it has led to collaborations between countries, as for example the US administration has done with the Australian company LynasCorp. (Cammarata, 2020).

Figure 2.8 Worldwide REEs production in 2019



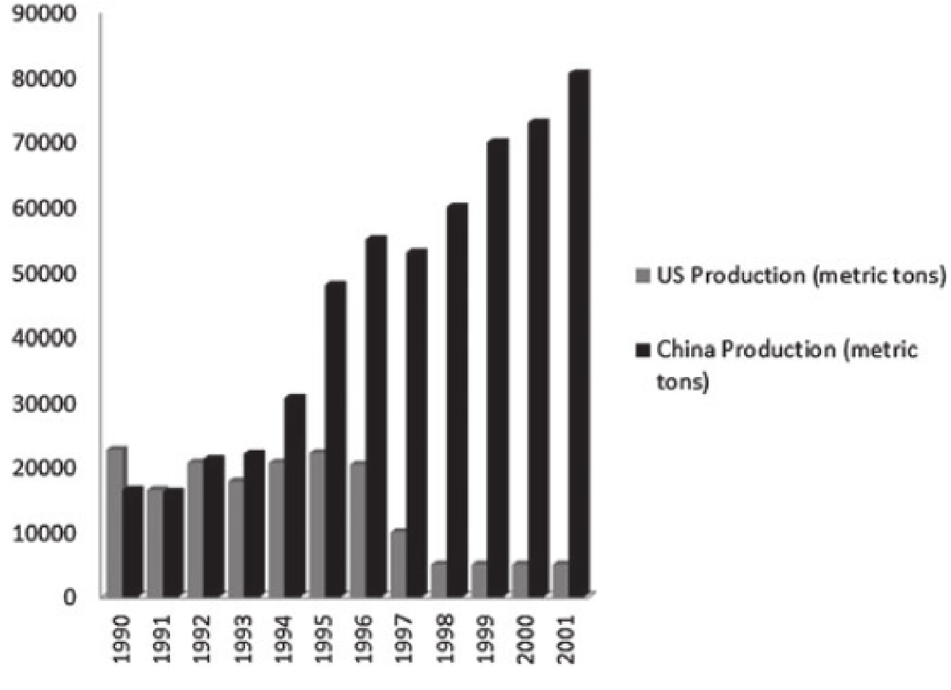
Source: Garside (2021c)

2.6.1 United State Era

The United States have been pioneers in the exploration of REEs deposits in their territories. They dominated world production by exporting raw materials all over the world before China gained ground and became the undisputed market leader (Van Gosen et al., 2017). U.S. manufacturing has followed a different development trajectory than China's, although similarities can be found, and China has taken some steps as a result of U.S. teaching. Surely the Chinese industry has outclassed the American one by becoming more technologically advanced, with more funds in its favour and with more reserves available (Kalantzakos, 2018). However, it is not correct to attribute to the Chinese power all the reasons for its rise or the decline of the United States. Since, in many ways, powers other than the Chinese, for years have only been concerned about the fastest and safest way to obtain reserves of REEs, especially after the experience of the Chinese embargo, but only in the last period economic efforts have been made and not to find alternatives, even more ecological, to Chinese supplies. The prevailing feeling is that nations like the United States have focused on today's lack of material without thinking of making long-term investments.

The decline of the United States began in the early 1990s and became official in 2000. The American production in this period of time has recorded a drastic decrease not proportional to the increase of the Chinese production that instead, as shown in Figure 2.9, has skyrocketed (Goldman, 2014).

Figure 2.9 U.S. and China production in metric tons of REOs



Source: Goldman (2014), page 152

The main difference between the United States, from which China has learned, and the latter is that, after an initial moment in which the government provided mainly economic support, later the private sector with its investments were the only stimuli present (Goldman, 2014). So, if in the first period, especially between 1950s and 1960s, state aids in favour of the REEs sector were recorded, in the following period private interventions were not sufficient to support the domestic sector. This strategic choice was not made by China on the contrary, whose government invested in an aggressive research and development campaign, then took control of the national reserves and closely controlled private companies (Goldman, 2014).

The need for REEs became clear to the United States already with the end of WWII, since they were widely used in the military sector (Kalantzakos, 2018). At that time the main sources of these materials were India and Brazil from which America supplied itself in large quantities (Klinger, 2015). To avoid a dependence on Indian production, the United States committed itself to researching both domestic sources and suppliers from other parts of the world.

Just in 1949 the bastnaesite reserves in Mountain Pass, California, were discovered (Kalantzakos, 2018) and it was recognized as one of the largest and richest sites of the time. The reserve was taken over by the main American mining company, the MolyCorp., opened in 1953 (Kalantzakos, 2018). Initially it was involved in the production of europium from bastnaesite. The techniques were later improved, and the extraction of lanthanum, cerium, neodymium, and praseodymium were added (Hurst, 2010). The company created the main source at global level of these raw materials for the whole of America between the 1960s and 1980s (UNCTAD, 2014). The U.S. government in that period continued to support both public and private sector research so much so that in 1965 cobalt-samarium permanent magnets were discovered (Goldman, 2014) and, thanks to their important magnetic force and their small size, could be used in a wide variety of applications such as in the electronics industry but also in the medical and automation industries.

Thanks to these discoveries the demand for REEs grew so uncontrolled that the domestic demand registered by MolyCorp. increased from 1,600 metric tons of REOs in the 60s to 3,600 metric tons in 1965, reaching 18,000 metric tons only eight years later. However, the costs of these processes were very high and for this reason other combinations of materials were studied, from which the neodymium magnets that are still widely used today were discovered. MolyCorp. managed to provide 70% of world demand of REEs in the early 1980s (Goldman, 2014).

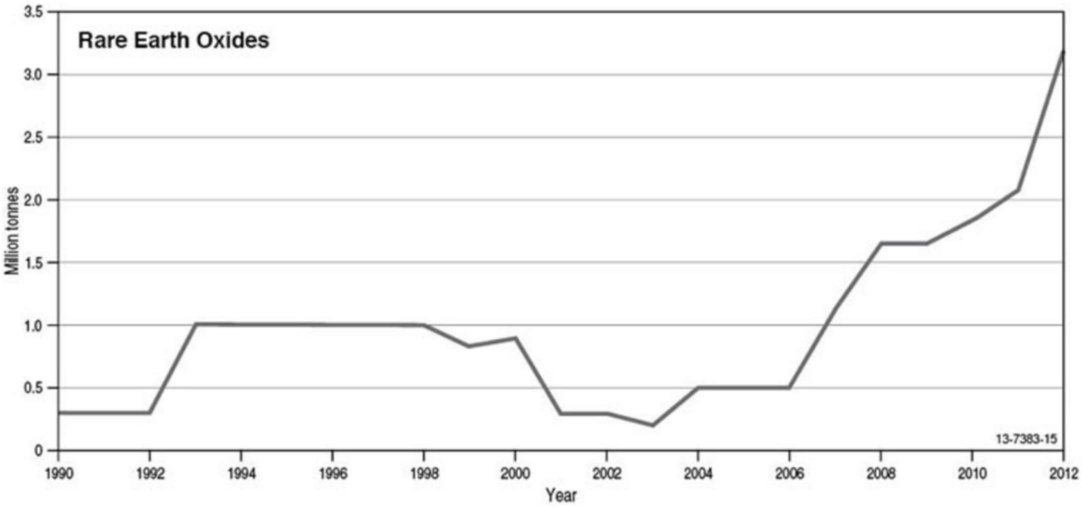
Nevertheless, the growth of the United States, which seemed to be unstoppable, sooner than one could imagine, was faced with a pupil who was able to learn from his history until it was able to overcome it, the Chinese colossus. An example of this can be found in the case of Neodymium–iron–boron (NdFeB) permanent magnets. The American company General Motors (GM) also invested in the development of this technology, but in 1995 two Chinese groups intervened by acquiring the section dedicated to the research and production of magnets. The agreement was sanctioned with the clause that the company would remain for at least five years in the U.S. territory but at the end of the period the production was transferred to China (Kalantzakos, 2018). This event demonstrates how China has never missed an opportunity to invest and acquire new skills outside its borders, while America has lost not only a business opportunity but at the same time also the technology. Moreover, the Asian counterpart was able to maintain extremely competitive prices compared to American ones thanks to the low cost of the workforce, environmental laws that were decidedly more flexible than those imposed by the American government (Ungaro, 2013).

Furthermore, it is important to recognise that not only the rules strictly imposed on the production of REEs had an impact on the American economy and production, in fact, the regulations applied to the final products that use these raw materials in the processing phases also had a strong influence, as for example in the oil industry (Goldman, 2014; Kalantzakos, 2018). Not even the giant MolyCorp. managed to survive and was shut down after a pipe burst threatening to turn into an environmental disaster in 1998. Added to this were state cuts to federal funds dedicated to research and development in the field (Goldman, 2014). The focus on REEs procurement in the U.S. has also increased in recent years due to the development of technology sectors such as hybrid cars. Both former President Trump and current President Biden have initiated and are pursuing policies aimed at developing the REEs industry and decreasing U.S. dependence on China as much as possible (Dreyer, 2020). The hope, in my opinion, is that the United States will be able to learn from the mistakes made in past years by trying to stimulate the production sector without forgetting investment in research, as well as recognizing the need for agreements with other countries to share know-how and create a stable production chain that respects environmental rules.

2.6.2 Australian production

The nation that has shown that it has sufficient reserves to meet at least a slice of the demand for raw materials and the capacity to process them is Australia, which accounted for almost 10% of world production in 2019 (Garside, 2021c).

Figure 2.10 Evolution of REOs resources in Australia



Source: Britt et al. (2013)

As Figure 2.10 shows, REOs resources in Australia have maintained an almost always positive trend, but a significant increase has only been recorded since 2006 (Britt et al., 2013). The main mining site is located in Mt Weld in Western Australia where the country's largest mining company, LynasCorp. operates. In addition to its bases in Australia, since 2012 LynasCorp. has also controlled a plant in Malaysia at the port of Kuantan; this choice is also dictated by the fact that the rules on the environment in this country are less stringent, allowing Australian industry to work under conditions similar to those in China (Lynas Corporation Ldt., 2020).

The Australian government, especially over the last two years, has been committed to implementing policies and legislation in favour of the mining sector by promoting a strategy known as Australia's Critical Minerals Strategy 2019 which includes actions to attract investment in the sector, incentives for research and development in the field, but also creating related infrastructure that can work together effectively to increase production levels (Australian Government, 2019).

Moreover, Australia’s ability to act as an alternative in supply diversification is also due to the fact that it has been able to enter into economic partnerships and agreements with powers such as the United States. Collaborations have also been made at political level to encourage joint work (Australian Government, 2019). In addition, one of LynasCorp.'s most recent projects is a collaboration with the United States company, the Blue Line Corp., for the opening of a processing plant in Texas, USA, in 2021 also thanks to funding from the U.S. government. The project will focus on the processing of HREEs, which tend to be more difficult to produce (Nainan et al., 2020). This will allow the Australian company to expand its reach and at the same time give the United States an opportunity to reduce its dependence on China (Gross, 2020).

Table 2.11 shows LynasCorp.'s sales volumes and sales revenue levels in terms of tons of REOs and Australian dollars respectively. Sales volumes have grown since 2017, but the figure that stands out among them all is the stop recorded in 2020. The cause is closely linked to the global pandemic situation that imposed the closure for the period between 23 March and 4 April 2020 and the relative slow recovery once the plants were restored (Lynas Corporation Ldt., 2020).

Table 2.11 LynasCorp.' sales volume and revenue between 2017 and 2020

	Sales Volume in tons of REOs (REOt)	**Sales Revenue in Australian dollars (A$m)**
2017	14,616	257.0
2018	17,672	374.1
2019	19,154	363.5
2020	14,172	305.1

Source: Lynas Corporation Ldt. (2020), page 8

It is important to remember that Australian production cannot compete with low Chinese costs and not even with high levels of Asian production, moreover it must comply with environmental laws in Australian territory and this makes it an unsafe alternative for some investors. Furthermore, as LynasCorp. extracts the resources on Australian soil but exports them to Malaysia for processing, any possible dispute between the governments of the two countries, as has already happened, fuels this uncertainty. Precisely for this reason, in recent years the company has decided to stockpile resources to try to respond to the growing demand in the future years (Nainan et al., 2019).

2.6.3 New global reserves

The race to find alternative sources of REEs has sparked interest in new deposits not yet considered. Among the different territories Greenland has emerged. According to some estimates, the Danish territory has a total of 38.5 metric tons of REOs, thus controlling a generous share of the total world reserves (Dempsey, 2020). Initially, the extraction of REEs was prevented by a declaration by Denmark in 1984. This ban specifically concerned harmful and radioactive materials but, since the extraction of REEs can also include elements such as thorium and uranium as waste, they were banned indirectly (Klinger, 2017). All this interest in Greenland has awakened Chinese attention, which has proposed a collaboration with mining companies in the area. Precisely for this reason, the United States and Australia are trying to gain control over the territory that seems to have the potential to become a worthy opponent to China's leadership on REEs (Vahl et al., 2013). The European Union, on the other hand, asked for preferential treatment which, however, was not granted (Klinger, 2017).

This project has positive aspects and others that are less so, in fact for many people it is seen as the possibility to increase the employment development of the island but at the same time the production of REEs is a process, as has been said several times, extremely polluting, for this reason there are various concerns for public and environmental health (Evans et al., 2016). The possibility of granting permits to international companies to establish new mining sites, could provide the economic independence necessary for Greenland to achieve complete autonomy from Denmark and therefore, more generally, from the European Union (Il Post Team, 2020).

However, the issue is not only economic but also political. As already mentioned, there have been numerous protests against the first concessions granted by the Siumut party in office to the Australian company Greenland Minerals to carry out research and evaluation in view of a possible mine near Mount Kuannersuit. This very discontent led to the fall of the government and the need to resort to early elections on April 6, 2021. The outcome of the vote has the power to influence decisions regarding the storage of REEs and other rare materials in the area. The biggest fear of local communities, which depend mainly on primary sectors, is the pollution of water sources (Il Post Team, 2021). However, according to the outcome of the elections, it seems that the possibility of establishing a mining site is shelved for now. In fact, the party which obtained the majority (36,6% against 29,4%) was the independentist party Inuit Atagatigiit, characterized above all by an environmentalist vision and therefore contrary to the project planned by the previous government (Gandolfi, 2021).

Another source of REEs is Afghanistan, which is listed among the top 10 mines globally. According to surveys conducted by the U. S. Geological Survey, the territory hosts 1.4 million tons of REEs (Katawazai, 2020). Interest in this territory comes primarily from the Soviet Union first, until 1989, and Russia later, between the 1970s and 1960s. Several powers have invested in geological operations in Afghan soil including the United

States and England, however these reserves are still considered less important than others (Klinger, 2017). According to some estimates, the deposits present in this extremely poor territory could reach the value of 3 trillion dollars (Katawazai, 2020).

However, it appears that there are also extraterrestrial sources of REEs, the Moon. Already since 1969 some scholars had analysed the lunar soil discovering the presence of these elements, then the supply crisis of 2010 and the consequent search for new sources has sharpened the interest (Klinger, 2017). Studying samples of lunar material recovered by the Apollo mission, some REEs components have been obtained as well as potassium (P) and phosphorus (K). However, to date it does not seem that the lunar territory hosts large quantities of these elements, at least not enough to be economically interesting (Jowitt, 2018). One aspect to be clarified regarding the exploration and therefore the search for REEs on the Moon will be to understand who will have the right to access these resources and under what terms. In fact, some private companies are involved in a program aimed at redefining the lunar territory as a common good not exploited (Klinger, 2017). It will certainly be interesting to see how the research evolves over the next few decades, and whether it will sooner or later be possible to use the space source as a reserve of REEs as well.

3. The Demand Side

This chapter intends to analyse the demand for REEs starting from the main sectors of use with a focus on the main players involved and the price trends of critical materials. It should be borne in mind that the demand for REEs on the world market is anything but static. It changes at relatively short intervals, mainly as a result of new developments and improvements in all sectors involving the use of these raw materials. For this reason, the study of the demand side presented in this thesis is a snapshot of recent years, but it is certain that there will be changes in the years to come.

The demand for REEs has increased dramatically, mainly due to technological developments in recent years, creating an unbalanced market. Global demand recorded in 2004 were 93,000 tons of REOs and increased to 126,000 tons in 2015 when production, mainly from China, reached merely 130,000 tons of REOs (Ortiz et al., 2014; Barakos, 2017). As detailed earlier, the characteristics of REEs that make them such strategically important materials are their versatility and inherent magnetism. They are in fact used in various fields of application among which the main ones are battery alloys, catalysts, ceramics, glass polishing powders, metallurgy and permanent magnets. According to the latest statistics in terms of volume of raw materials used, the permanent magnet and catalyst categories alone account for 60% of worldwide consumption in tons of REOs in 2018 (Castilloux, 2019).

On the other hand, if we look at the value, the magnets sector holds the lead with 90% consumption. This imply that the demand for neodymium, praseodymium, dysprosium and terbium will continue to increase (Castilloux, 2019). The strong growth in demand for REEs is mainly justified by the emerging clean and renewable technology sector. Indeed, recent discoveries in the field of electric motors or wind turbines to produce clean energy have contributed to the growing demand for these raw materials. By 2050, it has been estimated that more than 3 billion tons of minerals and metals will be used in the transition to a greener economy (The One Earth editorial team, 2021). Although China is the main producer of REEs production globally, it is important to remember that it simultaneously holds the role of the largest consumer of these materials along with the United States and Japan (Mancheri, 2012).

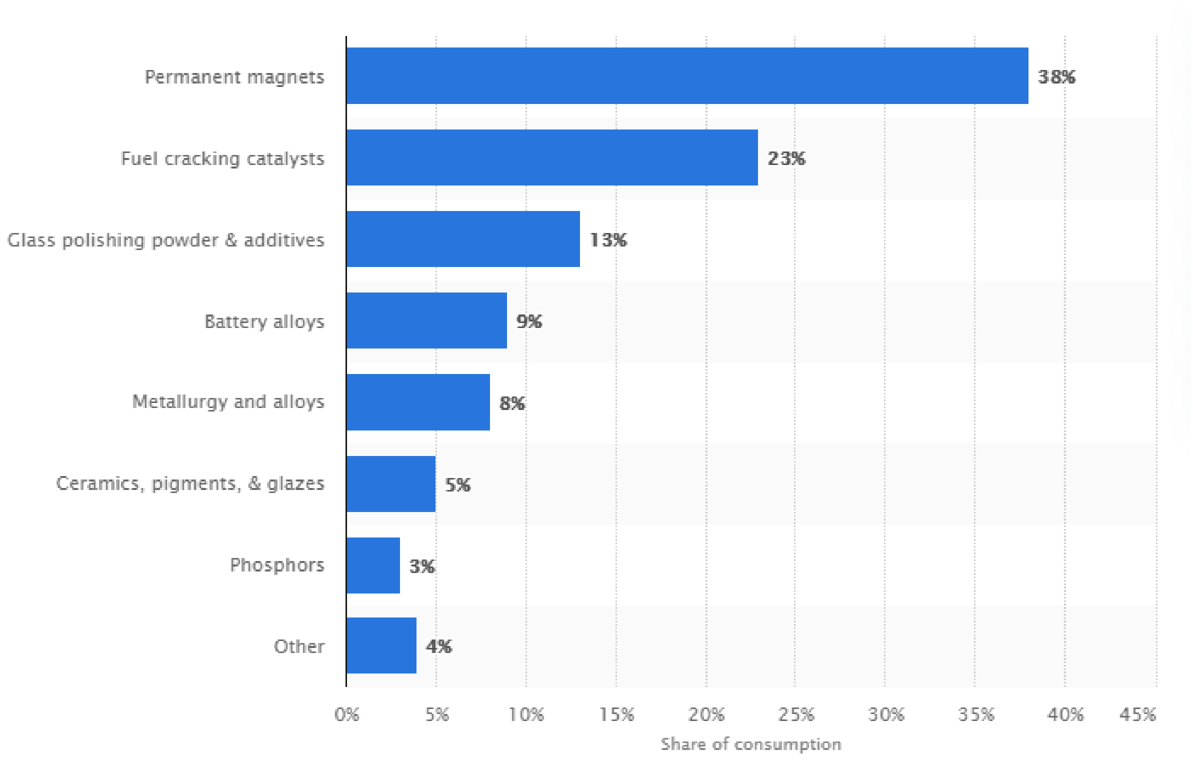
3.1 Global REEs Consumption

REEs consumption has increased dramatically since their discovery. Their versatility has made them critical materials in a variety of fields, from high technology to renewable energy production. This trend shows no sign of slowing down, fueled by the numerous discoveries in recent years. In general, the most abundant REEs, LREEs, are also the most widely used. However, HREEs remain central to a number of applications and are difficult to find, also due to their scarcity (UNCTAD, 2014).

The demand for REEs over the years has increased dramatically since mid-1990 reaching 75,500 tons of REOs in 2000. The peak was just before the supply crisis, in 2010, when demand reached 134,000 tons (Goodenough et al., 2017). In 2010, the crisis caused by China's export quotas prompted a rush for supplies and a consequent increase in demand. To protect their production lines, industries decided to stockpile as many raw materials as possible. However, following the dramatic rise in prices in 2011, consumption came to a standstill and companies producing end products on the basis of REEs looked to cheaper substitutes (Barakos, 2017). In any case, the demand for REEs can be attributed to a flow of constant growth, certainly due to the improvement of economic and standards of living conditions of the world as well as the increase in population (UNCTAD, 2014; Goodenough et al., 2017).

This upsurge has undoubtedly been driven by the introduction of new technologies. Specifically, Figure 3.1 shows the percentage of REEs consumption in the year 2019 according to different applications.

Figure 3.1 Global consumption of REEs by end use in 2019



Source: Garside (2020b)

It can clearly be seen that the main applications are permanent magnets, catalysts but and the glass polishing powder sector (Garside, 2020b). Historically, the nation that consumes the most strategic resources is also the largest producer, namely China. This is why, before the crisis, the Asian giant decided to place limits on exports. An attempt to preserve its reserves and the sources of consumption of its companies. This has also been made possible by the sudden growth of China's middle class, which has increased consumption of all personal and non-personal technologies that rely on the inherent capabilities of REEs (UNCTAD, 2014).

Economic and political crises such as the financial shock of 2008 and the supply crisis in 2010 that hit the REEs trade directly affected demand for these commodities. A significant decline was recorded in 2009 followed by a slight recovery and a subsequent collapse in 2011. Demand for REEs experienced a stable rebound from 2014 when it began its steady growth (ERECON, 2015). Moreover, as already mentioned, industrial consumption dictates the demand for resources, e.g. technological changes in the lighting industry have led to a shift from the use of Compact Fluorescent Light (CFL) lamps based on intensive use of REEs to Light Emitting Diode (LED) lamps, thus changing the demand for these raw materials. Table 3.2 shows the percentage of overall consumption per element (Seaman, 2019).

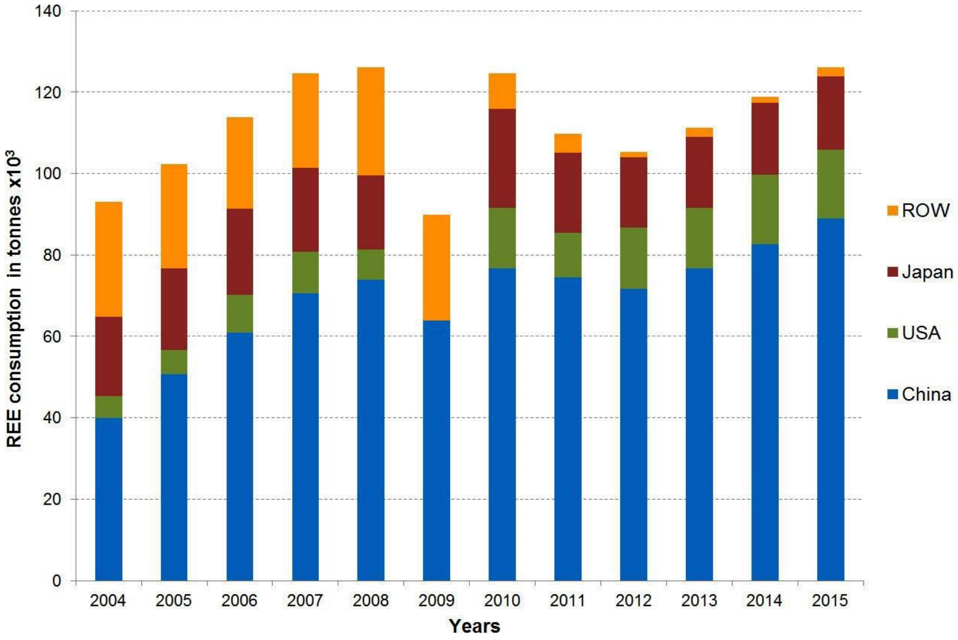
Table 3.2 Global REEs Consumption by element in 2015

Element	**Consumption Percentage**
Cerium	39.5
Gadolinium	1.1
Lanthanum	26.4
Neodymium	19.9
Others	1.9
Praseodymium	4.1
Yttrium	7.1

Source: Seaman (2019), page 18

Figure 3.3 compares the levels of consumption in China, Japan, United States and the rest of the world (ROW). The main global importer and consumer countries are Japan, United States and Germany in the European Union. However, China accounts for 60-70% of global demand for REEs, as shown in Figure 3.3. The U.S. recorded the import of about 18,500 tons of REEs in 2018, of which about 60% are used in the oil refining process (Schmid, 2019).

Figure 3.3 Global REEs consumption by country



Source: Barakos (2017), page 24

3.1.1 Chinese mutation: from main exporter to biggest consumer

REEs consumption in the Chinese industrial landscape has been increasing dramatically in recent years, thanks to the technological advancement and intellectual capital that China has been able to obtain and maintain. This is why it is interesting to see how the largest producer of REEs has also become the largest consumer at the same time. Between 2010 and 2012, China realized that its reserves would not last forever, particularly for HREEs, whose main deposits are almost exclusively in Asia. As time went on, China's own demand for REEs continued to grow, prompting it to look for new sites outside its borders where it could extract raw materials for processing and use by its own companies (Seaman, 2019).

Although data on Chinese consumption are not always available and those that are available are dated, it was not until 2000 that China's demand for REEs reached significant levels. Just in 2000, Chinese consumption was 19,000 tons of REOs compared to 91,000 tons of global consumption. The demand grew rapidly and by 2005 was already

52,000 tons, rising to 73,000 tons in 2009. At the same time, the consumption for personal technology such as laptops and smartphones, which are based on the characteristics of REEs, grew as the middle class grew. In these years, in terms of the sectors in which REEs held the role of central resources, 30% were in magnet manufacturing, 15% in metallurgy, and about 10% in chemicals and petroleum (Tse, 2011). The Chinese government's aim has always been to improve industries, such as the aerospace industry or the electricity industry, which use REEs and are considered crucial to the country's growth. To do this, China has focused on making available the raw materials needed by these sectors. For example, a sort of guide for the development of these sectors called 'Made in China 2025' has been created in 2015 with the intention of making the Asian country the new global leader of the future (Seaman, 2019). The aim of this policy is therefore to allow these sectors to maintain a stability that will give them the advantage they need to grow.

3.2 Main drivers of REEs consumption

3.2.1 History insights of Permanent magnets

As already mentioned, the major application of REEs are precisely the permanent magnets. Used in various industrial applications but also in everyday tools such as smartphones and tablets, permanent magnets have become indispensable. They allow the development of an increasingly modern technology and a sustainable and green economy by transforming energy into essential mechanical power for various applications.

The history of magnets began with the mineral lodestone, a material composed also of iron oxide that exerts an intrinsic attractive force. This was the first element in nature known to man with magnetic capabilities. It was discovered for the first time in Magnesia in Thessaly and it is from the name of this territory that the mineral was renamed magnet and magnetism (Mills, 2004). However, the knowledge of the phenomenon was still primitive and not very detailed. The first attempt to reproduce the magnetic properties was made around 1770's by an English scholar who, by mixing iron in water, managed to keep iron oxides in suspension (Moosa, 2014).

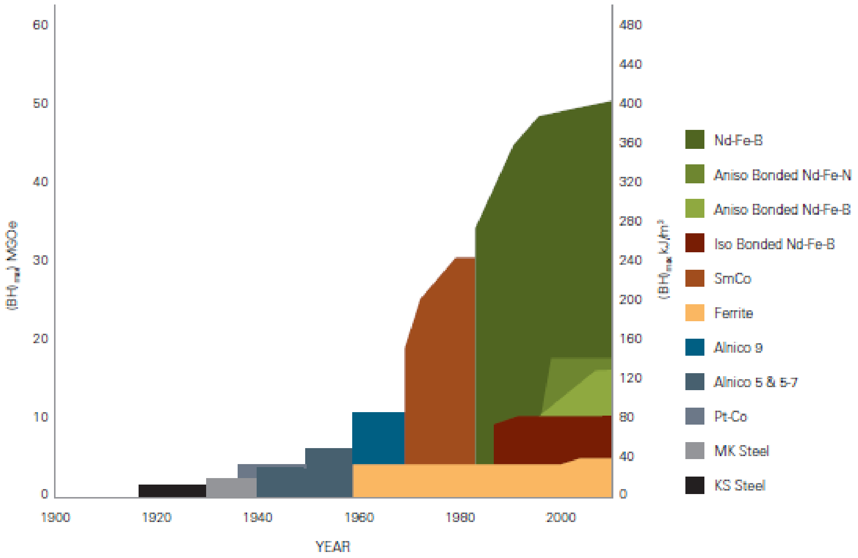
Later, in 1930, nickel, aluminum and iron alloy was introduced, creating a new generation of magnets named Alnico. In 1950's was introduced ferrite, a compound used as an alternative to Alnico, which is based on a mix of iron oxides, strontium carbonate and barium. It was successful mainly for the low production costs and the remarkable resistance to high temperatures but, at the same time, they are much more fragile (Moosa, 2014).

Though, the force exerted by this mineral was not sufficient. An improvement was obtained only in 1960’s with the discovery and use of REEs for the production of magnets which also improved the energy and coercivity, i.e. the magnetic intensity (Collins Dictionary, accessed 02/11/2020), of the magnets. It is, therefore, used for the first time the Samarium-Cobalt compound that allows creating magnets with high potential while maintaining an extremely small size. Moreover, this new type of magnet is more resistant than the ferrite version.

However, it was only in 1983 that magnets derived from the Neodymium-Iron-Boron alloy were created, thus generating a new group of permanent magnets based on the use of REEs, and in 1985 they replaced the Samarium-Cobalt (SmCo) magnets. Affordable but still characterised by high performance, neodymium magnets have the only problem of not being particularly resistant to high temperatures and also run the risk of corrosion if they come into contact with water (Moosa, 2014). In any case, they are still the best product today, especially for industrial, hi-tech and renewable energy applications since they are characterized by a high magnetic density despite their small size. The ability to guarantee a high level of attraction while maintaining a small size is what has made permanent magnets a key component of various end products (Hurst, 2010).

Figure 3.4 summarizes the development of the different materials used in the production of magnets over time.

Figure 3.4 Development of materials used for the production of permanent magnets



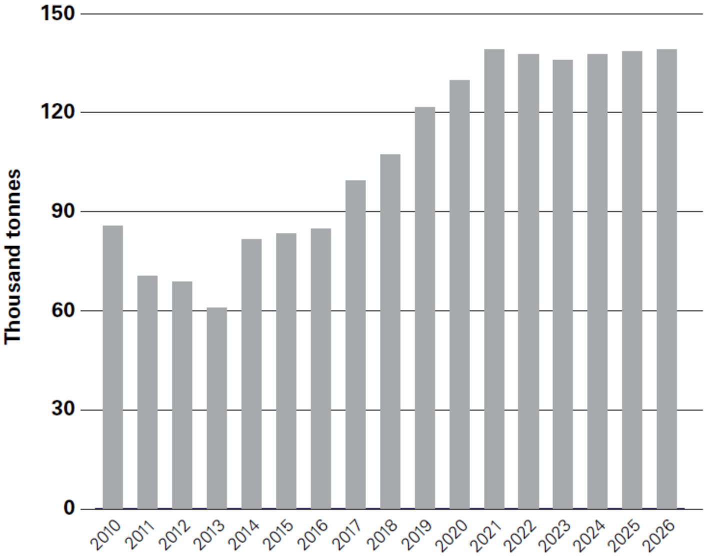
Source: ERECON (2015), page 22

The unit of measurement taken into account in this analysis is the maximum magnetic energy (BHmax) that these materials can reach. Ferrite is the only material that has not recorded a significant improvement. In a short space of time, therefore, permanent magnets became irreplaceable, and China set about securing the lead by acquiring the General Motors division specializing in the research and development of this particular product. In doing so, the main production moved to the Asian country, which at the end of 2007 had a production capacity of 80,000 tons with an annual growth rate of around 30% (Hurts, 2010).

3.2.2 REEs consumption for permanent magnets

Permanent magnets, thanks to their magnetic capacity and resistance to high temperatures in extremely small dimensions, have added value in various industrial applications and have become, to some extent, an indispensable part of life. In general, about two thirds of the magnets on the market are based on the use of compressed REEs (ERECON, 2015). The need to find REEs for their production has become a prerogative for several companies. Over the years, efforts have been concentrated on finding an alternative solution to the use of dysprosium in magnets, which gives the latter the ability not to lose their magnetic properties even at temperatures above 80°C. This element in particular is part of the HREEs extracted in smaller quantities, therefore more difficult to source, and available almost exclusively from the Chinese market, confirming once again the almost absolute dependence of the major industries on Asian production. For this reason, the objective of the major consumer countries of permanent magnets is to try to reduce the use of dysprosium from 4.5% to 1% in 2020 (Seaman, 2019).

Figure 3.5 Worldwide permanent magnets demand and forecast from 2010 to 2026

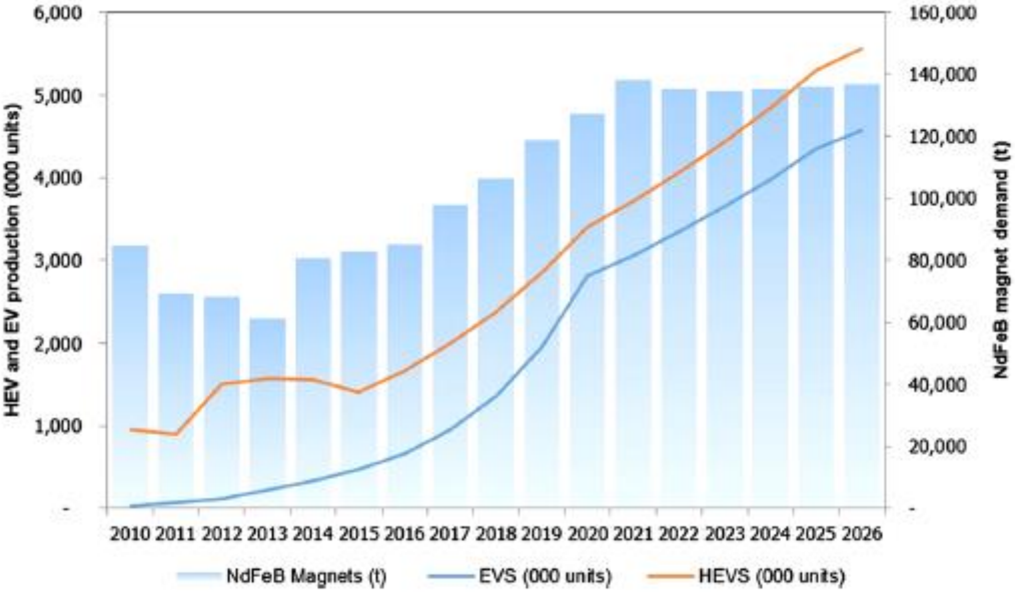


Source: Uren (2019), page 11

Figure 3.5 shows the change in demand for REEs permanent magnets from 2010 to a forecast of what consumption will be like in 2026. The most relevant data is the period between 2011 and 2013 where a drastic decrease in consumption is clearly visible when compared to the levels of the other years. Specifically, the production and consequently the consumption of magnets plummeted in 2010 from 85,000 tons to 60,000 tons. Signs of recovery were not seen until 2016 but the pre-crisis levels of 2011 were not fully restored until 2018 (Uren, 2019).

One of the main applications in which NdFeB permanent magnets are used, and which has led to a steep rise in demand for them in recent years are electric vehicles (EVs) and hybrid vehicles (HEVs). The production of this technology sold globally 2.3 million units in 2016 but is expected to reach 10.1 million units sold in 2026 (Goodenough et al., 2017). Figure 3.6 shows production levels for EVs and HEVs and the resulting demand for NdFeB magnets with a forecast through 2026. Interestingly, the significant increase in demand for the magnets coincides precisely with the development of the two green technologies. Increases in the consumption of neodymium, praseodymium and dysprosium have therefore been recorded (Goodenough et al., 2017).

Figure 3.6 Forecasting demand for NdFeB magnets and production of EVs and HEVs

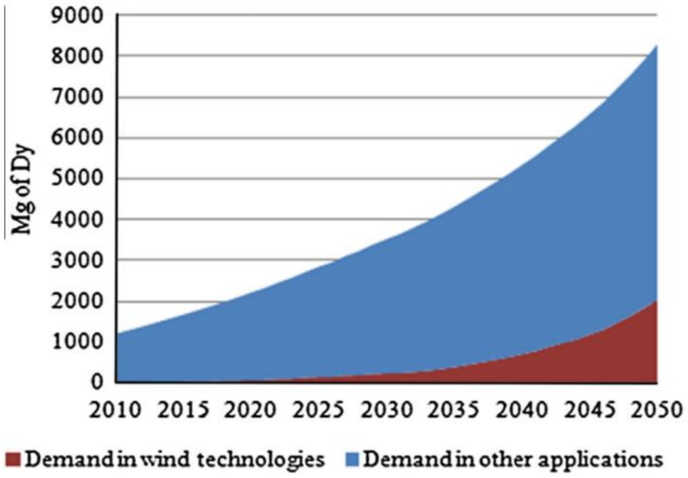


Source: Goodenough et al. (2017), page 203

At the same time, permanent magnets are also widely used in new technologies to support green energy. In order to meet the standards imposed by international agreements, in recent years the governments of several countries have begun to invest in applications to reduce emissions and produce the most renewable energy possible. The second most important application in which we find permanent magnets are the wind turbines. The clean energy produced by wind turbines has contributed substantially to global energy production, making them an important investment for major governments. This has implemented the need for REEs products including permanent magnets.

The main elements used for the production of permanent magnets are dysprosium and neodymium, which are among the most researched and least globally available REEs. The increased production of wind turbines has resulted in an increase in demand for these two materials as well. Specifically, Figure 3.7 represents the trend that has characterized the demand for dysprosium and the likely development through 2050. As can be seen, it seems that the increase in demand is inevitable, this is also thanks to the green sector (Elshkaki et al., 2014).

Figure 3.7 Dysprosium demand forecast



Source: Elshkaki et al. (2014), page 554

In 2016 alone, 8000 tons of permanent magnets were used to develop this technology. This has also contributed to the increase in demand for them and consequently for the REEs they are made of. In this particular case, however, only praseodymium and neodymium were used (Goodenough et al., 2017). Today, the percentage of wind turbines using magnets is 23%, although this is expected to grow to 72% in 2030 (Seaman, 2019).

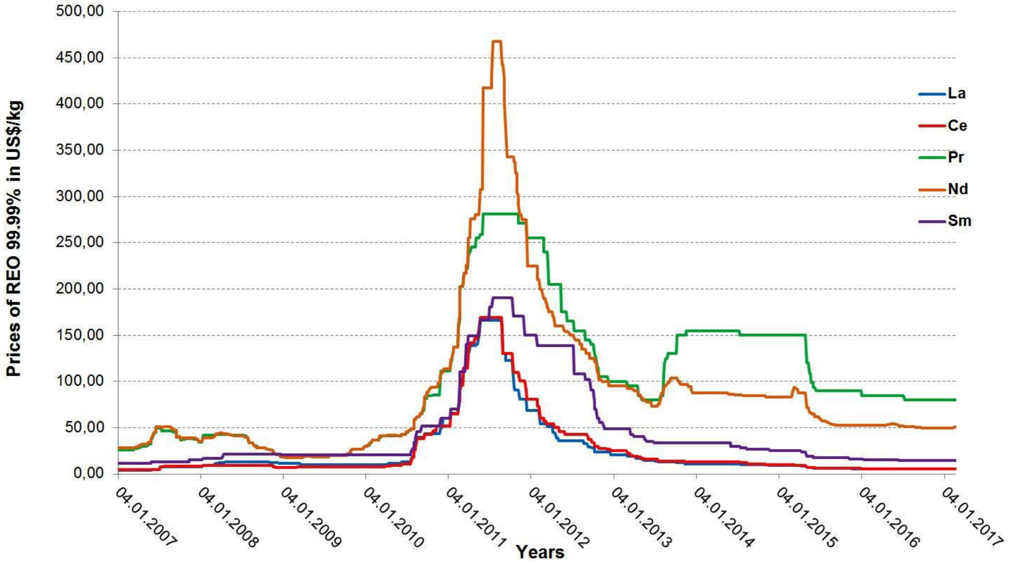
3.3 Rare Earth Prices

As has already been pointed out above, the REEs market is a very small but important market with very few producers. This commodity is currently not quoted at international level and for this reason it is difficult to create a clear picture of the level of demand and its prices. To date, there are no trade exchanges for REEs so consumers must make trade agreements and interface directly with producers (Leone, 2020). Precisely to try to keep the volatility of REEs prices under control, China has introduced serial indexes that are able to interconnect producers and buyers, among which China Rare Earth Price Index and China's Rare Earth Industry Prosperity Index (Gill, 2020). With the aim of connecting the major REEs companies and making the market and pricing mechanisms for REEs more transparent, the Baotou Rare Earth Products Exchange was established in 2013 following an initiative by China's leading company Baotou Steel Rare-Earth Hi-Tech Co Ltd (UNCTAD, 2014; China Briefing, 2014). A second attempt was made by the China Rare Earth Industry of Ganzhou in Jiangxi province, the second most important centre for REEs production along with the previous one. At the end of 2019, the Ganzhou Rare Metal Exchange was established to regulate the exchange of REEs with other metals (Daly et al., 2020). Surely the creation of a real exchange for the analysis of the REEs market would be a more practical and reliable tool.

In any case, it seems very difficult to predict the actual demand for REEs. The policy choices of the various actors involved, such as limits on Chinese exports, also have a direct effect on commodity prices. The political relationship between the U.S. and China itself has a direct impact on this market. Added to this is the growing need for raw materials from China itself, which has increased by around 30% in recent years, putting a strain on world supply (Yu et al., 2020).

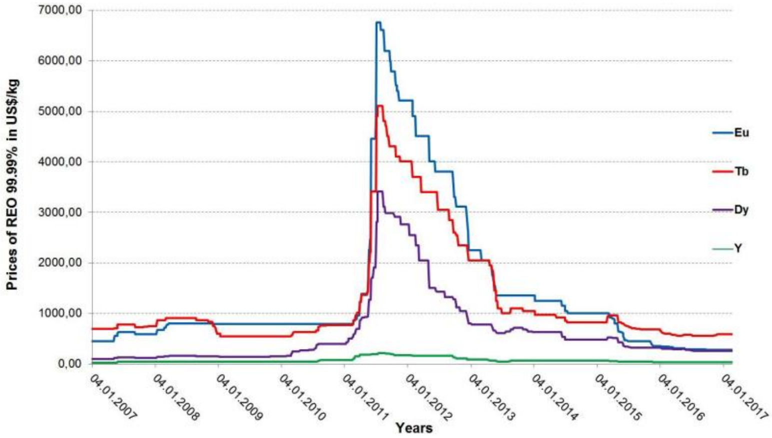
In general terms, HREEs have recorded higher and more volatile prices than the other group, due to their scarcity. Between 2001 and 2009, prices remained stable, but rose dramatically between 2011 and 2012, coinciding with the crisis at that time (UNCTAD, 2014). Figures 3.6 and 3.7 represent the price evolution between 2007 and 2017 for both LREE and HREE. The difference between the two trends does not lie in the peak they both record but in how the peak is presented. While in Figure 3.8 the prices of LREEs show an abrupt but constant increase as well as decrease, in Figure 3.9 the HREEs show an almost instantaneous increase and then a slower decrease. This shows that HREEs, being more difficult to source, have been more affected by the crisis and the resulting rush for supply. Neodymium and europium are the elements that have suffered most from the price increase, while yttrium has hardly been affected.

Figure 3.8 Prices development of the main LREE between 2007 and 2017



Source: Barakos (2017), page 19

Figure 3.9 Prices development of the main HREE between 2007 and 2017



Source: Barakos (2017), page 19

In fact, the 2010 supply crisis stimulated a race for supplies by all major consumers of REEs, which resulted in higher prices. REEs used in the production of magnets as neodymium rose from $45 per kilogram in 2007 to $270 in 2011. An upward trend was also recorded for dysprosium, which in the same years rose from $170 per kilogram to nearly $1,600. Even the most abundant REEs saw their prices rise unchecked, with cerium, for example, going from $30 per kilogram in 2008 to $100 in 2011 (Paulick et al., 2017; Uren, 2019).

Table 3.10 Price evolution of REEs between 2009 and 2012

REEs	**2009**	**2010**	**2011**	**2012**	**Price fall from 2011 to 2012 (in %)**
Ce	4,5	61	158	42,5	73
Eu	450	630	5870	4010	32
La	6,25	60	151,5	36	76
Nd	14	87	318	154	52
Pr	14	86,5	248,5	175	30
Tb	350	605	4410	3400	23

Source: Charalampides et al. (2016), page 4

Table 3.10 shows the decrease in prices in US$/kg and in percentage terms between 2011 and 2012, after an initial increase between 2009 and 2011. In particular, the greatest loss was recorded for cerium and lanthanum, whose prices fell by 73% and 76% respectively. After 2012, prices recovered to pre-crisis levels in 2010.

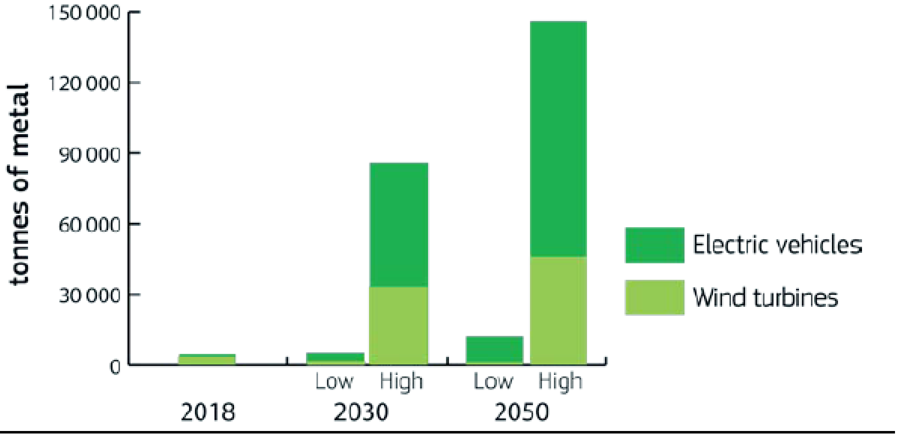
3.4 Future demand scenario

As already mentioned in the previous pages, what is clear is that the trend in demand for REEs tends to be always positive and to grow more than proportionally to the rate of supply. However, it is not yet possible to know with certainty how much demand will exceed supply. Various studies, analyzing the data currently in possession, have attempted to hypothesize the various scenarios that may occur in the future. In any case, it is important to remember that among the values considered, the effects of the Covid-19 pandemic and the related economic crisis have not been taken into consideration, since it is not yet possible to estimate the damage suffered (Alves Dias et al., 2020).

The expected annual growth rate for REEs demand is 6-7%, with a slight decline between 2024 and 2029 at a rate of 2.1% (Alves Dias et al., 2020). Other research suggests that demand for these critical materials could increase by up to 90% by 2050 (Chasan, 2020). The area that seems to be growing at a rapid pace is permanent magnets (Alves Dias et al., 2020). As a consequence of this there will be an increase in demand for the two main metals for magnets i.e. neodymium and dysprosium. The final two sectors that look set to grow significantly in the future are green energy applications such as electric vehicles and wind turbines.

As Figure 3.11 shows, certainly the demand for REEs needed for green applications will tend to increase in both the low and high scenarios. The element that stands out for sure is the vertiginous increase of the electric vehicle sector that in each case seems to increase more than wind turbines. It is, however, important to place the data in the actual context of the sectors analyzed and to take into account the technological advancement that affects them. In conclusion, it will be interesting to monitor the evolution of demand also based on the improvements that will be introduced in the green economy.

Figure 3.11 Future demand forecast of the main REEs for EVs and Wind Turbines



Source: Alves Dias et al. (2020), page 14

4. The Balance Problem

One of the main hindrances that the REEs market must face is the so-called Balance Problem. The Balance Problem, or Balancing Problem, refers to the balance between the demand by the economic markets and the natural abundance of the REEs in ores (Binnemans et al., 2013a). The issue concerns above all the volume of the material used, in fact, some REEs are technologically fundamental but still have a limited application. When a material is extracted, the elements that compose it cannot be selected and excluded, if not necessary. All components are always mined to obtain the materials that are in short supply, even those whose stock is present in abundance. For example, the extraction of the key and hard-to-find element for permanent magnets, neodymium, involves at the same time the production of other much more abundant REEs as cerium (Binnemans et al., 2013b). This leads to an imbalance in the storage of these raw materials. Maintaining the balance is crucial not only to prevent stocks from no longer meeting demand but also to avoid a price shock for all REEs considered critical. The best desirable condition is precisely the balance between supply and demand for each specific product. However, it is easy to deduce that obtaining the perfect equilibrium is extremely difficult. It is an idyllic condition that is difficult to obtain due to technological evolutions in application. Nevertheless, the REEs sector is trying to develop different solutions to solve this problem, for example thanks to the use of substitutes or stimulating REEs recycling.

4.1 Evolution of the Balance Problem

Initially, the Balance Problem was not given proper importance because the REEs market was based on the supply of mixed REEs, among which the most important was mischmetal, and no separation into pure form was required (Binnemans et al., 2018). Mischmetal is a term derived from German and refers to a mix of metals composed mainly of cerium and lanthanum, but in which is also present a small part of other REEs such as neodymium and praseodymium. With the creation of the first mischmetal from monazite ore, the REEs metals industry was born (Binnemans, 2015).

This situation quickly turned into an issue in the late 1960s and early 1970s, when europium, a pure REE, was first used. It was considered as a critical REE because it has a low natural abundance and it was high in demand (Binnemans, 2015). In the end of 1970s and at the beginning of 1980s, another element became extremely critical, i.e. samarium. It was fundamental for samarium-cobalt permanent magnets: when a limited availability of samarium was recorded, the consequence was a vertiginous increase in price (Binnemans et al., 2013a). Later, in order to satisfy the high demand of permanent magnets, neodymium and dysprosium became the main critical REEs.

In general, the minerals contain a REEs mixture that does not always meet the needs of the markets. The consequence is therefore an oversupply for some REE, such as lanthanum and cerium. This causes the prices for highly demanded materials to increase exponentially while those of the overrepresented elements decrease dramatically.

Table 4.1 HREE and LREE supply balance forecast for 2020

REOs Group	**Production in tons of REOs**		**Demand in tons of REOs**	
	World	*China*	*World*	*China*
Lanthanum (La) and Cerium (Ce)	122,500	70,000	95,000	55,000
Praseodymium (Pr), Neodymium (Nd), Terbium (Tb), Dysprosium (Dy)	36,000 (excludes recycled swarf)	23,500	45,000	36,000
Europium (Eu), Terbium (Tb), Erbium (Er), Yttrium (Y)	10,500	7,500	8,000	7,000

Source: ERECON (2015), page 69

Table 4.1 shows the difference between production and demand forecast for 2020 regarding the main REEs-extracted in tons of REOs both in the World and in China, since the latter is the largest supplier of REEs but also the largest consumer. The elements taken into consideration as example are: lanthanum and cerium as they are the most overproduced REEs; praseodymium, neodymium, terbium, dysprosium and europium, terbium, erbium, yttrium because they are the REEs used for the two main applications, permanent magnets and lamp phosphors (ERECON, 2015).

As can be seen from the Table 4.1, as far as the first pair of elements is concerned, production far exceeds demand. This is not the case for the second group of elements whose production, both worldwide and in China, cannot fully satisfy market demand. The direct consequence is therefore an imbalance between supply and demand in the market. Another factor to consider is that some REEs are mined as products of a major metal. This obviously has as a direct consequence the lowering of costs since the extraction of the metal would have happened in any case but, at the same time, the extraction of REEs is subordinate to the request of that metal (ERECON, 2015).

However, it is important to remember that the REEs market is constantly changing, above all because the importance of some REEs also depends on the technological progress that conditions their application. The more the technology evolves the more there will be a need for specific REEs.

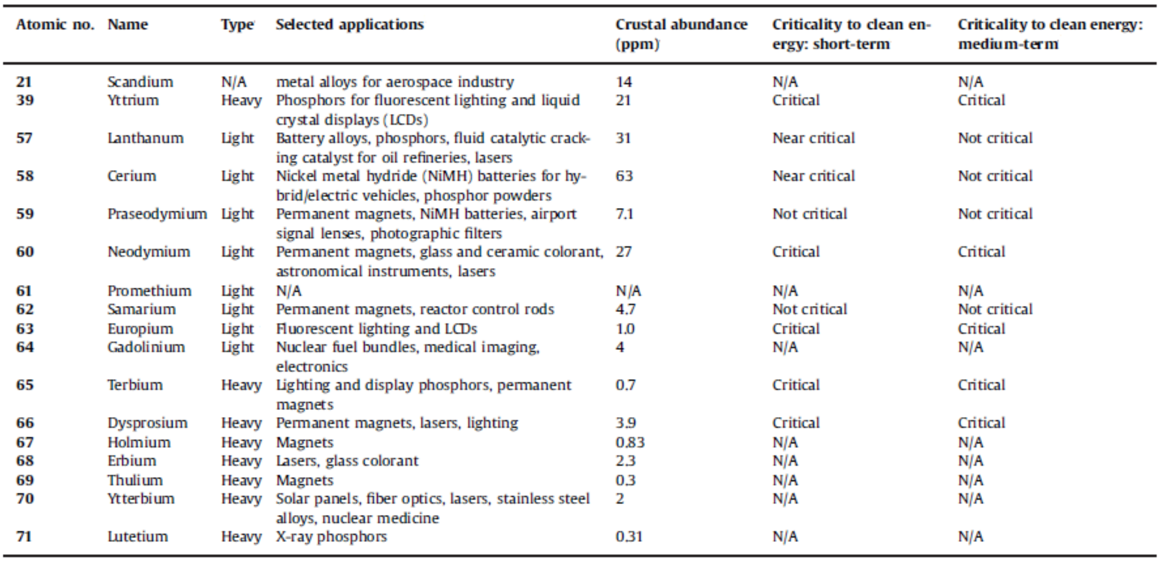
4.2 The evolution of the criticality of REEs since 2011

The role of REEs has always been fundamental to progress and for global economy. With the introduction and development of new solutions, innovations and technologies that exploit the adaptability of REEs, the need to ensure constant supply has become paramount. For this reason, the demand for certain raw materials including REEs has increased proportionally to the diffusion of these innovations. However, over the years, the criticality of each individual REEs has changed. Criticality is a dynamic state that changes over time and for this reason it is necessary to evaluate it periodically because the elements that we define as necessary today may not be essential anymore in a few years (Binnemans et al., 2018).

Different methodologies have been used to assess the criticality level of raw materials and, in particular, REEs. It can be measured both at global and regional level. Moreover, it is fundamental to stress the difference between the concept of criticality from that of resilience. The first is an analysis of the current situation, whereas resilience is related to the response of the system (Binnemans et al., 2018).

In order to estimate the evolution of the market and be able to secure access to raw materials, including REEs, in 2011 the United States Department Of Energy (US DOE) released a report in which it analyzed the level of criticality of the various elements used in different technological and green economy applications. In the Table 4.2, the various subjects were classified according to the possible scarcity of reserves in the short (from 0 to 5 years) and medium (from 5 to 15 years) (Stegen, 2015).

Table 4.2 Classification of REE according to their criticality (US DOE)

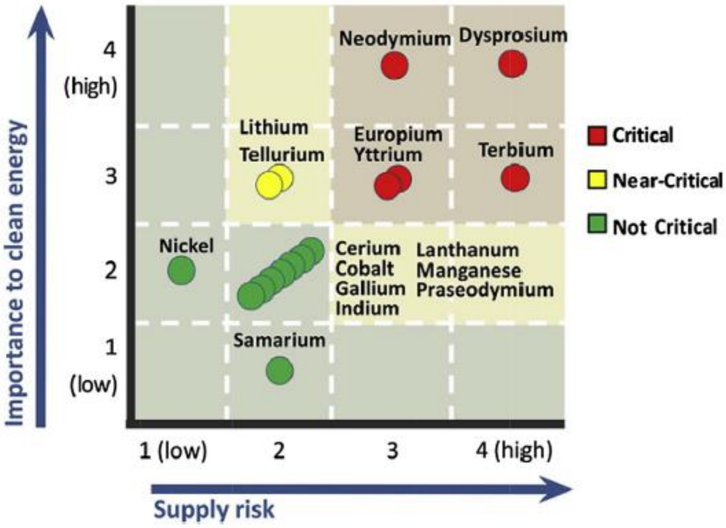


Atomic no.	Name	Type	Selected applications	Crustal abundance (ppm)	Criticality to clean energy: short-term	Criticality to clean energy: medium-term
21	Scandium	N/A	metal alloys for aerospace industry	14	N/A	N/A
39	Yttrium	Heavy	Phosphors for fluorescent lighting and liquid crystal displays (LCDs)	21	Critical	Critical
57	Lanthanum	Light	Battery alloys, phosphors, fluid catalytic cracking catalyst for oil refineries, lasers	31	Near critical	Not critical
58	Cerium	Light	Nickel metal hydride (NiMH) batteries for hybrid/electric vehicles, phosphor powders	63	Near critical	Not critical
59	Praseodymium	Light	Permanent magnets, NiMH batteries, airport signal lenses, photographic filters	7.1	Not critical	Not critical
60	Neodymium	Light	Permanent magnets, glass and ceramic colorant, astronomical instruments, lasers	27	Critical	Critical
61	Promethium	Light	N/A	N/A	N/A	N/A
62	Samarium	Light	Permanent magnets, reactor control rods	4.7	Not critical	Not critical
63	Europium	Light	Fluorescent lighting and LCDs	1.0	Critical	Critical
64	Gadolinium	Light	Nuclear fuel bundles, medical imaging, electronics	4	N/A	N/A
65	Terbium	Heavy	Lighting and display phosphors, permanent magnets	0.7	Critical	Critical
66	Dysprosium	Heavy	Permanent magnets, lasers, lighting	3.9	Critical	Critical
67	Holmium	Heavy	Magnets	0.83	N/A	N/A
68	Erbium	Heavy	Lasers, glass colorant	2.3	N/A	N/A
69	Thulium	Heavy	Magnets	0.3	N/A	N/A
70	Ytterbium	Heavy	Solar panels, fiber optics, lasers, stainless steel alloys, nuclear medicine	2	N/A	N/A
71	Lutetium	Heavy	X-ray phosphors	0.31	N/A	N/A

Source: Stegen (2015), page 2

The terms of comparison used by the US DOE are the REEs importance to the clean energy and the intensity of the supply risk. In Table 4.2, items are classified as critical if they have a high-risk index in the short and medium term, while items with a low risk index in the long term are classified as non-critical or near-critical.

Figure 4.3 Criticality matrix in the medium term (US DOE)



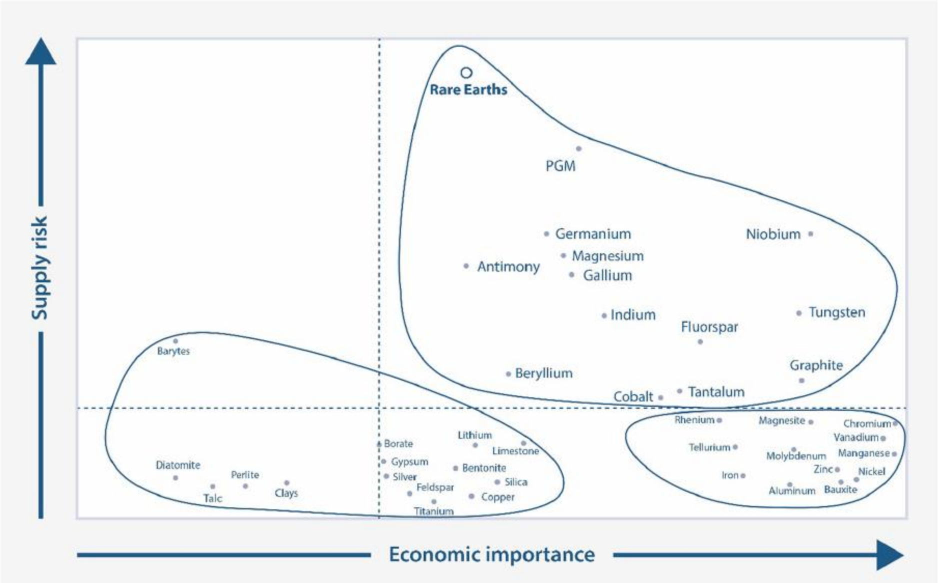
Source: Binnemans et al. (2013b), page 4

The same result comes introduced in Figure 4.3 from which it emerges that in the medium term five are the REEs that are considered particularly critical, namely yttrium, europium, terbium, dysprosium and neodymium (Stegen, 2015).

Similarly, the European Commission has studied and analysed the raw materials considered critical. Due to the European commitment to the implementation of a circular and green economy, the strategic need to find raw materials, in particular REEs, has become a central issue in European policy. Every three years, starting from 2011, a list was released which summarized all the Critical Raw Materials (CRMs). These lists are based on two fundamental criteria: the economic importance of the resources in question and the risk of supply. The following Figures 4.4, 4.5, 4.6 and 4.7 propose the evolution of the level of criticality of the various raw materials, including REEs, according to the European Commission, from 2011 to 2020.

The graphs are divided into four quadrants, in the upper-right corner there are raw materials characterized by a predominant economic importance and a high risk of supply. In the Figure 4.4, the REEs are grouped together and they can be found in the upper-right quadrant of the graph which corresponds to a high risk of supply and at the same time to a marked economic importance.

Figure 4.4 European Commission: Critical Raw Materials (CRMs) in 2011

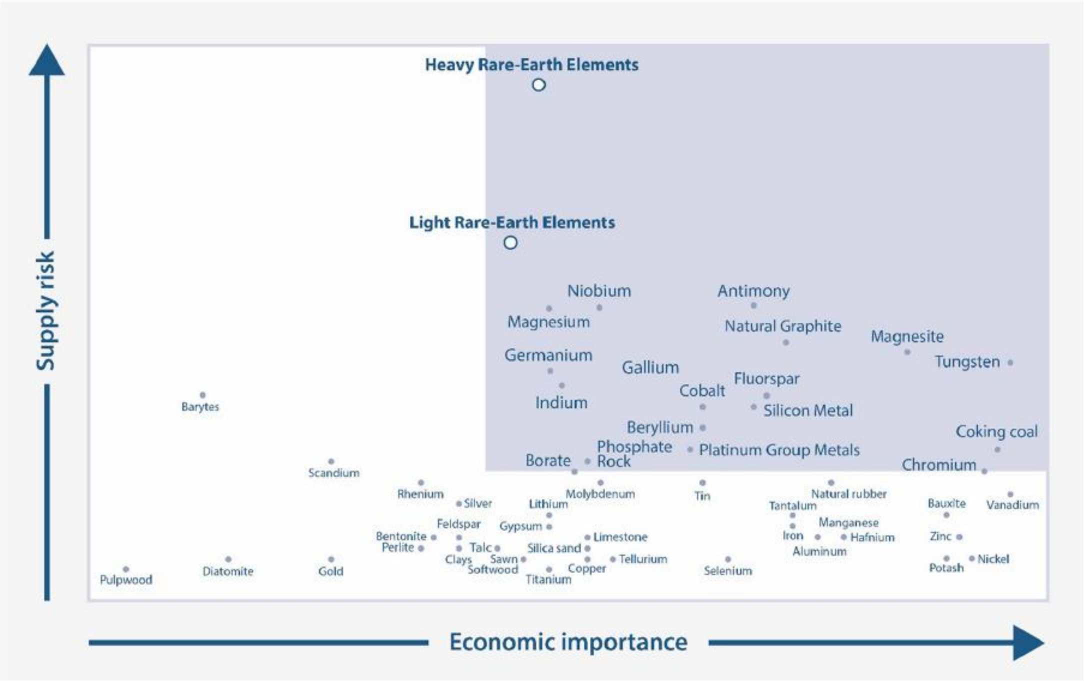


Source: Binnemans et al. (2018), page 128

However, the choice of bundling the different REEs in a single group does not allow to effectively understand the availability of each individual element and also fails to take into account the fact that, within the macro-group of REEs, the degree of criticality may differ from element to element (Binnemans et al., 2018).

The group of REEs produced the most is that of LREEs since the extraction of a REEs often systematically involves the extraction of others associated with it. On the contrary, HREEs are produced less but also have a lower demand (Ganguli et al., 2018). Precisely for this reason, in the next report it was decided to consider the REEs not as a single group, but the difference between LREEs and HREEs was respected. This has made it possible to present an analysis that is at least more precise than the previous one, even if it would be interesting to know the position in the graph of each individual element within these two macro groups. As shown in Figure 4.5, in the report drawn up in 2014, HREEs are the most critical in terms of risk of supply in comparison with LREEs, although they still show a common level of economic importance.

Figure 4.5 European Commission: Critical Raw Materials (CRMs) in 2014

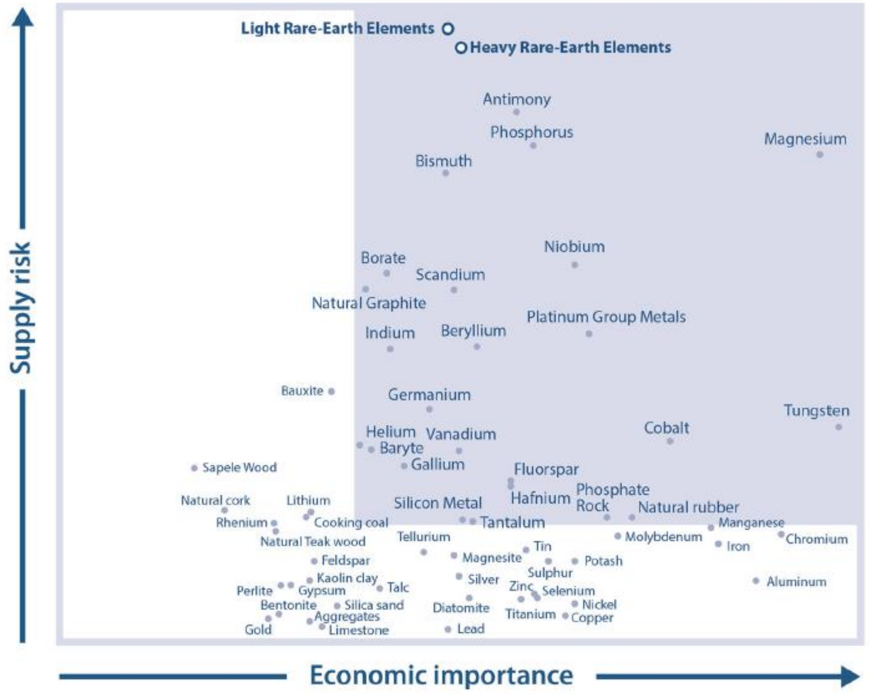


Source: Binnemans et al. (2018), page 129

While remaining among the raw materials with a higher degree of criticality, in the European Union report drawn up in 2017 there is a clear deviation from the two previous reports. In fact, the Figure 4.6 shows that the HREE group, although still at the top of the graph, is slightly below the second one.

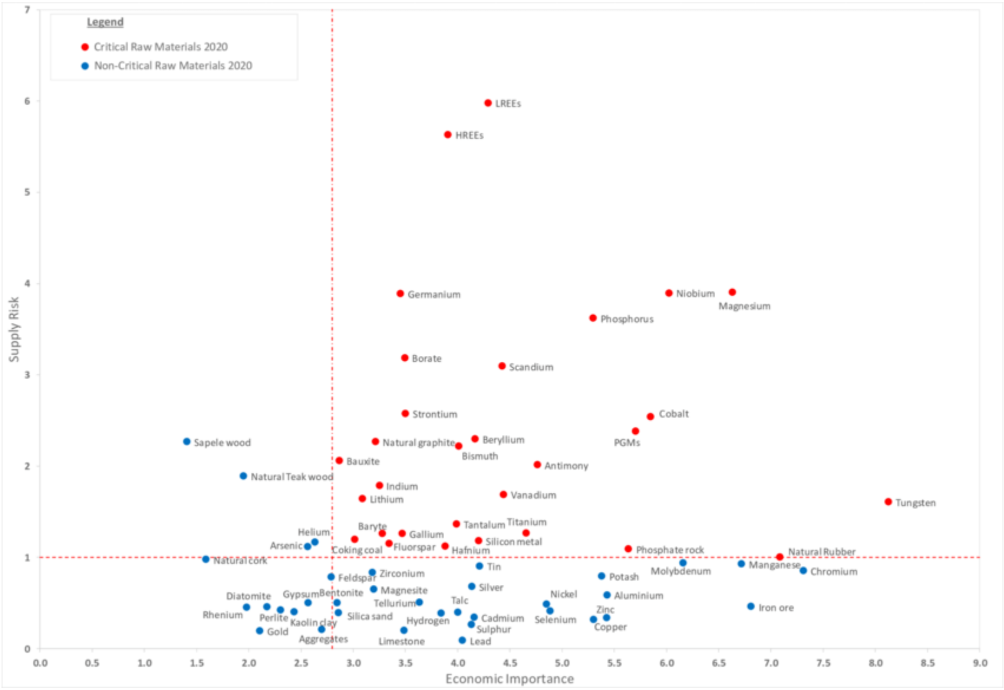
The same discrepancy was maintained for the year 2020. As can be seen from Figure 4.7, LREEs are still in the top left position in the graph, i.e. they are considered more critical than HREEs even though they are also in the same quadrant.

Figure 4.6 European Commission: Critical Raw Materials (CRMs) in 2017



Source: Binnemans et al. (2018), page 129

Figure 4.7: European Commission: Critical Raw Materials (CRMs) in 2020



Source: European Commission (2020a), page 3

This difference has several causes, among which it is possible to include the decline in the market for fluorescent lamps but also the attempt of reduction in the use of dysprosium in the production of NdFeB magnets (Binnemans et al., 2018). The results for the groups of elements were calculated on the arithmetic mean of the results of each individual material making up the group.

The latest updated list was released by the European Commission in 2020, see Table 4.8, in which HREEs includes dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium; while LREEs includes cerium, lanthanum, neodymium, praseodymium, samarium. This list contains 30 raw materials, in contrast with the list of 2011 in which 14 items were included, the list of 2014 in which 20 were present and the list of 2017 with 27 materials. For the first time, bauxite, lithium, titanium and strontium were also considered as critical materials, unlike helium which, despite continuing supply problems, has become economically less predominant therefore it was not included.

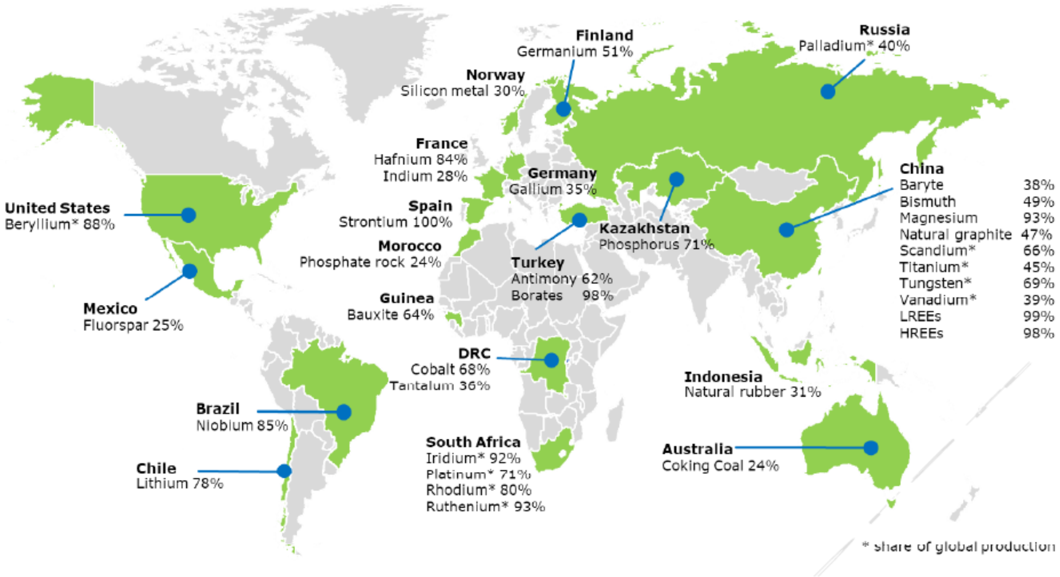
Table 4.8 List of CRMs in 2020 according the European Commission

Critical Raw Materials in 2020				
Antimony	Coking Coal	**LREES**	Phosphate rock	Tungsten
Baryte	Fluorspar	Lithium	Platinum Group Metals	Vanadium
Bauxite	Gallium	Magnesium	Scandium	
Beryllium	Germanium	Natural Graphite	Silicon metal	
Bismuth	Hafnium	Natural Rubber	Strontium	
Borate	**HREES**	Niobium	Tantalum	
Cobalt	Indium	Phosphorus	Titanium	

Source: European Commission (2020b), page 3

According to the report of the European Commission (European Commission, 2020b), the risk of supply can be caused by various factors including the monopoly of a single nation, which in this case would be represented by the control of China, and the difficulty of finding the raw material due to the political and social instability that characterizes some countries where the deposits are located. As can be seen from Figure 4.9 the supply of various critical raw materials is concentrated in certain geographical areas: mainly in Asia, Brazil and the United States.

Figure 4.9 European Commission: Main suppliers of CRMs in 2020



Source: European Commission (2020b), page 4

However, it should be kept in mind that the data reported in the previous Tables and Figures are to be considered as a snapshot of the moment in which they were processed and also taking into account the recent past. The reports must be evaluated carefully as the situation can change drastically and rapidly.

Moreover, the level of criticality is closely linked to the demand for a particular REEs, i.e. REEs that are not used for particular applications there is no criticality even if the risk of supply is high. The central element for the evaluation is therefore the importance of the material in the market. For example, since holmium demand is relatively lower than that of the dysprosium, the risk of holmium supply will have less impact on the economy than that of the dysprosium. Logically, as a consequence, a significant increase in demand can result in an increase in the criticality level of the substance because this higher demand can lead to scarcity of the resource and a consequent increase in price (Binnemans et al., 2018).

4.3 Specific application: Neodymium

Since they are used to produce essential elements in various engineering applications, REEs are referred to as "enablers" (Kalantzakos, 2018). The elements that make up the REEs group can have two functions: they can be "process enablers" or "product enablers" (ERECON, 2014). In the first case the REEs are used within the production process but without composing the final product. On the contrary, in the second case, the elements are directly inside the product giving it unique properties.

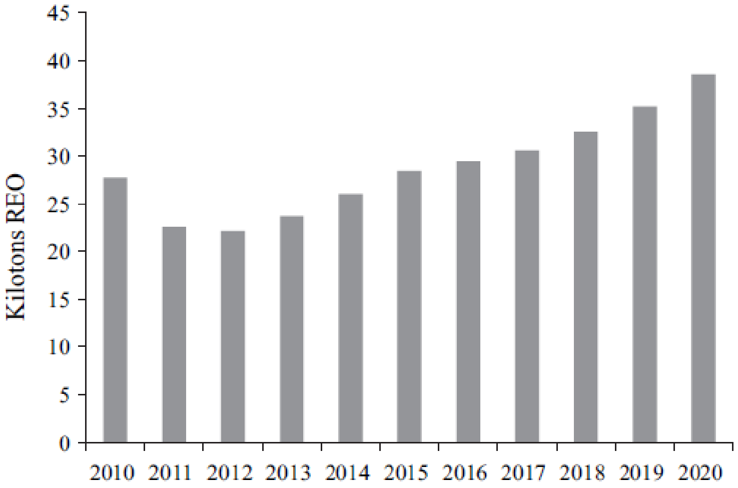
The most important examples of this second category is neodymium for LREEs and dysprosium for HREEs. Both elements are fundamental for one of the most important applications, i.e. permanent magnets. The use of REEs in this specific case allows to increase the attraction force of the magnets according to the volume, thus improving high-tech products such as electric motors and turbines. About two-thirds of the permanent magnets used today contain REEs (ERECON, 2015).

The magnets, produced using REEs and developed in the 1970s and 1980s, are based on the use of two NdFeB or SmCo alloys. The wider market focuses on the former, although the availability of samarium is greater than that of neodymium and the latter is less abundant. This is because, as mentioned in the previous paragraphs, NdFeB alloy is more in demand in applications requiring high performance magnets. At present, the share of SmCo magnets in the permanent-magnet market is less than 2%, and an excess of samarium is being produced (Binnemans et al., 2018).

Small quantities of other metals are used to improve the characteristics of the magnets, in this case it is necessary to remember the dysprosium. This material is essential to

improve the resistance to demagnetization and to increase the Curie temperature, i.e. the temperature at which they lose their magnetic properties (Rollat et al., 2016).
To date, there are no materials with better qualities than NdFeB for the production of permanent magnets. On the market, neodymium is therefore the most important REEs due mainly to its use and application in magnets. It is estimated that the consumption of permanent magnets will continue to increase at a rate of 7% per year, with a total estimated increase of 80% for the period between 2010 and 2020 (ERECON 2014).

Figure 4.10 Evolution and forecast of the global consumption of REEs in NdFeB magnets (in kilotons) from 2010 to 2020;



Source: Rollat et al. (2016), page 432

As can be seen from Figure 4.10, the demand for neodymium and dysprosium is expected to increase exponentially, as they are indispensable materials for the production of NdFeB magnets, a technology necessary for the transition to a green economy (ERECON, 2014). It is therefore clear that neodymium and dysprosium will remain for some time yet the two most important REEs and their complete replacement with a similar material, such as praseodymium for the first element, seems to be not enough.

4.4 Balance problem: possible solutions

Continuing to extract REEs with high demand and accumulate others with low request cannot be a long-term sustainable solution. This strategy has the only effect of constantly increasing raw material prices since the production practice of REE mixtures is extremely expensive (Binnemans et al., 2013a). Although many mining companies are looking for new deposits and many old sites that were decommissioned are now being reopened, many countries are looking for alternative solutions to survive the lack of critical REEs. To date, several possible solutions have been examined to deal with the balancing problem. These include diversification of resources, reduction of their use, introduction of new applications, substitution and, especially recycling (Binnemans et al., 2013a). Moreover, it is essential to underline that with these solutions it is also possible to minimize the environmental impact that the extraction practice has, aspect that will be analyzed in the following chapter.

The first possible way to reduce at least the problem of balancing is to diversify resources. It is possible to incur new minerals from those usually mined if new research projects are developed and thus new deposits are triggered. For example, phosphate rocks, generally used to produce phosphate-based fertilizers, are an alternative source of REEs. Another alternative source for the extraction of REEs is industrial waste from, for example, aluminum production (Binnemans, 2014). However, it is not so easy to create a new mining site, moreover several years are needed for a mine to be considered fully developed.

Alternatively, trying to use limited quantities of REEs that are considered critical may be another solution. However, in this case it is necessary to verify that the performance of the final products is not compromised (Binnemans, 2014). An example is the use of dysprosium in permanent magnets. Its use is necessary so that the magnetization remains even at high temperatures but if this characteristic is not preponderant, its use would be a waste (Stegen, 2015).

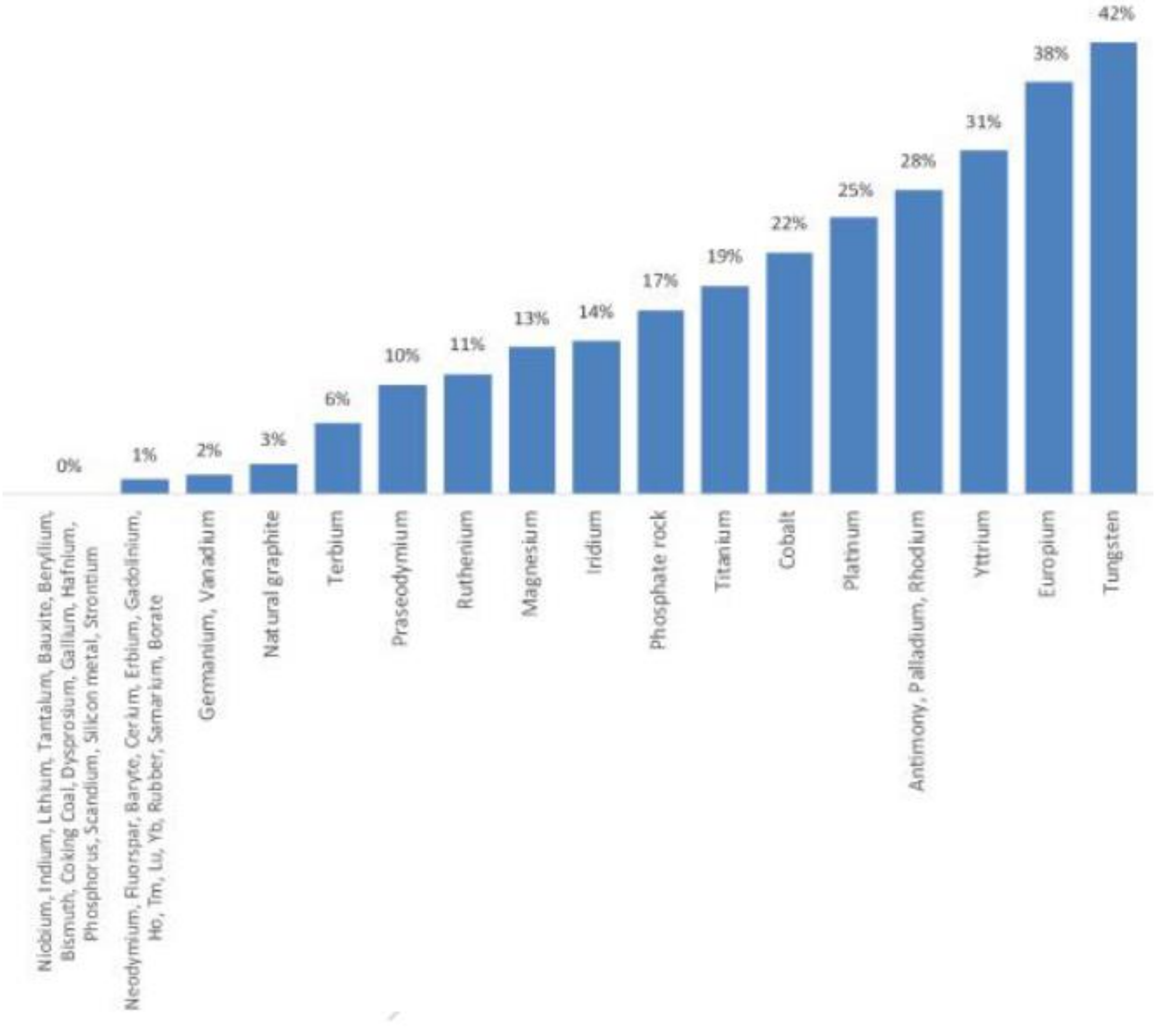
Another option would be to exploit all the REEs that are mined in abundance such as lanthanum and cerium. The elements that are easy to find are also cheaper so trying to adapt new technologies to this type of material could be an effective option. In any case, this possibility is still at its primordial stage, so further research will be needed before this can be considered relevant (Binnemans, 2014).

The search for substitutes among REEs as a solution to the balance problem but also to the environmental impact that the extraction of this has, seems to have the potential to be an interesting alternative. REEs, although sharing very similar chemical characteristics, have different properties which is why substitution is not so easy (Binnemans, 2014). According to the annual report released by the U.S. Geological Survey, substitutes are available to date but appear to be less effective (U.S. Geological Survey, 2020). As for NdFeB magnets, neodymium, an extremely critical element, can be partially replaced by a material considered easier to find such as praseodymium. However, the substitution percentage is really very limited and does not exceed 5% (Stegen, 2015).

However, substitution is not limited to the mere change between one element and another. It should be kept in mind that the market for REEs and their consequent use varies constantly, so a material that is considered critical today may no longer be so in a few years. Or the substitution may introduce a totally new technology such as, for example, the passage from plasma screens to Organic Light Emitting Diode (OLED) screens that do not contain REEs (Binnemans, 2014). In any case, while substitution is an option with potential for success, it still has several shortcomings that do not allow it to be considered the most immediate option.

Although not yet fully developed, the recycling technique in many respects appears to be the best option and the one in which to invest the most. By choosing this option it is possible to produce different and new technologies and try to keep the market as balanced as possible, moreover it can come to create an alternative source of materials while polluting less (Binnemans et al., 2013b). Recycling seems to get good results in NiMH batteries, permanent magnets and phosphors for lamps (Binnemans, 2014). It should also be considered that the recycling option could alleviate the dependence of some nations that do not have direct access to REEs reserves and must necessarily turn to other producers (Guyonnet et al., 2018).

Figure 4.11 The use of recycled material to meet the demand for raw materials.



Source: European Commission (2020b), page 10

Figure 4.11 represents the recycling rates according to the European Commission; the values presented in the graph show the percentage of the world's demand for raw materials that can be met with recycled elements (European Commission, 2020b). What you can see from the graph is that the recycling method for some critical raw materials and REEs can be extremely profitable, let's pay attention for example to the case of tungsten and europium. Neodymium recycling, on the other hand, is low, only 1%, but the recovery of this element from waste could help to meet the demand, which is always very high (European Commission, 2020b). It seems possible to maintain more than 90%

of the magnetic properties when the magnets are recycled (Ganguli et al., 2018), consequently, it will be important for research to focus on developing innovative techniques to recover elements such as neodymium. However, as shown also in Figure 4.11, it is possible to apply this alternative route only partially for some REEs.

Moreover, the recycle method should be taken into consideration since the costs of extractions are reduced to a large extent (Ganguli et al., 2018). As mentioned earlier, recycling and substitution options are also important in reducing the pollution associated with REEs production (Guyonnet et al., 2018), this aspect will be analyzed more in detail in the next chapter.

In conclusion, despite the alternative routes just described to the use of REEs in various technologies and applications, it is still not possible to do without their properties. The goal of some countries to create a decarbonized economy as well as the rampant digitization of the modern world has increased the demand for REEs, elements that have proven to be key to the implementation of various technologies (The One Earth editorial team, 2021). As a result, the problem of supply, and thus that of balance, remains an extremely topical issue. In the next period it will also be possible to evaluate the effects of the Covid-19 pandemic on the REEs market, in any case the concentration of sources in specific geographical areas is not a positive element but a limitation (European commission, 2020b). In addition, the attempt to move towards a more responsible and sustainable economy suggests that the demand for REEs will increase in the future, so there is an immediate need to invest in research to develop the techniques described above to ensure adequate supply. I also believe that world powers should at the same time maintain stable relations and work in synergy with each other so as to develop a well-organized and functioning production chain.

5. The “Dirty Elements”

In addition to the balance issue discussed in the previous chapter, another aspect to be analysed is the consequent environmental damage. It seems paradoxical, but critical materials as the REEs that have such a strong impact on the surrounding environment and ecosystem are also fundamental to all those technologies that are essential to fight climate change. As the use of REEs for the creation of technological end products and green economy applications has increased, so has the awareness of the environmental impact of extracting these materials. Starting with the former US giant MolyCorp. and ending with the Chinese government, the commitment to deal with pollution from REEs extraction and processing has increased over time and today research focuses on finding alternatives to common processing. In my opinion, a contradiction has therefore arisen behind the use of REEs since a material with such a polluting production process is used to improve the renewable energy industry in wind turbines or electric motors for example.

First and foremost, China has borne and accepted for years the environmental price unfortunately necessary to become and remain the world leader in the production of these elements and continues to do so today even though the rules have become more stringent. Despite constant complaints about the Asian power's control of the market, no other power has been able to deal with these collateral consequences, thus adhering to the so-called 'Not in my Back Yard' syndrome (Ali, 2014). This is the case of the complaints in Malaysia after that the Australian Company decided to establish the most polluting production processes there since Australian state laws did not allow otherwise. At the same time, as already mentioned, MolyCorp., the leading American REEs company, was closed down because of toxic residues that had polluted the water surrounding the work area. Obviously, the issue is not limited to the impact on the environment but also on human beings, as the workers in these industries are the direct victims of these harmful practices.

The aim is therefore to analyse the solutions that are possible today, from recycling to REEs substitution, bearing in mind that the path towards the cleanest possible production of REEs is only just beginning and that it will be necessary to invest heavily in research, promoting collaboration between the private and public sectors, but also between institutions in different countries in order to create a common production practice.

5.1 Environmental and social impact

As has been pointed out, the impact of REEs extraction and processing has affected both the environment and the social network that depends on this sector. Specifically, in China, problems of environmental pollution, water pollution but also toxicity of workers have been recorded among which long-term respiratory problems and cancer (Shin et al., 2019). As the number of extraction sites increased, scientists' attention to the waste from these practices also increased. There are four steps in the production process that can lead to environmental damage: the mining process, the refining process, the waste management and the disposal (Klinger, 2017). The processing of the extracted materials is perhaps the most polluting step in the whole process, and the waste produced is often disposed of incorrectly, making it extremely dangerous. REEs needs to be monitored mainly because of waste containing thorium and uranium, which are highly radioactive (Charalampides et al., 2016; Huang et al., 2016).

Of the two resulting elements, uranium may have an economic side since it can be commercialized. Thorium, on the other hand, is a more complicated matter, as it is not only considered to be highly harmful but is also extremely expensive to store and dispose of (Barakos, 2017). It has been calculated that each ton of REEs results in the production of approximately 9,600 cubic meters to 12,000 cubic meters of toxic waste gases, as well as one ton of radioactive wastewater (Klinger, 2017), making the environmental damage involved almost incalculable. The release of substances into the water damaged not only drinking water sources but also water used to irrigate fields (Kalantzakos, 2018).

This was the case at the most famous REEs site in the United States in Mountain Pass, California. In this instance, waste from the production process had polluted the groundwater in the area surrounding the mine. Unable to avoid these side effects, the mining base was decommissioned. In addition to the environmental damage already mentioned, several studies have shown this type of waste to be highly harmful to humans, increasing the risk of contracting diseases such as cancer (Ives, 2013). At the same time, the disposal of radioactive components is subject to high costs, e.g. for the storage of waste, its elimination, and the rehabilitation of the surrounding land (Charalampides et al., 2016).

Consequently, it is important to take environmental and social impacts into account when assessing the feasibility of a new mining project in an attempt to minimize harmful effects and waste. It would certainly be preferable to use available resources in trying to re-establish some disused mines instead of starting new mining projects (Seaman, 2019). Undoubtedly, the difficulty of establishing clear and uncompromising regulation in developing countries such as Malaysia, for example, is very complex. The increase in contamination was also due to the fact that in certain regions such as China, REEs were used as fertilizers in agriculture (Barakos, 2017). This practice is in use, and in several cases, there has been a change in fauna due to the adaptation of plants to REEs-rich soil (Charalampides et al., 2016).

Although what has been said so far remains highly topical and important, it must also be remembered that REEs are not harmful elements per se. What makes them elements to be monitored are the bad practices related to their production and the lack of strict rules from the beginning of their exploitation (Klinger, 2017; Barakos, 2017). This therefore highlights the shortcomings of the modern extraction system, and in addition to finding alternative methods to reduce dependence on REEs from China, research should also focus on investigating less invasive and damaging extraction practices.

5.1.1 Bayan Obo and Ganzhou cases in China

China's permissive environmental laws have allowed the country to produce faster and in much larger quantities compared to its competitors, making China the largest source of REEs in the world. Chinese territory has suffered most from excessive pollution and toxic waste generated by the chemical reagents used. This is also due to the prolific illegal production that does not follow any official regulation, making government control difficult (Charalampides et al., 2016). The cost of environmental damage is extremely high and so is the clean-up project. The profits of the industries located in the area could not meet the costs necessary to cope with the environmental damage (Kalantzakos, 2018). Investments for several billions of dollars have been made in order to rehabilitate and reclaim the area near the city of Ganzhou (Liu et al., 2016). Around 302 mines with associated toxic production waste have been abandoned in the city, representing 97.34 square kilometers of damaged soil. Studies have shown that it will take at least 70 years to resolve the situation (Liu et al., 2016).

The Bayan Obo site is the largest and most productive on the Asian continent. This has obviously brought with it considerable problems so that, in 2010, China decided to reduce the export of these raw materials and among the various reasons there was also the need to preserve Chinese territory. In the surroundings of the extraction and processing site were stored the wastes of the production process that, in the 50's, was defined as "the largest lake of REEs". In fact, in the area were crammed about two hundred million radioactive wastes (Klinger, 2017). In 2013, the area where the site is present, hosted 11 square kilometers of mud containing high quantities of thorium (Ives, 2013). About 10 km from the extraction site, there is one of the most important rivers in the region, the Yellow River, a source of water for several villages, which risks becoming a means of dispersing this waste more quickly (Liu et al., 2016; Kalantzakos, 2018). The impact of mining also affects the health of the surrounding villages, one example being Dalahai, a village called 'the village of death' since between 1999 and 2006 many people died of cancer, respiratory diseases and other devastating illnesses (Huang et al., 2016). Pollution problems also affected farmland in nearby villages, whose farmers reported a shortage in crops (Klinger, 2017).

While, near the city of Ganzhou, Jiangxi Province, considered by the Chinese government as "Rare Earth Kingdom", mining sites are located near two other important water sources namely Dongjiang River and Ganjiang (Liu et al., 2016). According to data released by the Ministry of Land and Resources of the Chinese government, $5.8 billion was invested in the city of Ganzhou in 2012 to restore environmental damage in the surrounding land caused by REEs companies (Shen et al., 2020).

It will take time for China, and more generally the whole world scene, to realize the damage generated by the massive production of REEs and the irreversible consequences associated with these processes. In 2003, as a result of the Radioactive Pollution Prevention Law, the Chinese government listed REEs mines as sources of high levels of radioactive materials (Klinger, 2017). The Central Government of the People's Republic of China (PRC) is trying to limit or remedy the damage resulting from the production of these materials by introducing stricter regulations and targeted inspections but also by granting economic support to local governments. However, it seems to be rather complicated to try to maintain environmental standards also because of the illegal market of REEs that seems to escape the control of the central government (Shen et al., 2020).

In 2019, it is estimated that China will need $440 billion to improve sanitation and pollution in areas near REEs mines, but also to meet state-mandated environmental standards. The Chinese government is involved in a 'war on pollution' that has reached out-of-control levels (Stanway et al., 2019).

5.1.2 MolyCorp. case in California and LAMP case in Malaysia

The company MolyCorp. can be regarded as the American emblem of the REEs industry. However, it has been violently affected by government regulations regarding environmental safety, as well as by the economic weight of the Chinese advance in the sector. The mine was closed for the first time in 2002 due to leaks of waste liquid from the pipes, which in some cases had not been reported to the competent authorities (Ali, 2014). Wastewater had spilled contaminating the surrounding area of Ivanpah Dry Lake

(Barakos, 2017). Between 1984 and 1998, seven pipe breaks were recorded that released 600,000 gallons of polluted wastewater (Ali, 2014; Klinger, 2017). The company had to pay more than $1.4 million in compensation (Ali, 2014). In 2013, as the site reopened, the water systems were also modified with newer technology and in line with imposed environmental regulations (Ganguli et al., 2018).

Although less impactful than the mines in China, one of the most illustrative cases of the harmful effect of producing critical metals such as REEs was the Lynas Advance Materials Plant (LAMP) plant in Kuantan, Malaysia. The Chinese giant's biggest competitor, LynasCorp., had decided to exploit the Kuantan territory to establish its $200 million processing plants (Teo, 2012) in order to circumvent the Australian government's stringent environmental laws. The company is located 25 kilometers from the city and this has caused protests from the citizens of the region, who did not approve the Australian company's choice, but also complaints from environmentalists who were well aware of the impact the plant would have on the surrounding area (Ali, 2014). In north-central Malaysia, a REEs processing plant owned by Mitsubishi Chemical had already been accused of polluting the surrounding area. The plant was closed down in 1992, after being accused of causing serious damage to the health of people living in the surrounding area (Teo, 2012). The company had to invest roughly $100 million to clean up the area, cramming all the radioactive material into the soil of a hill near a forest reserve (Bradsher, 2011).

5.2 Possible alternative paths

Waste from electronic equipment is increasing significantly every year. In Europe alone, 16kg of waste electrical and electronic equipment (WEEE) per person was recorded in 2016 and is estimated to reach 12 million tons in 2020 (Álvarez-de-los-Mozos et al., 2020). This condition is emphasized by the fact that most electronic products, such as smartphones and tablets, have a very short lifetime (Long et al., 2016). The impact of REEs on the global production cycle is undisputed, but what needs to be assessed is the price we are willing to pay to keep production at the levels required by technological progress. Precisely for this reason, the objective of research is to study of alternative sources and methods to ensure the supply of REEs while at the same time trying to reduce the negative aspects of production process (Long et al., 2016). Several strategies are being considered to minimize environmental impact and reduce waste (Long et al., 2016) and among these alternatives, the most significant in terms of the results obtained and future feasibility are substitution and recycling. The engagement of governments with subsidies and regulations that favour alternative practices instead of traditional production methods plays a central role in changing attitudes and seeking overall improvement.

At the same time, the development of a network of consumers who are more aware of the different production processes can also help to limit the damage resulting from the manufacturing of REEs. However, it is necessary to emphasize once again that the scientific world's knowledge is still relatively limited and that in the future it will be important to focus economic and intellectual resources on improving the results obtained so far. In this context, greater collaboration between the public sector and private corporations is desirable, not least to channel research efforts into alternative sources and methods.

In conclusion, surely the choice of an alternative has become a fundamental way to reduce the environmental impact as well as to alleviate the gap between supply and demand but at the same time to find a cheaper source of REEs, perhaps succeeding in deposing the Chinese leadership (ERECON, 2015). The objective of companies should therefore be to develop a way to isolate waste from the REEs extraction and refining process in order to avoid contamination of the surrounding environment (Huang et al., 2016).

5.2.1 Recycling

Although it is considered the best option for solving the difficult issue of environmental impact, only 1% of REEs are effectively recycled and reused in new products (Jowitt et al., 2018; Kalantzakos, 2018; Li et al., 2019). The recycling process can be broken down into 4 stages namely collection, dismantling, separation and processing (Tsamis et al., 2014; Shin et al., 2019). According to the latest studies, the end products that are easiest to recycle are batteries and phosphors, the latter being mainly used in the creation of displays, and permanent magnets (ERECON, 2015). The main limitation of recycling is certainly the fact that it takes a huge effort, both economic and in terms of resources and time, to recycle a small amount of REEs when the market demands tons of these metals on a daily basis. One example was the crisis in 2010 and 2011, when REEs prices plummeted, making recycling economically unviable (ERECON, 2015).

Waste from technology products, also known as e-waste, is increasing at a fast pace , partly due to the massive technological advancement that society is experiencing (Tan et al., 2015). Generally, residues from production processes, end-of-life products or industrial waste are recycled. However, it should be kept in mind that, according to the latest estimates, it is almost impossible in the medium to short term for raw materials from the recycling of finished products and waste to meet the growing demand on their own. This is not only due to the obvious difficulties in the material recovery process, but mainly because the finished products have a lifespan of several years, making it impossible to keep up with the hectic worldwide demand for REEs (ERECON, 2015). To this must be added that, more often than not, the final products are not designed to be dismantled in an environmentally friendly way. Often components such as magnets for example are encapsulated or glued, making their removal difficult and costly both in terms of money and time (Alves Dias et al., 2020). Therefore, although there are still legitimate doubts with this solution, according to recent estimates this practice is the best viable option as shown by the data in Table 5.1.

Table 5.1 Recycling estimate forecast in 2020

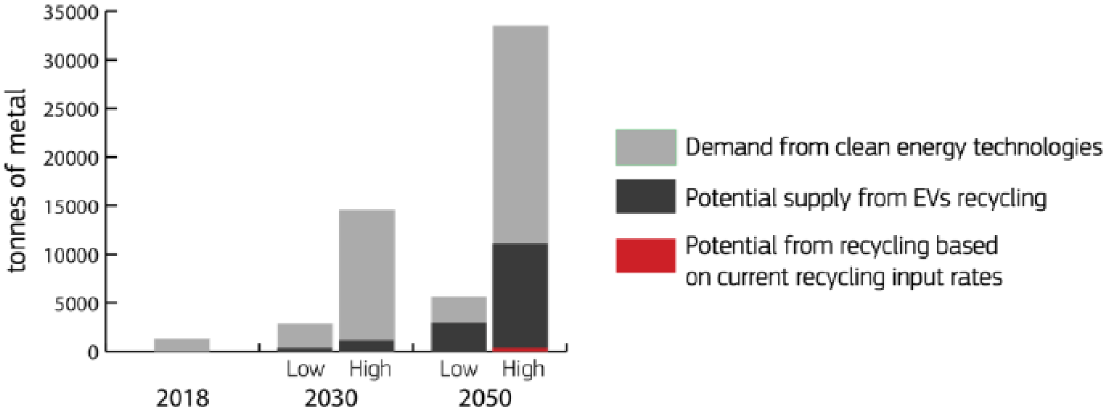
REEs Main Applications	Indicative lifetime of end-products in years	Estimated REE old scarp in tons	Pessimistic recycled scenario in tons of REEs	Optimistic recycled scenario in tons of REEs
Permanent Magnets	15	20,000	3300	6600
Lamp Phosphors	6	4167	1333	2333
Batteries	10	5000	1000	1750
Total		29,167	5633	10,683

Source: Jowitt et al. (2018), page 3

The forecast we can see in Table 5.1 for the year 2020 takes into account two possible scenarios - the optimistic and the pessimistic. The first element that emerges is definitely that permanent magnets, which are the main application of REEs, has a longer life cycle but at the same time produces more waste. However, it also turns out to be the application for which, even in a pessimistic scenario, recycling leads to more satisfactory results.

Figure 5.2, on the other hand, shows the recycling potential for REEs central to renewable technologies such as neodymium, praseodymium and dysprosium. It is clear that by 2050 the demand for critical materials will increase enormously and that the potential supply from recycling material from products such as electric vehicles could at least partly meet this demand. However, it is also clear that the recycling rate is still dramatically low (Alves Dias et al., 2020).

Figure 5.2 REEs demand forecast and potential supply from recycling



Source: Alves Dias et al. (2020), page 18

In general, these figures allow us to say that, in an optimistic scenario, approximately one third of the waste can be recovered. Above all, what limits the use of recycling is the extremely high costs that do not make it a sustainable option (Dutta et al., 2016). For this reason, research in the laboratory must focus on reducing the costs that companies still incur when they decide to recycle REEs. By making the process a cost-effective option, more industries could consider it in their production processes. Finally, it is important to keep in mind that the material that is recycled, in contrast to the first extraction, does not contain any toxic material, so it will be possible to sustain a more respectful production (Dutta et al., 2016).

Recycle from NiMH Batteries

One of the sectors where more effort is being put into creating a material recovery chain and in particular REEs is that of the Nickel-Metal-Hybrid (NiMH) batteries used in hybrid and electric vehicles. In fact, the use of REEs in this type of product has increased exponentially with technological evolution. A conventional vehicle contains around 0.45 kg of REES, while a hybrid vehicle using NiMH batteries contains around 4.5 kg (Kalantzakos, 2018). Before 2011, batteries were not recycled, at most only the nickel was saved to be used in other productions (Tsamis et al., 2014). The main REEs used in

NiMH batteries globally are lanthanum (10%) and cerium (6%). To date, the most recycled batteries appear to be non-rechargeable batteries, about 73.2% of the recycled battery market at European level, while rechargeable batteries account for only 26.7% (Mathieux et al., 2017). It should also be added that the recycling rates for batteries are rather low compared to other products, but this is due to the fact that they have a very long-life cycle of at least 10 years, especially those used in vehicles. As a result, recycling times are getting longer, and we are unlikely to achieve significant results until 2025 (Mathieux et al., 2017). Although it seems that it will still take several years to establish an effective recycling methodology, some companies have become pioneers in the field by setting up a battery recycling plant, as in the case of Umicore in 2011. The French company Recupyl, on the other hand, has created a recycling system through several partnerships with other hybrid or electric car manufacturers, thus creating a proactive and interconnected structure using a patented hydrometallurgical recycling system (Mathieux et al., 2017).

Recycle from Permanent Magnets

As far as permanent magnets are concerned, several projects have been designed to develop recycling methods that are not only practically but also economically feasible. Since China has used REEs reserves as a diplomatic weapon, other countries have invested heavily in R&D to focus on recycling magnets as an alternative source. These include REE4EU, promoted by the European Union, but also the efforts of the Japanese company Santoku, although the results are still limited (Alves Dias et al., 2020). The major contribution comes from the Japanese company Hitachi and the University of Birmingham, the latter in particular has developed a method that involves the use of hydrogen and atmospheric pressure to separate magnets from other components (Tsamis et al., 2014; Shin et al., 2019). Similarly, South Korea has been actively interested in recovery processes (Shin et al., 2019). Several projects are evolving to recover end-of-life permanent magnets, including Toyota's efforts to extract magnets from hybrid car engines and return them to their original use (Mathieux et al., 2017). As mentioned above, permanent magnets are mixed with other elements, which makes their recycling more complex. We are talking about sintered magnets, which are generally covered with a nickel or zinc coating and bonded together with other components inside various electronic devices (Tsamis et al., 2014). At the same time, when they are dismantled in powder form, they do not lose their magnetic charge, so it is important to know both the composition of the elements to be recycled and their position within the finished product in order to speed up the process as much as possible and at the same time to check beforehand that the quantity contained is sufficient to justify the work and effort involved in obtaining the material to be recycled (ERECON, 2015).

Recycle from Phosphors

Phosphors contain a fair percentage of REEs in them, around 23% (Tan et al., 2015). They are found in the form of oxide powder and contain mainly HREEs, in particular more than 70% of europium, terbium and yttrium are used in phosphors, making them extremely important products to recycle. They are mainly used for the production of LCD and Plasma screens but also for fluorescent lamps. The advantage regarding phosphors and their recycling is that products, such as phosphor lamps, are already recovered since they contain mercury and therefore partially recycled (Tsamis et al., 2014). There are three main recycling techniques: direct reuse in different applications, recycling of components through chemical and physical separation, or using acids to dissolve phosphors and recover individual REEs (ERECON, 2015).

It is therefore clear that the choice to recycle cannot be summarized only in the need to limit the environmental impact that this type of production, like many others, has as a consequence, but it must be stressed that the recycled material ends up as a new supply resource. Another positive aspect, which goes unnoticed in some ways, of the practice of recycling is the saving of energy, water and chemical components that are used instead in primary production (Tsamis et al., 2014). Table 5.3 shows the main barriers encountered in the practice of e-waste recycling and compares their applicability to the field of REEs.

Table 5.3 Main barriers to REE recycling in e-waste

Barriers to e-waste recycling	Applicable to the REE?
End-products contain small amounts of metals targeted for recycling (g to <mg)	Yes
Lack of economic incentive to recycle as a result of low metal value per unit; primary sources used instead	Yes, after reduction in REE prices associated with removal of Chinese export restrictions in 2014
Current commercial recycling technologies cannot recover the small amounts of the metals in question that are present in modern products not adequate for recovering small amounts of metals present in modern products	Yes, but laboratory experiments that may scale to industry may remove this barrier
End-products to be recycled contain a complex mixture of metals that change over time as a result of technological advances	Yes, although the recycling of mischmetals and REE alloys may remove some obstacles
End-product collection procedures are scarce or do not exist	Yes, although less the case for e.g., REE magnets
Prohibitive cost of the collection and transportation of end-products to recycling facilities	Unclear
The recycling process is not part of a collection chain that incorporates smelters	Unclear
End-product design and incorporation of target metals makes separation of recyclable material difficult	Yes
Public awareness of impending loss of crucial resources is low	Somewhat; the public are aware of the criticality of the REE but there are abundant REE resources already known

Source: Jowitt et al. (2018), page 2

The limitations blocking the recycling of these critical materials are the lack of suitable technologies, but also the scarcity of information about the amount actually available for recycling as well as the presence of contaminants can make large-scale recycling projects difficult (ERECON, 2015). A central role is also played by the price volatility of REEs scraps because they must be high enough to make the practice economically acceptable (Kalantzakos, 2018). Another underestimated aspect is the regulations not only at national but also at global level, which makes it difficult to transfer raw materials to appropriate recovering locations. The bureaucracy involved in sending waste weighs heavily on the feasibility of this procedure, not to mention the delay it entails. (ERECON, 2015). Extra element limiting the development of REEs recovery is the lack of companies specializing in this practice (Tsamis et al., 2014). These barriers can only be overcome if efforts are made at government and intergovernmental level to improve knowledge and acquire new information. In addition to the imposition of limits and regulations, various strategies are proposed, including for example the creation of a fairly regulated market, as well as the encouragement of engagement in environmental and recycling projects with tax relief and economic incentives at industry level. (Dutta et al., 2016). Thus, it has been shown that the practice of recycling certainly has the potential, if well exploited, to become a reliable secondary source of raw materials (Habib et al., 2014). In fact, it turns out for example that resources from REEs recycling are expected to be able to meet 4% of REEs demand in wind turbines through 2050 and 5% thereafter (Elshkaki et al., 2014).

To summarize, certainly recycling will not remove all the environmental and health problems associated with the REEs process but, since it does not involve the production of radioactive elements for example, it will be a viable alternative to at least reduce the impact of this production practice. Several companies are also trying to automate this process in order to limit the involvement of human beings as much as possible and thus diminish as much as possible the harmful impact that this production process has on the health of workers. The choice to automate also reduces costs and can be a strategy to increase the performance of the production system.

5.2.2 Substitution

The second viable option that could reduce the economy's dependence on REEs and the environmental impact of this production method is to find usable substitutes. Since products containing REEs have lifecycles that include several years, it is doubtful whether it will be possible in the short term to create an alternative source of these materials through recycling, and for this reason the most plausible option is the substitution of these materials.

However, to date it has not yet been possible to bargain substitutes with the same capacity and characteristics as the elements usually used, as the available options do not appear to be efficient enough (Kalantzakos, 2018). The chemical and magnetic capabilities of REEs make them irreplaceable for many industrial applications (Jowitt et al., 2018). A practical example is the neodymium used for permanent magnets. Although several companies are researching possible alternatives to reduce dependence on this REEs, no material with the same magnetic force and strength as neodymium has yet been discovered (Kalantzakos, 2018). The latest research is focusing on producing magnets with a reduced amount of critical REEs such as dysprosium. According to a study by the European Commission, the use of neodymium and praseodymium in NdFeB magnets may decrease from 31% in 2010-2012 to 20% in 2030. Nevertheless, to date no significant data have been recorded in this field (Pavel et al., 2016). This leads to a lower yield and therefore the search for suitable alternatives is still in its full development phase. A study conducted by the European Commission in 2017 developed the substitution index to calculate how difficult it is to replace a material considered critical. The values vary between 0 and 1 where the former represents raw materials that can be easily replaced and vice versa regarding 1. According to this index the value for the HREE results to be 0.96 if the analysis is based on the economic importance of the material and 0.89 instead if based on the risk of supply. Similarly, the values for LREE do not seem to differ much, registering a value of 0.90 in the first case and 0.93 in the second (European Commission, 2017b). This reinforces even more the argument that the economy needs to be linked to REEs resources. Since, for now, it is very problematic to find substitutes with the same potential as REEs, the characteristics sought among substitutes are competing between performance and low costs.

6. Conclusions

Each of us owns a smartphone or even more than one, works daily with laptops and tablets and electric or hybrid cars are becoming more and more frequent on the streets around the world. Thanks also to the increase in per capita wealth, especially among the middle class, and the improvement in living standards, there has been an increase in demand for high-tech products. There is a fair amount of REEs in each of these products, allowing them to be faster, stronger and smaller in size. For a long time, the REEs market and everything related to them remained a niche sector, unknown to many, even though their role was becoming increasingly important until they reached the status of critical and therefore fundamental material.

The development of this market itself, which has seen several changes of scene, is significant. In the early 1990s, control of the market was in North American hands with MolyCorp. as the world's leading extractor of REEs. This did not last long as China was able to acquire the necessary skills to discover important deposits within their own national borders and beyond, extract the raw materials and process them, something that America was not yet able to do. Slowly China has been gaining ground, involving also foreign researchers in its laboratories, thus trying to expand its know-how and not only its impact on the market at an economic level. On the contrary, this foresight has been the main shortcoming of the United States, which has not invested in research and development and, at the same time, has been unable to respond adequately to the extremely competitive prices offered by its Chinese counterpart and has not encouraged synergistic work between the state and the private sector, gradually losing control of the market. The leadership shift only became clear to all geopolitical powers in 2010 when a real material supply crisis broke out. In fact, China had decided to drastically reduce export quotas due to a diplomatic quibble with Japan, thus demonstrating its power. Exports were soon re-established also thanks to the intervention of the WTO, but this served as a warning to the other powers: the near monopoly was directly controlled by the Asian state.

Chinese hegemony will probably continue to persist since, to date, there is still no counterpart capable of competing on both the reserves and the technological level. Chinese control is not only due to the fact that they have more reserves in their territory, but more importantly to the fact that they have acquired and improved their REEs processing capabilities over the years. In the last couple of years, the Chinese giant no longer has the sole interest of being the largest exporter of raw materials but has realized the importance of going a step further and becoming the main supplier of value-added products that in turn contain these critical materials. However, the real question should be whether it is really necessary to reach Chinese standards taking into account the consequences and the high social and environmental price this entails. As has already been pointed out in the thesis, the rampant fear of being left without raw materials has been a problem repeatedly considered in the REEs market.

The mistake that has been made by the different powers involved has been to focus only on this lack without considering possible solutions that can be developed in the long term. What emerges is the growing concern of governments to find a continuous source of REEs without, however, significantly worrying about finding alternatives to their use. There is also a second aspect to consider, potential new producers of REEs, which could partially take control away from China, should be able to develop a complete production chain able to compete with the already mature Chinese one.

Probably the most appropriate choice for the other REEs producers would be to improve the production side, not necessarily trying to replicate the Chinese leader's numbers, but rather to collaborate with their experts, invest in research and development especially for renewable sources and substitutes. They should also encourage the use of alternatives by proposing state aid and facilitations. Only through cooperative work between the private and public sectors will it be possible to find viable and sustainable solutions in the long term with regard to the problems that this practice entails. Cooperation plays an important role in this field, which will determine what happens in a few decades.

Another element that has also emerged in this thesis is one of the two main issues affecting the REEs market, namely the balance problem. Supply fails to meet demand, especially for certain REEs considered most critical. In addition, the environmental impact of REEs production is the second major problem to deal with. For years, studies have been underway on how to reduce pollution from the extraction and processing of REEs, which in China has had devastating effects not only on the soil and water in the vicinity of mines and factories, but also on the health of workers and inhabitants of neighboring villages. It is paradoxical that such polluting products are essential for the clean energy sector. The impact is so serious that it has awakened the interest of governments themselves, which in recent years have invested in research to find a less invasive production process or alternative solutions. Among the latter, recycling and substitution of REEs in products where it is possible has certainly stood out. Specifically, the most successful practice is recycling, which, although still under development, is the most efficient choice both in terms of environmental impact and as an answer to the problem of balancing supply and demand, as it would create a secondary source of REEs.

What has emerged from the study of the REEs market is certainly the need to create a proactive model that is able to adapt and optimize available raw materials without waste, thus making production processes smoother. The market is in continuous evolution also due to the fact that inside there are complex dynamics that involve not only the supply and demand side but also the technological development of the sectors in which they are used as well as the political aspects since, it has been seen on several occasions, REEs have been used as an offensive tool for geopolitical disputes.

This latter role of REEs we are seeing and still experiencing because of the ongoing bitter fight on several fronts between China and the US. According to the broader political project 'America First', the strategic importance of these materials was sanctioned by Donald Trump through an executive order declaring the emergency, thus underlining the urgency of developing a massive domestic production. It is well known that the entire US defense system relies on the supply of REEs (Moore, 2020). US President Trump had never made a secret of his attempt to undermine China's economic strength in some way, including by trying to acquire the REEs-rich territories in Greenland, but the latest developments do not seem to suggest that the new Biden presidency has chosen an alternative path. It appears that even with the Biden administration, America has recognized the criticality in supplies of these considered critical materials and the need to find a short-term solution (Boak et al., 2021). Already during his campaign, President Biden had shown his interest in investing in companies involved in the production of materials needed for the green industry. Biden's goal seems to be the creation of a stable supply chain for all products considered critical, including REEs (Scheyder, 2020). This objective was confirmed with the executive order issued by the White House on February 24, 2021, through which the President has already launched an analysis of supply chains considered essential (Franck et al., 2021). However, what Biden could take into consideration in a more concrete way than his predecessor is the environmental impact of the production process of materials such as REEs, so it is hoped that the attention in the coming years will also focus on research into innovative techniques that can promote a more environmentally sustainable production system. The commitment of the United States in developing a functional supply chain has also been realized through the investment of the Pentagon for the opening of a new plant for the processing of REEs in Texas with the collaboration of the Australian company LynasCorp. (Cammarata, 2020). This demonstrates how powers other than China are trying to collaborate in order to decrease their dependence on the Asian power which, as already mentioned, still holds control of the market.

These aspects certainly serve as food for thought for a market that is unknown to many but which in reality conceals an irreplaceable power, especially in the period in which we are living. Moreover, it should be taken in mind that the pandemic has accelerated the digitization of many processes, leading to an increase in the demand for REEs (Haski, 2021) and at the same time highlighted the shortcomings and mistakes made so far by economic powers such as the United States (Nagle, 2021).

In conclusion, the lesson that Western powers should learn from the Chinese reality is to invest as much as possible in research and development in order to achieve not only self-sufficiency but at the same time create a knowledge network that is not limited to their own national borders. Legislation at national level should not only be supportive but should stimulate the move towards a circular economy in which waste is minimized as much as possible. Cooperation between the various institutions also makes it possible to create a solid structure of know-how, useful as a basis for the formation of a flourishing and innovative economy, in which China proves to be a step ahead of its Western counterparts every day. It will be interesting to monitor the evolution of this market in the coming years, REEs in fact are strategic geopolitical elements and therefore will have a major impact not only on the economies of the most powerful countries but also on their relations.

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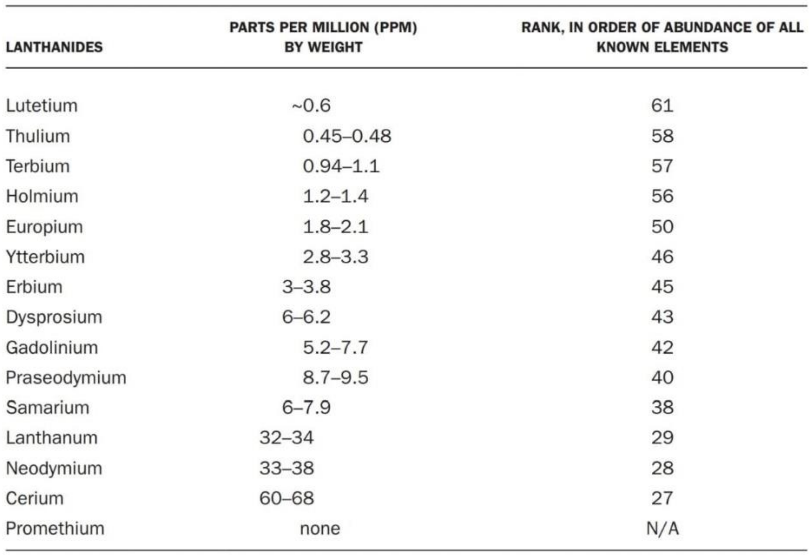
Appendix A

Estimation of the presence of REEs in the Earth's crust

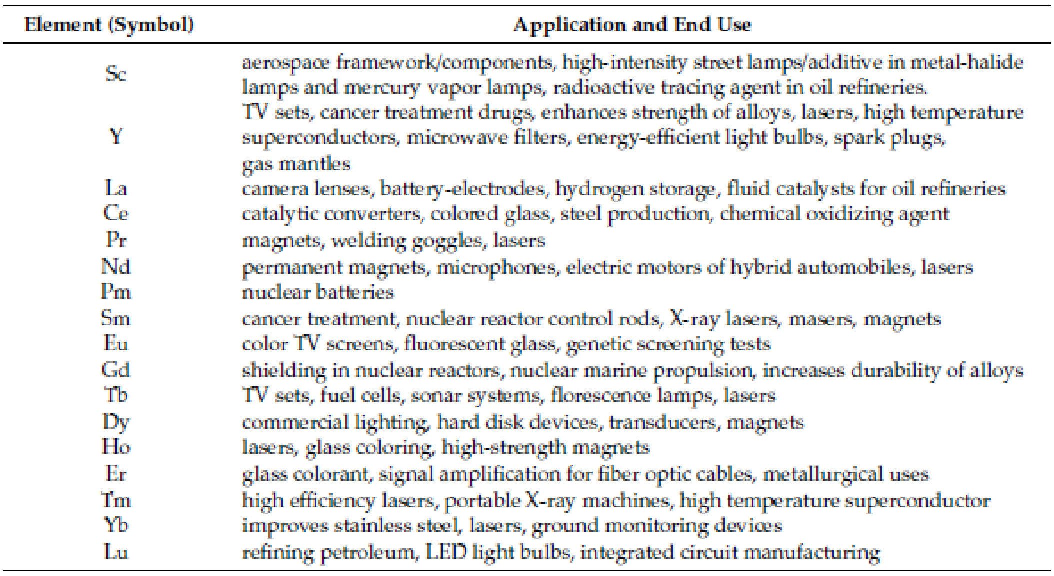


LANTHANIDES	PARTS PER MILLION (PPM) BY WEIGHT	RANK, IN ORDER OF ABUNDANCE OF ALL KNOWN ELEMENTS
Lutetium	~0.6	61
Thulium	0.45–0.48	58
Terbium	0.94–1.1	57
Holmium	1.2–1.4	56
Europium	1.8–2.1	50
Ytterbium	2.8–3.3	46
Erbium	3–3.8	45
Dysprosium	6–6.2	43
Gadolinium	5.2–7.7	42
Praseodymium	8.7–9.5	40
Samarium	6–7.9	38
Lanthanum	32–34	29
Neodymium	33–38	28
Cerium	60–68	27
Promethium	none	N/A

Source: Klinger (2017), page 44

Appendix B

Major applications of REEs

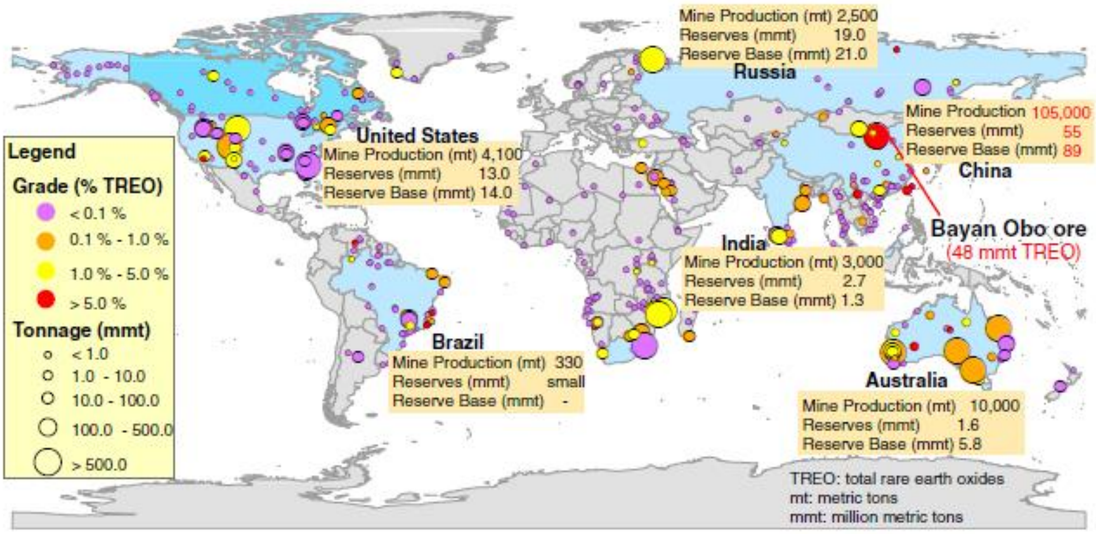


Element (Symbol)	Application and End Use
Sc	aerospace framework/components, high-intensity street lamps/additive in metal-halide lamps and mercury vapor lamps, radioactive tracing agent in oil refineries.
Y	TV sets, cancer treatment drugs, enhances strength of alloys, lasers, high temperature superconductors, microwave filters, energy-efficient light bulbs, spark plugs, gas mantles
La	camera lenses, battery-electrodes, hydrogen storage, fluid catalysts for oil refineries
Ce	catalytic converters, colored glass, steel production, chemical oxidizing agent
Pr	magnets, welding goggles, lasers
Nd	permanent magnets, microphones, electric motors of hybrid automobiles, lasers
Pm	nuclear batteries
Sm	cancer treatment, nuclear reactor control rods, X-ray lasers, masers, magnets
Eu	color TV screens, fluorescent glass, genetic screening tests
Gd	shielding in nuclear reactors, nuclear marine propulsion, increases durability of alloys
Tb	TV sets, fuel cells, sonar systems, florescence lamps, lasers
Dy	commercial lighting, hard disk devices, transducers, magnets
Ho	lasers, glass coloring, high-strength magnets
Er	glass colorant, signal amplification for fiber optic cables, metallurgical uses
Tm	high efficiency lasers, portable X-ray machines, high temperature superconductor
Yb	improves stainless steel, lasers, ground monitoring devices
Lu	refining petroleum, LED light bulbs, integrated circuit manufacturing

Source: Cardoso et al. (2019), page 5

Appendix C

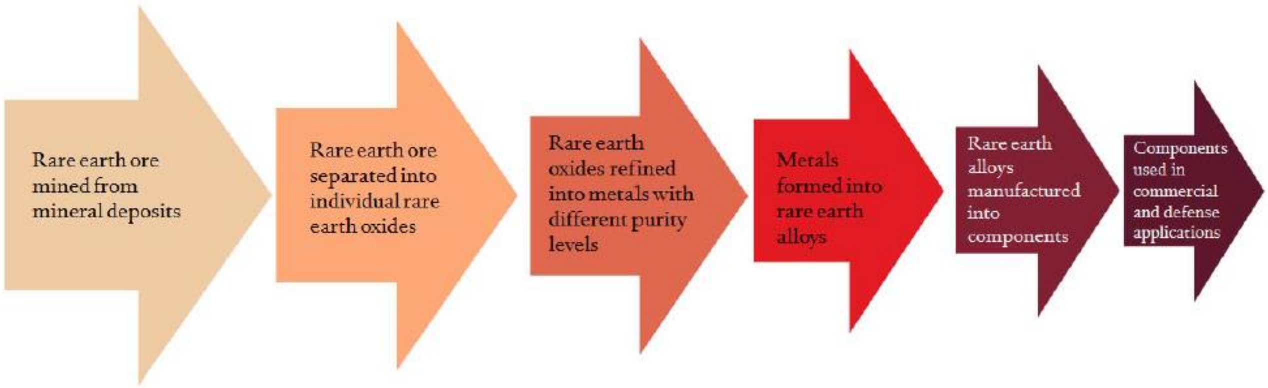
Global distribution of reserves and deposits



Source: Huang et al. (2016), page 533

Appendix D

Main steps of REEs production



Source: Gholz (2014), page 2