3 Market analysis of rare earth elements

Having provided the main technical foundations of wind turbines in Chapter 2, we subsequently proceed to analysing the particularities of the market for rare earth elements (REEs) since they are among the most vulnerable materials.

First of all, the term “rare earth elements” has to be clarified. It is actually a misleading name (Angerer et al. 2009) because the elements belonging to this group are quite abundant in the earth’s crust; however, they generally occur in such small concentrations that most deposits are not worth mining solely for their REE content (Cordier 2011a,b; Haxel et al. 2002). Within ore deposits, REEs tend to occur as compounds (Liedtke and Elsner 2009).

The REE group consists of 17 chemical elements that are characterised by similar properties (Walters and Lusty 2010). It comprises the 15 lanthanides as well as scandium and yttrium. Table 3.1 gives an overview of the single elements together with their atomic number and symbol in the periodic table of the elements (Cordier 2011a; Liedtke and Elsner 2009). Due to the REEs’ conjoint occurrence and similar properties, the extraction of one special element is very difficult and capital-intensive (Liedtke and Elsner 2009; London 2010; Walters and Lusty 2010).

Depending on the respective element, the crustal abundance of REEs ranges from 0.5 ppm to 60 ppm. Neodymium as the most important REE for permanent magnets has an abundance of 28 ppm. Copper, by comparison, is ranked at 50 ppm (Cordier 2011a). As these data illustrate, the occurrence of single REEs may vary widely. A rough classification can be made corresponding to the atomic numbers: as a rule of thumb, REEs with even atomic numbers are more abundant than those with odd atomic numbers (Haxel et al. 2002; Walters and Lusty 2010).

Moreover, light and heavy REEs can be distinguished, the former containing atomic numbers 57 to 64 and the latter comprising atomic numbers 65 to 71 plus yttrium (Cordier 2011a; Walters and Lusty 2010).[1] Concerning these groups, it can be stated that the concentration of light REEs is usually higher than that of heavy REEs (Haxel et al. 2002; Liedtke and Elsner 2009; Walters and Lusty 2010). Accordingly, the majority of REE deposits has an 80 to 99% content of just four elements, namely lanthanum, cerium, praseodymium and neodymium (Haxel et al. 2002).

[1] Scandium is not included in this kind of classification (Cordier 2011a).

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Name of element	Atomic number and symbol	Name of element	Atomic number and symbol
lanthanum	$_{57}La$	dysprosium	$_{66}Dy$
cerium	$_{58}Ce$	holmium	$_{67}Ho$
praseodymium	$_{59}Pr$	erbium	$_{68}Er$
neodymium	$_{60}Nd$	thulium	$_{69}Tm$
promethium[a]	$_{61}Pm$	ytterbium	$_{70}Yb$
samarium	$_{62}Sm$	lutetium	$_{71}Lu$
europium	$_{63}Eu$	scandium	$_{21}Sc$
gadolinium	$_{64}Gd$	yttrium	$_{39}Y$
terbium	$_{65}Tb$		

Table 3.1: List of rare earth elements. Source: compiled by the author, according to data from Cordier (2011a) and Liedtke and Elsner (2009).

[a]Unstable element.

REEs can either be produced as rare earth oxides (REOs) or as rare earth metals (REMs). REMs can further be subdivided into individual products, i.e. a pure metal consisting of only one element, and metal compounds that are called *mischmetal* (Angerer et al. 2009) whereby mischmetal is a mixture of different REEs as it naturally occurs (Papp et al. 2008). The only REEs produced as individual metals are lanthanum, cerium, neodymium and yttrium. Together they comprise about a quarter of total production (Angerer et al. 2009).

In the following, a comprehensive market overview is presented to account for the special forces on the REE market. From the confrontation of supply- and demand-side influences, consequences for the price path are deduced. As it turns out that the REE market is characterised by substantial imbalances, mitigation options to combat this problem are evaluated.[2] Finally, an outlook on the future market development is given, leading over to Chapter 4 where different options for the future wind turbine deployment are assessed.

3.1 The supply side

Since raw materials are unequally distributed across the earth, their supply is commonly subject to vulnerability. There are many potential disturbances: global companies may arise trying to obtain market power, suppliers may delay deliveries, or producing countries

[2]In contrast to its meaning in climate policy analyses conducted with economic models such as ReMIND-R, mitigation in this context does not stand for an emission reduction target. The term is rather used in a broader sense to describe possibilities for easing the problems that arise from the market imbalance.

may be politically unstable, to name just a few examples. Additionally, due to the market's global interconnections, policy measures taken by single governments can hardly exert influence. This framework poses particularly big problems in the case of resources with limited substitutability (Angerer et al. 2009).

The market for REEs is highly vulnerable in this respect because currently 97% of mine production originate from one country - China (Liedtke and Elsner 2009). This fact results in a notable import dependency for most other countries. Predominantly industrialised countries with a substantial share of high tech industries are affected, e.g. the USA as well as many EU member states are 100% import-reliant (Angerer et al. 2009; Cordier 2011b; EC 2008).

As the previously mentioned criticality of REEs is mainly caused by supply-side problems (Behrendt et al. 2007), the market analysis starts with this issue.

3.1.1 Reserves and resources

For an assessment of available quantities of a certain material in the earth's crust, the measures of reserves and resources are central. Figure 3.1 illustrates how the dimensions are interrelated. Reserves indicate the geologically registered amount of a material that can be exploited both technically and economically under currently prevailing conditions (Behrendt et al. 2007; EC 2010). The resulting number will therefore vary over time, depending on technology and price levels, so it must not be misinterpreted as an indicator of absolute scarcity (Moriarty and Honnery 2011). Resources, on the other hand, encompass reserves plus additional identified deposits where mining might become possible in the future, provided that technological progress and rising prices ensure economic efficiency (Behrendt et al. 2007; EC 2010). As Rogner (1997) points out, there is a positive feedback effect between prices, reserves and resources: as raw material prices rise, the extraction of previously unprofitable resources becomes cost-effective, reclassifying them as reserves, while at the same time the incentive to pursue exploration activities is enhanced, thereby facilitating technological progress. Theoretically, under the assumption of an infinitely high price, the total resource could be exhausted (Tietenberg 2006). On an intermediate level between reserves and resources, the reserve base, comprising reserves, is the share of resources complying with minimum standards to be exploited today or in the near future (Behrendt et al. 2007; EC 2010). Finally, on the uppermost level, the resource base adds to the resources the amount of undiscovered resources, i.e. it measures the overall abundance of a material in the earth's crust (EC 2010) and is therefore a geological rather than an economically determined dimension (Tietenberg 2006). Just like reserves, resources are a time-dependent measure since formerly unknown deposits can be discovered (EC 2010), augmenting the resource stock and diminishing the stock of undiscovered resources accordingly.[3] It is also evident that there are no data for the resource base as no one can determine with certainty the amount of undiscovered resources.

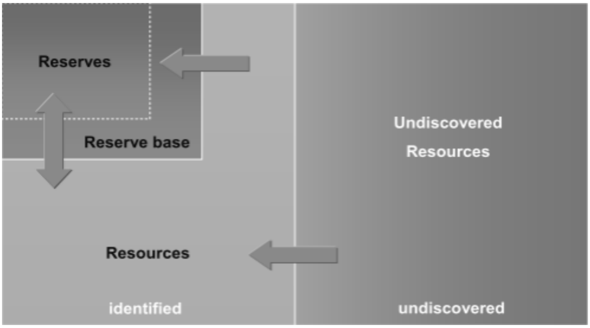

Figure 3.1: Relation of reserves, reserve base, resources, and resource base. Source: EC (2010).

Another frequently-cited measure is the reserves-to-production ratio, stating for how many years today's reserves will suffice to maintain the current level of demand (Behrendt et al. 2007). Yet, this is not a reliable figure because it neglects any technological progress, including new recycling and substitution possibilities, as well as changes in the price level that may occur over time (Behrendt et al. 2007; Wacker and Blank 1999). The resources-to-production ratio is defined analagously (Angerer et al. 2009).

Applying these measures to REEs, one has to bear in mind that they are a depletable resource, which means that natural replenishment can be disregarded within a time horizon relevant for humans. Dynamic efficiency therefore requires the maximisation of the present value of net benefits gained from REEs, implying a balance of today's and tomorrow's uses (Tietenberg 2006). As a foundation for the allocative decision, Table 3.2 summarises the values of the defined categories for REEs.[4] Data for single elements are unfortunately not available (Angerer et al. 2009). It has to be noted that statistical data are usually provided in REO equivalents, whereby the REE-to-REO ratio is about 1:0.85, but both terms are usually treated as approximate equivalents (Goonan 2011).

[3] As a recent example has proven, even the discovery of one single deposit can have a major influence on the data (EC 2010): in 2011, additional REE sources of significant scale have been found on the ground of the Pacific Ocean, near Hawaii and Tahiti. In a depth of 3,500 to 6,000 m, about 100 billion t have been identified. The area covers 11 million km^2 and it is estimated that due to the high REE concentration 1 km^2 could satisfy 20% of current worldwide demand. However, it has not been explored yet whether mining the deposit is technically feasible (Tagesschau 2011b).

[4] It should be noted that the aforementioned discovery of new REE deposits in the Pacific Ocean does not affect reserves data as their exploitability is not given yet. However, the amount of resources has increased, so the resources-to-production ratio is meanwhile probably higher than stated here.

Measure	Value	Unit
Reserves	88,000,000	t REO
Reserve base	150,000,000	t REO
Reserves-to-production ratio	715	yr
Resources-to-production ratio	1,220	yr

Table 3.2: Reserve and resource data for REEs. Source: compiled by the author, according to data from Angerer et al. (2009), Behrendt et al. (2007) and Kurronen et al. (2010).

In the context of this thesis it is also relevant to identify the geographical distribution of reserves. Table 3.3 presents the most recent available data. Although almost half of the total reserves is currently concentrated in China, the remaining deposits are widely dispersed (Walters and Lusty 2010). To account for the regional concentration of reserves, the Herfindahl-Hirschman Index (HHI) is a commonly used benchmark. It is calculated as the sum of the squared shares of raw materials occurrence within the corresponding countries, but can as well be applied to raw materials production or market power of companies (Rosenau-Tornow et al. 2009). As the respective shares are written as fractions, the HHI can cover a range between 0 and 1 with a larger value indicating a smaller number of agents with correspondingly more market power each (Tour et al. 2011). For the concentration of REO reserves, Angerer et al. (2009) report a HHI of 0.23, i.e. a moderate value.

Although the reserve distribution gives useful insight into the mining potential, actual mine production figures are more significant for evaluating the current situation on the market. There is a wide consensus in literature that reserve- and resource-related scarcities will not play a major role in the foreseeable future, but possible shortages may rather arise from production bottlenecks (see e.g. Behrendt et al. (2007), EC (2008), and Tietenberg (2006)). Table 3.4 illustrates the amount of REOs extracted by country. Owing to non-disclosure of data by some countries, the table has to remain incomplete.[5] Furthermore, figures are often estimated and may differ depending on the source; in case of inconsistent data, the most recent figures were selected or, if there were several sources dating from the same year, the one that seemed to harmonise best with pre-existing data was chosen.

As Table 3.4 indicates, China plays the role of a quasi-monopolist on the REE market, accounting for more than 95% of supply in any of the six recent years. The implications of this phenomenon are discussed in detail in Section 3.1.2.

When considering a rather long-run perspective, between 1990 and 2006 global REO mining expanded on average by 7% annually (Goonan 2011); from 1992 to 2008 total world

[5] Data for CIS and the category “Others” were not available at all.

Country	Reserves (t REO)
China	55,000,000
CIS[a]	19,000,000
USA	13,000,000
India	3,100,000
Australia	1,600,000
Brazil	48,000
Malaysia	30,000
Others	22,000,000
Total[b]	113,778,000

Table 3.3: Geographical distribution of REE reserves. Source: compiled by the author, according to data from Cordier (2011b).

[a]Commonwealth of Independent States.
[b]Total figure has been calculated by the author and does not comply with the reserve data from Table 3.2 since the latter mainly relies on data from 2009 and 2010. However, as more recent data for reserve base, reserves-to-production ratio and resources-to-production ratio were not available, the older reserve figure has been kept in the previous table to assure consistency within Table 3.2.

production increased by more than 100% with the maximum being reached in 2006 (Walters and Lusty 2010). To give an impression of the importance of single REEs, Figure 3.2 shows their share of total REE production in 2010.[6]

As mentioned previously, REEs usually occur as compounds, which means that the extraction of one particular element is not only determined by its own economics, but also by those of its co-products. Secondly, REE compounds are itself by-products of other minerals (EC 2010), so the same interdependence applies on a higher level as well. Thirdly, it has already been shown that China possesses significant market power, and fourthly, the extraction and processing of REEs causes external effects, most notably environmental damage (Lohse 2011b). Hence, there are four particularities to consider on the REE market. The subsequent section takes a closer look at market failure arising from these circumstances.

[6]The data illustrated here do not contradict the statement in the introductory section of Chapter 3 that lanthanum, cerium, neodymium and yttrium as individual metals together comprise a quarter of total production; they are additionally produced as REOs or within mischmetal, and Figure 3.2 accounts for overall production.

Country	2005	2006	2007	2008	2009	2010
China	119,000 97.5%	133,000 97.1%	120,000 96.8%	125,000 97.6%	129,000 95.6%	130,000 97.0%
India	2,700 2.2%	2,700 1.9%	2,700 2.2%	2,700 2.1%	2,700 2.0%	2,700 2.0%
Russia	n.a.	n.a.	n.a.	n.a.	2,470 1.8%	n.a.
Brazil	527 0.4%	527 0.4%	645 0.5%	550 0.4%	550 0.4%	550 0.4%
Malaysia	150 0.1%	430 0.3%	380 0.3%	233 0.2%	350 0.3%	350 0.3%
Total	122,000	137,000	124,000	128,000	135,000	134,000

Table 3.4: Mine production by country. Source: compiled by the author, according to data from Cordier (2011a), Cordier (2011b), USDE (2010) and Walters and Lusty (2010). For each country the first row indicates the absolute amount in t REO, the second row refers to the country's share of the known world production in the respective year. Since data for Russia are only available for 2009, affecting total world production and the countries' shares only in that year, intertemporal comparability is limited. Due to rounding the shares may not add up to 100%.

3.1.2 Mining, processing, international trade, and market failure

Co-production. Current production levels are not sufficient to cope with increasing demand for several REEs. Above all, neodymium, dysprosium, europium and terbium are facing excess demand (Cordier 2011a).[7] Whereas production increased by a factor of 2.45 between 1990 and 2000, demand for neodymium and dysprosium as magnet materials expanded by a factor of 9 to 10 in the same time period (Angerer et al. 2009) and has further accelerated since then (London 2010). Owing to their status as co-products, i.e. the fact that multiple individual REEs occur as a bundle (USDE 2010; Walters and Lusty 2010), the price of a certain REE depends on the prices of the elements it is combined with, the respective abundance of each material in the ore, and separation and refining costs of the whole package. If REEs are to be extracted, the main driver is often neodymium because of its use in a wide range of applications (USDE 2010). Yet co-production implies that according to the composition of the ore deposit, further REEs are "unintentionally" extracted, too. Thereby a situation of excess supply is provoked on the markets of the other, less desired elements, causing their prices to fall accordingly, which yields a feedback effect on the economics of the originally desired product. All in all, about 25% of REEs

[7] Demand-side patterns are examined in Section 3.2.

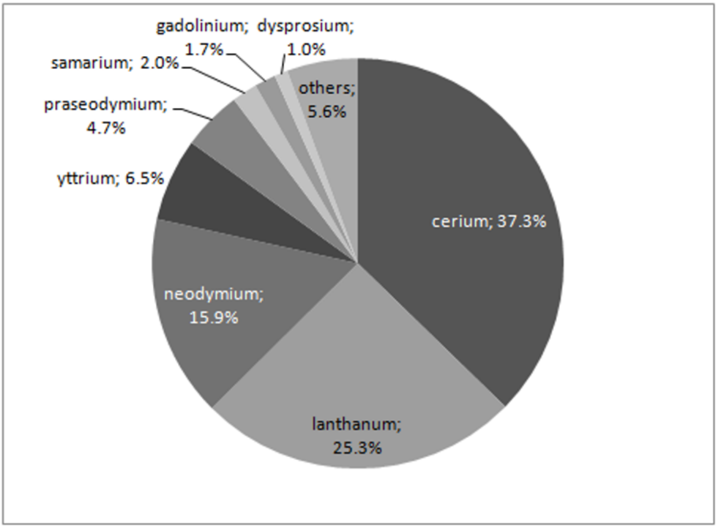

Figure 3.2: Estimated REE production by element in 2010. Source: compiled by the author, according to data from USDE (2010).

extracted are in excess supply (Angerer et al. 2009).

By-production. Similarly, the availability of by-products depends on the characteristics of the main product. By-products are typically characterised by a low price elasticity of supply because production is primarily targeted at the main product and thus reacts basically to incentives on the main product's market (EC 2008). However, the role of by-products must not be underestimated either: apart from the market conditions of the primary product, prices, ore grade and recovery rates of by-products also influence their extraction, though possibly to a moderate extent (Papp et al. 2008). By-products can, on the one hand, provide supplementary revenue for the producer, but on the other hand they induce higher production costs (EC 2010). REEs appear as by-products of four main minerals: bastnäsite, monazite, xenotime, and ion absorption clays (Angerer et al. 2009; USDE 2010). An isolated examination of individual REEs independent from their co- and by-products is therefore not possible.

Chinese quasi-monopoly. On the markets for raw materials, concentration both on country and company level is widely spread (EC 2008). Concerning global REO production from a historical perspective (see also Figure 3.3), a trend toward dominating exporters can already be observed from the mid-1960s on, when the Mountain Pass mine in California started operations. The USA quickly became the primary producer of REOs until in the mid-1980s China entered the world market, gradually crowding out competitors by means of its extraordinarily low production costs that were feasible due to low labour and energy costs as well as minor legal standards regarding environmental protection and mining permission (Aston 2010; Cordier 2011a; Haxel et al. 2002). Finally, since the beginning of the 1990s, China has been dominating the market to an increasing extent.

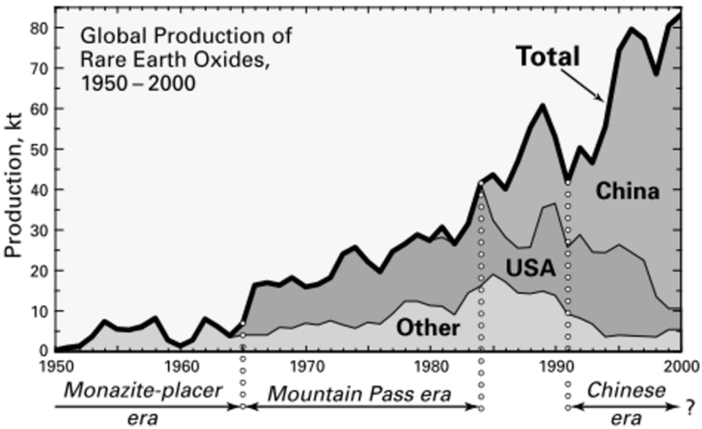

Figure 3.3: Historical development of global REO production. Source: Haxel et al. (2002).

Today, China has gained a market share of 97% (Liedtke and Elsner 2009) and profits from its abundant endowment with REE deposits, supporting the rapid deployment of electronics and other industries in Asia (Haxel et al. 2002). As domestic demand for raw materials is substantial because of the prevalent extension of infrastructure (Papp et al. 2008), China predominantly strives for self-sufficiency of raw materials to ensure that its development can be maintained independent of imports (London 2010). Besides, China engages in REE mining projects abroad and encourages processing of REEs within its own borders (Liedtke and Elsner 2009).

Whereas foreign investment in REE extraction is confined, it is facilitated in the value-added manufacturing sector processing REEs (USDE 2010). REE processing to the point of semi-fabrication is mainly carried out within China, whereas the production of assemblies is internationally distributed (Goonan 2011). However, manufacturing of sintered neodymium-iron-boron (Nd-Fe-B) magnets is subject to intellectual property rights and therefore exclusively conducted by ten licensed companies in China, Japan and Germany (USDE 2010). Domestic demand for permanent magnets in China has soared since 2008, while at the same time magnet exports dropped (Cordier 2011a). Moreover, China takes over an increasing share of wind turbine production: while in 2007 only 10% of the world's wind turbines came from China, the figure has steeply risen to 30% in 2009 (REN21 2010).

REE extraction in China is primarily undertaken in two mines, the largest share being covered by Bayan Obo in Inner Mongolia; this deposit contains the majority of Chinese REE reserves (EC 2010; Haxel et al. 2002) and yielded more than 40% of total worldwide production in 2007 (Liedtke and Elsner 2009). The second main deposit is located in the tropical southern part of China, predominantly in the provinces Longnan and Jiangxi where especially high concentrations of the less abundant heavy REEs occur, making it a valuable source (Haxel et al. 2002; Liedtke and Elsner 2009). Furthermore, in the south of China several smaller and partly illegal mines are operated, smuggling their output abroad (Milmo 2010; USDE 2010). In 2008 approximately one third of Chinese REE exports was smuggled (Walters and Lusty 2010). The government tries to subdue these activities and has already initiated the closure of illegal mines and the merger of mine-operating companies under state control (Hein 2010).

Owing to the high domestic demand for raw materials, China has imposed export restrictions and charges an export tariff on REEs that ranges between 15 and 25%, depending on the material under consideration (London 2010; USDE 2010). Additionally, import tariffs on 600 construction materials and components are levied (Tagesschau 2010b), thereby creating a competitive advantage for domestic intermediate products.

Another kind of export restriction arises from the export quotas assigned by the government. In the past, they have steadily been reduced (Milmo 2010) and are supposed to be cut by another 2 to 3% every year since China expressed plans to pay more attention to resource protection and establish a strategic domestic REE stockpile (Tagesschau 2010a; USDE 2010). Between 2003 and 2009, REE exports already dropped by 40%; whereas originally 75% of REE production were available for export, the fraction meanwhile has declined to about 25% (Milmo 2010), reaching 30,258 t REO in 2010 (USDE 2010).[8]

The various kinds of export restrictions have already brought the World Trade Organization (WTO) to the scene. The distortion of competition by China has sharply been criticised because both the higher raw materials prices on the world market and the impact of artificial shortages on downstream industries imply a subsidisation of Chinese companies that are of course not subject to the export constraints. This violates WTO directives as well as certain commitments China had to agree to upon its WTO accession (EC 2010). There

[8] The quota for 2011 is still under discussion.

are also initiatives on the part of individual governments to negotiate higher export quotas with the Chinese administration (Tagesschau 2011a).

From the perspective of importers, the security of supply of Chinese REEs depends on its political and economic stability and its willingness to cooperate with other countries (Haxel et al. 2002). The EC (2010) suggests to use the Worldbank Worldwide Governance Indicator as a reference point to judge these patterns. The most recent data for the category "political stability" are from 2010 and rank China 8th among the 10 largest economies in the world as defined by GDP. When considering all countries, China appears in the 10th to 25th percentile[9] in 2010, the worst rating since 1996 (The World Bank Group 2011a,b). A recent example for China's arbitrary behaviour on the raw materials markets can be seen in its relation to Japan: after China had already drastically cut RE metal shipments to Japan in 2008 (Cordier 2011a), political controversies between both countries in 2010 resulted in a complete blockade of RE minerals exports lasting three weeks (Aston 2010).

In addition to market power on the country level, a concentration is also observable at the company level, whereby the two aspects are closely interrelated. Chinese REE companies represent a market share of 97% (Liedtke and Elsner 2009) and are de facto treated like state corporations. Besides the negative implication of market control, this combination also results in financial solidity, which is essential for firms operating on the volatile REE market (EC 2010). The largest share of REE exports is covered by Inner Mongolia Baotou Steel Rare Earth International Trade Company, the central institution to coordinate purchase and marketing of REOs and metals from the Baotou region (Cordier 2011a). Several other national corporations exist in China, though their individual market power is rather limited with the exception of Ganzhou Rare Earths Co. (Liedtke and Elsner 2009). The remaining 3% of supply on the global REE market are shared among Indian state corporations with about 2%, a Brazilian firm with less than 1% and some small Western enterprises (Liedtke and Elsner 2009; London 2010).

In order to circumvent Chinese export quotas and reduce the import dependency of REE-processing industries, importing countries pursuit several strategies. One option is to invest in foreign mining projects, thereby securing raw materials supply; another possibility is the build-up of national inventories for critical resources (Behrendt et al. 2007). Furthermore, many binational long-term delivery contracts exist (EC 2008).[10] An ultimate alternative would be to move REE-dependent companies to China, so they are not subject to export restrictions any more, which is up to now only a theoretical consideration (Hein 2010; Walters and Lusty 2010). Additionally, REE importers strive for higher material efficiency along the whole product life cycle as well as the development of economic recycling technologies on a large scale (Angerer et al. 2009; EC 2008, 2010); selected mitigation potentials are analysed in more detail in Section 3.4.

[9] The higher the assigned percentile, the better political stability in a country is judged.
[10] For an overview of national strategies implemented in individual countries, see USDE (2010).

Negative externalities. On top of the market failure associated with the aforementioned particularities - co-production, by-production, and quasi-monopolistic market power - the REE industry is characterised by another drawback, namely external effects in the form of environmental burden. Resource exhaustion often raises a conflict with sustainability (Angerer et al. 2009), but as there are very few suppliers on the international REE market, thus having the chance to act strategically, the problem is reinforced: a global policy for sustainable mining and trading is hardly enforceable (Behrendt et al. 2007).

Environmental damage is caused by the REE sector along two stages of the supply chain, extraction and processing. Starting at the point of mining, radioactivity is released when REEs are extracted from monazite. Monazite contains thorium as a further by-product, which is only weakly radioactive itself, but occurs in compound with highly radioactive intermediate daughter products. Therefore monazite deposits have largely ceased to be exploited (Haxel et al. 2002).

Moreover, the extraction, separation and refinement of REEs require the use of chemicals that leave behind toxic sludge. The waste products often end up in the ground water, causing pollution of the environment, disease and poisoning of the local population, and contamination of farmland (Lohse 2011b; Walters and Lusty 2010).

Finally, REE production is very energy-intensive. However, the majority of energy in China originates from coal-fired power plants (Walters and Lusty 2010), so the whole process contributes to air pollution and the greenhouse effect.

Regarding the environmental performance of countries, there is a similar index like the Worldbank Worldwide Governance Indicator. The Yale Center for Environmental Law and Policy at Yale University regularly publishes the Environmental Performance Index (EC 2010). It provides a measure for the proximity of countries to environmental policy goals from the areas of environmental public health and ecosystem vitality. The most recent results date from 2010, ranking China 121st out of 163 countries, or in the 4th out of 5 groups. Since the previous assessment in 2008 it has even been downgraded, indicating a degradation of environmental performance over time (Yale University and Columbia University 2011). Yet, in March 2011 China released new environmental standards that have been in force since October 2011 and set emission limits for 15 pollutants, affecting 60% of Chinese REE-producing companies (Lohse 2011b).

It should also be noted that REEs not only harm the environment, but are increasingly used to enable energy-efficient and emission-reducing technologies (Walters and Lusty 2010).[11] Hence the overall effect has to be considered, although it is difficult to offset both aspects and calculate the net impact. To the knowledge of the author this has not been done yet. There are however consistent claims in the life cycle literature on wind turbines (that in some cases employ RE permanent magnets) confirming the superior role of wind

[11] See Section 3.2.2.

power among different electricity-producing technologies with regard to criteria such as environmental footprint, sustainability issues and external cost (Arvizu et al. 2011; EC 2003; Jacobson 2009; Weinzettel et al. 2009).[12]

When the consequences of raw materials extraction and processing are assessed in literature, the analysis is mostly restricted to the associated negative externalities and ignores the following supply chain integration, which may be justified by the fact that subsequent positive effects often do not benefit the same people whose utility has decreased due to negative external effects from production. There the question arises how to define the society whose welfare is to be maximised: in case the world population is considered as a whole, the net effect may either be positive or negative, but if the population of a mining region is regarded individually, the welfare effect might well be detrimental.

Based on the assumption that the true social cost of raw materials exceeds their market price, owing to environmental burden and unconditional dependency of certain industries, economic theory offers a solution for correcting market failure. Tietenberg (2006) proposes to impose an import tariff on the materials under consideration and use the revenue to finance a national stockpile. That way, on the one hand the importing country can ensure continuous supply,[13] on the other hand research efforts for substitutes and probably also domestic production of raw materials are facilitated. Eventually, this strategy also conforms to the polluter-pays principle as the tariff is borne by those who demand the critical materials or their derivatives.[14] Yet in practice it is difficult to calculate the optimum tariff rate since pollution is not the only externality on the REE market. The existence of market power can to a certain degree countervail environmental degradation (Tietenberg 2006) because due to the quasi-monopoly, REE production would be inefficiently low in the absence of further kinds of market failure, but the negative externality implies that the quantity resulting from perfect competition would be inefficiently high. Thus an import tariff has to be adjusted to the net effect.

[12] The methodology of those assessments is often not made transparent, so it cannot be guaranteed that all of the studies include raw materials extraction impacts and account for the fact that some wind turbines contain REEs and others do not. As mentioned previously, the detailed analysis of environmental impacts of REEs still constitutes a gap in literature.

[13] USDE (2010) notes that the build-up of a state inventory is associated with two major disadvantages: first, the government in reality does not have perfect foresight and therefore cannot determine the optimal extent of the stockpile; second, state demand for the inventory competes with private demand on the market, so it is possible that excess demand is exacerbated in the short run.

[14] A shifting of the tariff burden to the producers is highly improbable in the case of a quasi-monopoly.

3.2 The demand side

Following the analysis of supply-side attributes of the REE market, the demand side is now investigated. Before identifying the most important applications of REEs in the industry, the fundamental forces driving demand are considered.

3.2.1 Determinants of demand

There is widespread consensus in literature that demand for raw materials is determined by two forces: economic growth and technological progress. Global GDP recently grew by about 3.8% per year, mainly driven by the strong expansion of emerging markets like China. Economic growth is predominantly responsible for demand on the commodities market - i.e. the market for materials that are extracted in large amounts and are employed in a broad range of applications. The role of technological development is prevailing on markets of specialties whose worldwide annual production does not exceed several 1,000 t. REEs can be attributed to the second group (Angerer et al. 2009; EC 2010; Goonan 2011).

As a consequence, demand for REEs rose sharply during the last decades because many newly developed technologies rely on them. Especially during the last 10 years demand has tripled (Milmo 2010). Up to 2007, supply still exceeded demand. Yet in 2008, the REO consumption level of 129,000 t (Goonan 2011) could not be covered by current production any more (see Table 3.4), so existing stocks had to be resorted to.

Although REEs are necessary inputs to many technical applications, from the perspective of the individual producer they usually comprise only a tiny share of total material requirements. Hence, in overall cost calculations of assembling industries they represent a correspondingly small part, so it can be assumed that price elasticity of demand for REEs is relatively small (USDE 2010). The implications of this assumption will be discussed in Sections 3.3 and 3.4.

In order to determine whether market power also exists on the demand side, Figure 3.4 lists the main importing countries of REE products in 2008.[15] It can be seen that demand is more widely dispersed internationally than supply. Though there are a few major importers, they do not represent a significant market share for themselves, which becomes apparent when the data presented in the figure are related to total demand as given above. Neither can an outstanding concentration at the company level be noticed because of the wide range of different applications of REEs in miscellaneous industries, as shown subsequently.

[15] The USA denotes an exception since data were only available for 2007.

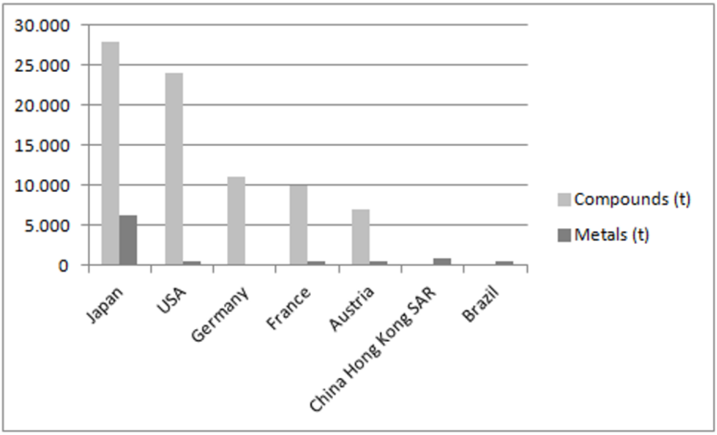

Figure 3.4: Demand for REE products by major importing countries. Source: compiled by the author, according to data from Walters and Lusty (2010).

3.2.2 Main applications of rare earth elements

Many industries compete for scarce raw materials (Angerer et al. 2009), and especially the clean energy sectors contribute to a large share of REE demand and are expected to grow even further in the future (USDE 2010). Table 3.5 gives an overview of the most relevant components manufactured from REEs and some examples of their applications.

In general, the industries reliant on REEs can be attributed to two groups: mature sectors - like catalysts, glassmaking, lighting, and metallurgy - and emerging sectors - including battery alloys, ceramics, and permanent magnets. Emerging markets still account for slightly less than half of REE demand, but it is noticeable that the largest share of consumption from these industries is driven by neodymium, praseodymium and dysprosium: the three elements together represent 85% of total REE demand from the emerging sectors (Goonan 2011).

Permanent magnets seem to be the most important individual component. They are employed in highly efficient electric motors and generators that power hybrid vehicles and e-vehicles, but are also used in renewable energy technologies such as wind turbines, small hydropower stations, or tidal power plants. Further possible applications are magnetic levitation trains, waste sorting, medical imaging techniques, and several IT technologies. Currently wind turbines are the most significant single field of permanent magnet application (Angerer et al. 2009; EC 2008; Goonan 2011; Hatch 2008).

Component	Applications	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Sc	Y
Permanent magnets	electric motors and generators, automated waste sorting, high-resolution diagnostic imaging techniques, miniaturised IT applications			x	x		x		x	x	x							
Phosphors	plasma displays, LCDs, energy-saving lamps, fluorescent lamps, radar equipment, cathode ray tubes	x	x	x	x			x	x	x			x					x
Catalysts	petroleum production, auto catalysts, chemical processing	x	x	x	x		x											
Glass industry	colouring, UV resistant glass	x	x		x													
Metallurgy and alloys	battery alloys, fuel cells, steel, aluminium/magnesium	x	x	x	x													x
Polish	polishing powders for TVs, computer monitors, mirrors, silicon chips	x	x		x													
Ceramics	colouring, stabilisation, capacitors, sensors, refractories	x	x	x	x			x	x		x					x		x

Table 3.5: Components, respective applications, and REEs employed for their production. Source: compiled by the author, according to data from Angerer et al. (2009); Cordier (2011b); EC (2008); Goonan (2011); Hatch (2008); Haxel et al. (2002); Liedtke and Elsner (2009); London (2010); USDE (2010); Walters and Lusty (2010).

Pr	Nd	Gd	Tb	Dy
70%	76%	69%	11%	100%

Table 3.6: Consumption of REEs in Nd-Fe-B permanent magnets as a share of total demand for the respective element. Source: compiled by the author, according to data from Goonan (2011). Data refer to 2008.

Permanent magnets nowadays are predominantly manufactured from neodymium, iron and boron (Nd-Fe-B) as this is the material yielding the strongest magnetic power. Nd-Fe-B magnets have widely crowded out samarium-cobalt magnets (Sm-Co) since the mid-1980s (Angerer et al. 2009). Sm-Co has been used since the 1970s because of its high efficiency and temperature stability, but regarding material costs it is not competitive with Nd-Fe-B (Kurronen et al. 2010; USDE 2010) as iron is much more abundant and therefore cheaper than cobalt. Moreover, magnetic power of Nd-Fe-B is up to 2.5 times higher (Walters and Lusty 2010) and remains stable for decades unless sudden temperature increases or corrosion occur. Meanwhile, solutions to overcome these vulnerabilities have been found: in humid environments, e.g. when applying permanent magnet technology to offshore wind power plants, surface coating of the magnets protects them from corrosion (Kurronen et al. 2010). For achieving an improved heat resistance, neodymium can be partially substituted by dysprosium (Cordier 2011b) or terbium (Kurronen et al. 2010) whereby 5 to 10% of neodymium content are replaced with one of the other materials. However, both additives belong to the REE group as well, with terbium being much scarcer and hence more expensive than many other REEs, including dysprosium; therefore terbium is rarely used as a permanent magnet supplement (London 2010; USDE 2010).

Another option is the use of didymium in magnets, a mixture of 75% neodymium and 25% praseodymium[16] (Cordier 2011b; London 2010). The 3:1 ratio is consistent with the natural abundance of the two elements and contributes to reduction of material costs as well as corrosion prevention (USDE 2010). Gadolinium plays only a minor role as a permanent magnet supplement (Goonan 2011).

Table 3.6 indicates that the permanent magnet sector demands large shares of total consumption of almost all of the REEs incorporated.[17] Especially demand for neodymium has risen sharply in recent years and has even outpaced supply (London 2010). Whereas permanent magnet production accounted for 55% of neodymium demand in 2006 (Angerer et al. 2009), its proportion had already reached 80% in 2009, out of which 10% were

[16]Praseodymium is generally employed as an additive or substitute in REE applications rather than a primary material (USDE 2010).

[17]Samarium demand has been omitted as Sm-Co magnets are hardly produced any more. Note that the table provides data with respect to permanent magnets, not to wind turbines that are one of their possible applications. A similar, but more extensive overview of end uses for REEs by amount of single REOs in all sectors can be found in Goonan (2011).

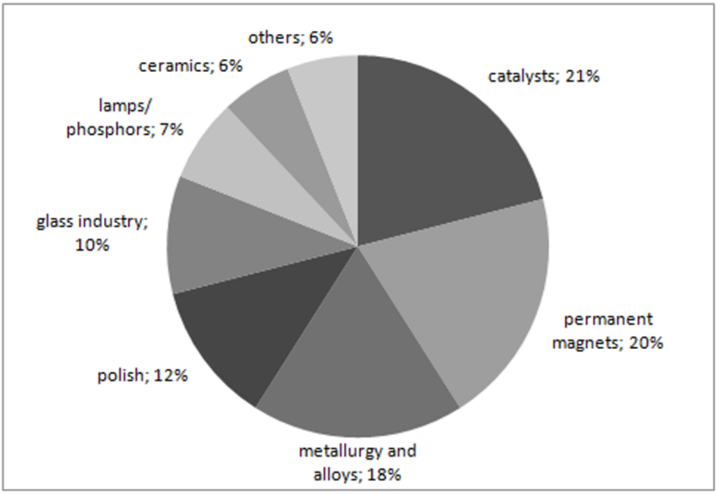

Figure 3.5: Share of REO consumption by major industries in 2008. Source: compiled by the author, according to data from Goonan (2011), Liedtke and Elsner (2009), London (2010) and Walters and Lusty (2010).

applied to wind turbines and hybrid vehicles (USDE 2010). Measured by value, magnets even represent 38% of REE consumption (Walters and Lusty 2010). In 2008, roughly 20% of total REO demand originated from the Nd-Fe-B magnet industry (Goonan 2011).

Figure 3.5 illustrates the relative importance of major industries for REO demand. In addition to the largest sectors named explicitly, the category "others" includes potential future markets like laser technology (Angerer et al. 2009; London 2010), hydrogen storage (Angerer et al. 2009), magnetic refrigeration (EC 2008; Haxel et al. 2002) and nanotechnology (EC 2008) that today only comprise a negligible share. Altogether, the sectors dependent on REE inputs are estimated to cover approximately 5% of global GDP (Milmo 2010). Yet, since many applications rely on the particular properties of certain single materials whose demand does not necessarily coincide with their natural abundance, supply-demand imbalances are prevailing on the REE market (Liedtke and Elsner 2009). The following section takes a closer look at the resulting price trends.

3.3 Price trends

Economic theory predicts that non-renewable natural resources are characterised by opportunity cost because once extracted and consumed, the resource is lost and cannot be used for another purpose any more. Therefore, the price of exhaustible resources reflects not only the marginal cost of extraction, but also has to cover opportunity cost. Hence, a smaller quantity is traded for a higher price than in the case of renewable resources, as Figure 3.6 illustrates for the static case. Considering a dynamic framework, the shadow price rises over time with the interest rate of the economy, a relation that is commonly referred to as the Hotelling rule (Wacker and Blank 1999). However, this theoretical setting only applies to perfectly competitive markets where agents have perfect foresight. In the following, the theoretical considerations are confronted with empirical data from the REE market to determine whether those assumptions are fulfilled here.

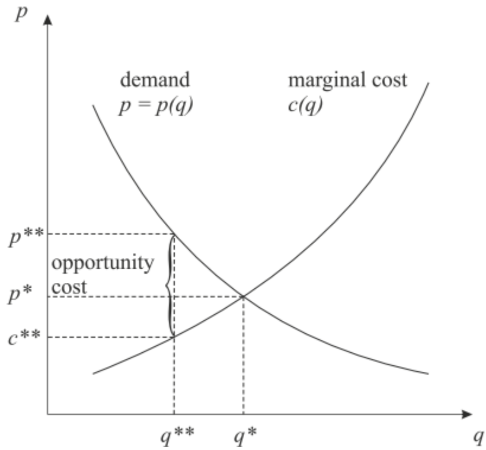

Figure 3.6: Pricing of a non-renewable resource. Source: Wacker and Blank (1999), modified by the author. Notation: q - quantity, p - price, c - marginal cost. Variables with an asterisk represent equilibrium values for renewable resources, those with two asterisks stand for the market outcome of non-renewable resources.

As Behrendt et al. (2007) point out, raw materials prices in general are highly volatile in the short and medium term. This may be due to supply-demand disequilibria that can either result in price fluctuations or quantitative shortages (USDE 2010). Several studies have empirically investigated the determinants of price development over time and come to the conclusion that production costs mark the lower limit (as predicted by economic theory) that is usually exceeded by internal influences and by external factors. Internal influences relate to effects on the raw material's own market such as changes in demand or supply patterns that yield imbalances, the occurrence of market power, scarcities, and prevailing expectations. These parameters mainly affect price development in the short run. External factors include geopolitical events, national policies like environmental legislation, economic growth, inflation or deflation, and natural disasters. The external determinants tend to induce rather long-term price developments. Regarding co- or by-production, the markets for minor products are usually more sensitive to shocks owing to close interrelationships with the major or co-products (Papp et al. 2008; USDE 2010; Walters and Lusty 2010).

Historically, nominal price development underwent several significant highs and lows that can be seen in Figure 3.7.[18] Starting with REE extraction on a commercial scale in the 1950s, prices fell after a peak in the mid-1950s until the early 1970s, mainly driven by the opening of Mountain Pass mine that represented a sudden positive supply shock. Subsequently, costs of production increased due to inflation and risen energy costs, resulting in higher REO prices. Yet in the early 1980s prices stabilised for a few years to rise again in 1985, induced by a decrease in demand that was answered by an even greater decrease in supply. In the 1990s, China considerably expanded its production (Walters and Lusty 2010) (see also Figure 3.3), thereby causing excess supply which led to lower price levels that are even estimated to be consistent with short-term marginal cost (USDE 2010). By the year 2000, the Nd-Fe-B magnet industry had acquired a significant impact, particularly driving demand for neodymium and dysprosium; when China - that had meanwhile become the major player on the market - reacted by expanding REE production, excess supply of other REEs that occurred as co-products was the consequence. In order to counteract price reductions, China restricted supply again, but did not succeed in guaranteeing high prices as at the same time REE demand from the IT sectors dropped, so supply still exceeded demand (Walters and Lusty 2010). Prices reached a trough in 2006, but since then have continuously increased until 2008. From 2007 on, Chinese domestic demand played an increasing role and export restrictions were introduced, contributing to rising prices as well (Papp et al. 2008). The following drop between 2008 and 2009 was due to the financial crisis that led industries to reduce their raw materials demand (EC 2008); the crisis was mainly perceptible in the automobile industry where demand for Nd-Fe-B magnets fell drastically, but recovered in the second half of 2009. As a consequence, sharp price increases have happened since 2009 (which is not visible in Figure 3.7 any more) (Cordier 2011a). In 2010 the prices of many individual REEs have escalated by 300 to 700% (USDE 2010); between October 2010 and July 2011 REO prices increased tenfold (Kern 2011). It is predicted that in the future excess demand will continue to prevail, bringing about further price rises. The EC (2008) refers to the REE market as underlying a super cycle.

[18] As mentioned earlier, data are usually provided for REOs which also applies for price information. REM prices closely follow the respective REO prices (USDE 2010).

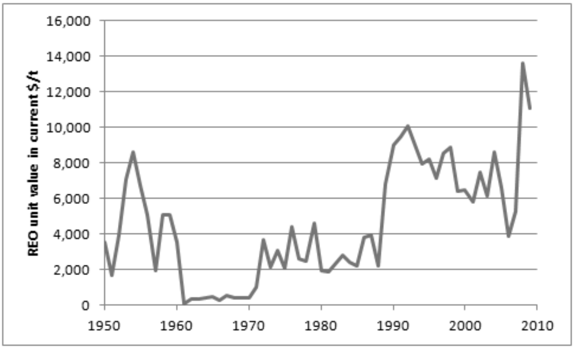

Figure 3.7: REO prices in current US dollars per metric ton from 1950 to 2009. Source: compiled by the author, according to data from Kelly and Matos (2010).

Papp et al. (2008) note that REO prices in the long run, when denoted in current US dollars - as in Figure 3.7 - closely follow inflation rates. Therefore an inflation-adjusted version is provided in Figure 3.8 with prices being normalised to 2008 levels. In contrast to the previous graph, the upward trend since the 1970s is not clearly visible any more. However, it is well-known from economic theory that the (inflation-adjusted) price of a non-renewable natural resource should rise over time to account for increasing scarcity (Tietenberg 2006). As this is not the case here, it can be concluded that owing to several disturbances on the REE market, prices are no reliable indicators of actual scarcity.[19]

All in all, shocks that were predominantly caused by technological change on the demand side and the emergence of market power on the supply side made the REE market pass from excess supply to a situation of excess demand. Total demand for REOs had risen by 46% in 2008 compared to 2003 (Walters and Lusty 2010) while export restrictions from China started to take effect and reduce the availability of raw materials.

Prices of individual REEs can vary considerably and do not necessarily follow the trajectories depicted for REEs as a whole; an example for the price development of selected REOs is given in Table 3.7.[20] As a general rule, heavy REEs are usually more expensive than their lighter counterparts (USDE 2010) which can be justified by their lower abundance (Walters and Lusty 2010). However, as light REEs also underly Chinese export restrictions, they have recently been subject to price increases as well (USDE 2010). Re-

[19] Rosenberg (1973) already discovered a similar pattern for several natural resources: he points out that despite remarkable fluctuations in the short run, the long-term price trend shows only a moderate upward slope.

[20] Yet in contrast to the downward price trend shown until mid-2009, prices have risen considerably since then (USDE 2010).

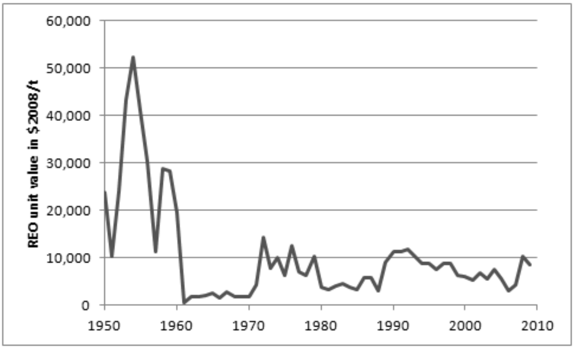

Figure 3.8: REO prices in 2008 US dollars per metric ton from 1950 to 2009. Source: compiled by the author, according to data from Kelly and Matos (2010).

garding rare earths used in wind turbine generators, the USDE (2010) study suggests that neodymium, dysprosium and terbium availability will be highly critical both in the short and medium term, whereas praseodymium and samarium are assessed to be uncritical. Data for gadolinium are not provided.

Yet for some REE consumers, current prices play only a subordinate role because they have signed long- or short-term agreements with resource producers, fixing the price in advance. Similar contracts exist on a bilateral level (Behrendt et al. 2007; USDE 2010). The tendency toward supply agreements results from the lack of stock exchange trading on the REE market (Liedtke and Elsner 2009). Instead, the role of an intermediary is often taken over by companies that specialise in raw materials trading (Walters and Lusty 2010). The absence of a freely adjusting market brings about weak and potentially unreliable price signals (USDE 2010).

Although the enormous short-run price swings that occurred in the last two to three years are not representative of the medium- to long-term market development, they can be explained by the previous statements that both REE supply and demand are characterised by low price elasticities: they imply a supply and demand curve with relatively steep slopes each, so exogenous shocks primarily yield price reactions and only minor quantity reactions. It is reasonable to assume that the low price elasticities hold for a short-term assessment whereas in the long run the market can adjust more easily, e.g. by the means discussed in Section 3.4, so the long-run price elasticities are higher, which justifies the moderate price development monitored over a longer time horizon.

To answer the question raised at the beginning of this section, the analysis has proven that the REE market cannot be considered a perfectly competitive market as assumed in

REO	Price June 2001	Price June 2002	Price June 2003	Price June 2004	Price June 2005	Price June 2006	Price June 2007	Price June 2008	Price June 2009
La	7.00	2.30	1.50	1.62	1.45	2.15	2.82	8.83	5.90
Ce	4.00	2.25	1.68	1.62	1.37	1.65	2.63	4.38	3.80
Nd	11.00	4.35	4.42	5.75	6.05	11.07	31.15	32.88	14.50
Pr	6.20	3.94	4.19	8.00	7.55	10.70	30.37	32.61	14.50
Sm	9.00	2.98	2.67	2.67	2.60	2.40	3.12	4.80	4.75
Dy	35.00	20.00	14.60	30.30	36.40	70.44	88.30	120.80	112.00
Eu	310.00	240.00	235.40	310.50	286.20	240.00	311.00	491.00	495.00
Tb	135.00	170.00	170.00	398.20	300.00	434.00	575.40	740.00	360.00

Table 3.7: REO prices for selected elements from 2001 to 2009. Source: Lynas (2010). Prices refer to a minimum purity of 99%.

economic theory (USDE 2010). Instead, the price mechanism is disturbed by different kinds of market failure and the existence of widespread longer-term price agreements.

3.4 Mitigation options for market imbalance

It has already been revealed that the REE market is currently characterised by a situation of excess demand. This section investigates possibilities to potentially overcome the disequilibrium. The most frequently named measures are recycling and substitution of critical materials[21] (Tietenberg 2006; USDE 2010).

However, excess demand is a quite recent phenomenon; until the mid-2000s, the REE market was rather characterised by oversupply, so processing industries had little incentive to pursue recycling or substitution (Walters and Lusty 2010). It remains to be seen whether their efforts will now increase - this is not self-evident because of their low short-run price elasticity of demand. Since research and development into mitigation options raise additional costs, REE-consuming firms will only invest in them if they expect raw materials prices to remain high in the longer term (USDE 2010) or if they are forced to find solutions to sustained quantitative supply disruptions.

[21] Further options, like the discovery of new resources or efficiency increases due to technological progress, are considered exogenous from the perspective of the individual firm and therefore remain unregarded here. (Although companies can actively pursue research and development activities on their own, the success of technological advancements is to a large part dependent on exogenous influences.)

3.4.1 Recycling

For an economy, waste products of non-renewable resources have two implications. On the one hand, environmental degradation causes welfare losses for the society. On the other hand, the waste may be recycled, i.e. used as a secondary resource stock, thus yielding a welfare gain (Wacker and Blank 1999). It is therefore utility-enhancing to pursue recycling as it can contribute to a reduction of negative externalities.

In detail, recycling has numerous advantages. First, it serves environmental preservation by lowering waste flows, being conducive to energy efficiency, and reducing air pollution, thereby abating climate change impacts (EC 2008, 2010; Kuhn et al. 2003). Second, it can substitute for primary raw materials (EC 2010), which can result in a restructuring of international resource markets if formerly import-dependent countries develop alternative ways to access raw materials and hence weaken the market power of primary resource suppliers (Kuhn et al. 2003). Third, as a consequence of the second point, the overall reserve base is expanded (Kuhn et al. 2003; Tietenberg 2006), an effect which Pittel et al. (2010) refer to as creating a "quasi-'renewability' of the resource stocks".

However, recycling faces several barriers to being widely implemented. First, in many countries practical hurdles prevent recycling: waste management and collection systems are inappropriate, so recycling would imply significant transaction costs; furthermore, reliable information regarding the quality of recycled materials is often lacking, so consumers tend to distrust them (EC 2008). In addition, newly developed technical applications often have a long lifespan, thereby creating a lag between resource demand and the availability of corresponding scrap materials (EC 2010). Second, the negative environmental impact of the recycling process, originating from the use of partially toxic chemicals, is a frequently named counter-argument (Wacker and Blank 1999). Third, Kuhn et al. (2003) remark that balanced sustainable growth imperatively requires a recycling rate of unity; yet the laws of thermodynamics signify that the physical theoretical upper limit is smaller because recycling involves losses (Tietenberg 2006), which is why it is sometimes called "downcycling". Economic activity without environmental damage is therefore infeasible (Wacker and Blank 1999).

The implications of recycling for resource stock development over time can be expressed as follows:

$$S_t = S_0 + S_0 a + S_0 a^2 + S_0 a^3 + \cdots, \tag{3.1}$$

with S_0 denoting the original (primary) resource stock, a the recovery rate, and S_t the resource stock at time t that includes both primary and secondary materials. When considering an infinite time horizon, Equation 3.1 can be modified to

$$S_t = \frac{S_0}{1-a}. \tag{3.2}$$

Both equations prove that only a recycling rate of 100%, i.e. $a = 1$, can provide an infinite resource flow over time. If this is not the case, as the laws of thermodynamics postulate, the secondary resource stock becomes infinitesimally small, resulting in a finite supply of overall resources (Tietenberg 2006).

Figure 3.9 illustrates how REE scrap is currently disposed of. Recycling comprises a fraction of 0%, hence sustainable utilisation is far from being practised today. Graedel (2011) confirms that the recycling rate of REEs as a whole is below 1%. The global average recycled content as a share of total input to metal production accounts for less than 1% for most REEs, but falls in the range between 1 and 10% for lanthanum, cerium, praseodymium, neodymium, gadolinium and dysprosium (Graedel 2011).

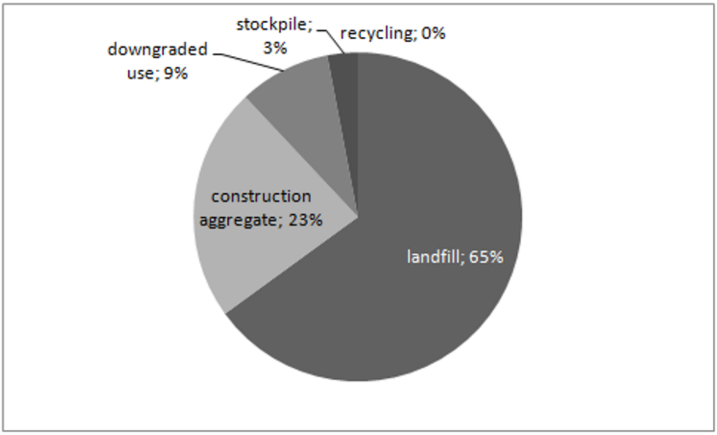

Figure 3.9: Current ways of REE disposal. Source: compiled by the author, according to data from Goonan (2011).

As for permanent magnets in particular, the feasibility of recycling has been demonstrated (Horikawa et al. 2006; Takeda et al. 2006), but the cost is still unknown (Jacobson and Delucchi 2011). Future prospects, e.g. by Angerer et al. (2009), appraise the recycling potential of Nd-Fe-B magnets to remain limited by 2030. Walters and Lusty (2010) point out that magnets produced from recycled materials may contain impurities and therefore provide an inferior performance. Additionally, another particularity of REEs impedes recycling. It is related to their dissipative use, which means that they occur in final products in very small concentrations and quantities (Behrendt et al. 2007). Consequently, the material is too widely dispersed to be economically collected in the first place, but even if it could be collected, an efficient recovery process would be infeasible under current conditions since large amounts of inputs, especially energy, are required to separate and regain the materials (Moriarty and Honnery 2011). Primary resource prices were quite low in the past, but if the price trend observed in the last three years is sustained or recycling technologies are improved, recovery of secondary resources will become economic as their value increases (Goonan 2011). However, this will only hold as long as the material intensity in final products remains unchanged; further miniaturisation and efficiency gains in applications will counteract this development by augmenting the effort of the recovery process (Moriarty and Honnery 2011).

A more probable alternative to conventional recycling is the reuse of permanent magnets. Owing to their decade-long lifespan without performance degradation, they can relatively easily be disassembled from disused applications and reintegrated elsewhere. Yet, if the magnets already suffer from corrosion or have been covered by plating materials that are unwanted in successive applications, the reuse may also be prohibitively expensive (Goonan 2011; Walters and Lusty 2010).

For many countries whose industries heavily rely on natural resource inputs, such as the EU member states, secondary materials are the only domestic possibility of resource supply (Angerer et al. 2009; EC 2008). Meanwhile it has become increasingly difficult for the EU to obtain scrap on the international secondary resource market. Whereas its imports of non-ferrous and precious metal waste fell by 40% between 2000 and 2008, exports rose by 125% during the same period, yielding shortages and price increases. This is due to scrap being illegally transported outside the EU rather than being recycled or reused domestically (EC 2008). Moreover, a level playing field on the global market for secondary raw materials is lacking: several non-EU countries raise export taxes, subsidise domestic waste treatment, or have implemented much less rigorous environmental directives (EC 2010).

As this section has shown, the incidence of REE recycling is currently negligible and is not expected to improve considerably in the near future. In the following it is analysed whether substitution possibilities allow for a more optimistic outlook.

3.4.2 Substitution

As indicated previously, REE demand in the short run is relatively inelastic owing to pre-existing production technologies and equipment used in their processing. In the long run, however, these constraints lose importance, the modes of production are more variable, and the absolute value of price elasticity of demand increases. Hence, price changes have to be sustained to advance the adoption of substitutes (Tietenberg 2006). As in the case of recycling, the incentive for companies to substitute for REEs was rather limited so far since fierce price increases have only occurred during the last three years.

Generally, substitution is most efficient if it allows the replacement of a scarce and critical input with a more abundant material (EC 2010; Moriarty and Honnery 2011). Yet the applications employing REEs mostly rely on their specific properties (London 2010), so substitutes are either not available at all or they provide a lower-grade performance (Cordier 2011b). If there are substitutes for certain kinds of REEs, they often contain other REEs or even more critical materials (Walters and Lusty 2010).

Concerning permanent magnets in particular, a substitute for neodymium yielding comparable performance has not been discovered yet (Angerer et al. 2009) in spite of 20 years of scientific research on the issue (Walters and Lusty 2010). If neodymium became prohibitively expensive, the production of Sm-Co magnets could be resumed on a larger scale, but again efficiency losses would have to be accepted (Angerer et al. 2009). Moreover, although excess supply of samarium is predicted to sustain, guaranteeing comparably moderate prices, cobalt is usually considerably more expensive than the alloys used in Nd-Fe-B magnets. Since samarium also comprises only a small share of overall REE production (see Figure 3.2) and is hardly used for industrial purposes (see Table 3.5), it is unlikely to become a major driver of REE production (USDE 2010), so its supply is expected to depend on its co-products more strongly than in the case of neodymium, implying an even lower price elasticity of supply.

If substitution of REEs in the permanent magnet sector is difficult to achieve, their replacement in other sectors can be an option to mitigate overall demand. For example, lithium-ion batteries can be employed instead of nickel-metal-hydride batteries, thus decreasing the need for cerium, lanthanum and neodymium (Goonan 2011). Furthermore, in metallurgy, nuclear energy, hydrogen storage, glass polishing and ceramics there are viable alternatives to REE utilisation, but these only represent a small market share; most applications are expected to remain dependent on REEs (Walters and Lusty 2010).

Another possibility would be the substitution of other types of magnets for entire permanent magnets, first of all electromagnets. Their main weakness, though, is the much larger size, resulting in greater space requirement within the final application (Aston 2010). Morcos (2009) suggests the use of sintered ferrite permanent magnets that do not rely on REE inputs. Although they provide an inferior performance in wind turbines when it comes to low wind speeds, their component materials are more abundant and therefore lower-priced, so the return on investment for sintered ferrite permanent magnets is estimated to be equal or even slightly better than that of Nd-Fe-B magnets.

Finally, the replacement of permanent magnet generators in wind power plants with ceramic high-temperature superconductors is recommended.[22] However, they contain yttrium, another rare earth (USDE 2010), and therefore substitute one critical material for another, which may postpone the problem, but not solve it.

All in all, research is currently pursued in order to find materials that can either completely replace REEs or reduce the requirement for them, but significant progress is anticipated to take several years (Aston 2010). The only reasonable alternatives at the present time seem

[22] For ceramic superconductors, "high temperature" means that they can operate at up to -140°C.

to be the replacement of entire rare earth permanent magnets, especially with sintered ferrite permanent magnets (Morcos 2009), or REE substitution in other industries.

3.5 Consequences for future market development

The analysis in this chapter has shown that the REE market is highly complex and subject to many interrelations. Although the absolute abundance of REEs in the earth's crust turned out not to be that critical, the low concentrations in which they naturally occur impose severe restrictions upon economic production. Additionally, four kinds of market failure on the supply side complicate the situation: REEs are mined as by-products of other minerals, they are bound together as co-products, their mining and processing causes environmental damage, and China has quasi-monopolistic market power. The fact that almost half of current worldwide reserves is concentrated in China points to the probably persistent nature of its position, but also reveals the existence of alternative mining locations to be developed in the future.

Regarding the demand side, REEs are classified as specialty materials rather than commodities, which implies that the need for them is predominantly driven by technological progress. Recently many new applications requiring REEs as inputs have emerged or are at present being investigated. One of the most important applications of REEs is their use in permanent magnets that are, inter alia, employed in wind turbines.

The combination of supply restrictions and increasing utilisation of REEs in the industry yields supply-demand imbalances that have led to drastic price increases, especially in the last three years. However, as far as the long-term price trends are concerned, an increase that exceeds inflation rates could not be observed. This contradicts economic theory as depletable natural resources should face rising prices over time to account for increasing scarcity. It can thus be concluded that the prices witnessed at the market do not reflect actual scarcities, but are disturbed by the market failure described above and the prevalence of price agreements.

To mitigate current shortages and price fluctuations, recycling and substitution options of REEs have been examined. Recycling is hardly being pursued today and faces obstacles indicating that it will only become economic in the case of persistently high prices for primary resources. From a present-day perspective, reuse of permanent magnets appears to be more viable than conventional recycling. As for substitution, a replacement of REEs within permanent magnets is not possible so far if efficiency is supposed to be maintained. Instead, substitution of less critical materials for REEs is feasible in some other sectors, which could also contribute to excess demand mitigation. Alternatively, magnet concepts without REE inputs can be adapted, apparently the most realistic option in the short and medium term.

Now the question arises how the REE market will continue to develop in the future. A look at the literature reveals that the trend toward rising demand is commonly believed to prevail. For example, Milmo (2010) estimates total rare earth demand to amount to 200,000 t per year by 2014, up from 129,000 t in 2008 (Goonan 2011), which is the most recent historical value available. The most important applications are expected to be automotive catalytic converters, permanent magnets, rechargeable batteries and lamps, altogether demanding especially large amounts of high-purity REE products. For permanent magnets in particular, the compound annual growth rate is anticipated to account for 8 to 15% in the same time horizon (Cordier 2011a,b; Liedtke and Elsner 2009; Walters and Lusty 2010).

A frequently used indicator for expressing the expected future natural resource demand from emerging technologies is its share of current worldwide resource production (Angerer et al. 2009; EC 2010). Values for neodymium range from 1.66 (EC 2010) to 3.82 (Angerer et al. 2009) in 2030. These figures have to be interpreted as follows: if yearly neodymium production remains unchanged, i.e. at current levels, by 2030,[23] demand from emerging technology sectors will exceed supply by a factor of 1.66 (or 3.82, respectively). For comparison, in 2006 the indicator constituted 0.23 (EC 2010) or 0.55 (Angerer et al. 2009), respectively.[24] Even though the magnitude of the indicator differs among the sources, the principal statement that demand from emerging technologies will substantially rise remains valid.[25] Moreover, at the present time there are no phase-out technologies foreseeable that rely on neodymium (Angerer et al. 2009).

Concerning the materials employed in wind turbine generators, only praseodymium and samarium are assessed to be sufficient in the short to medium term. Neodymium, dysprosium and terbium shortages are already perceptible today and they are expected to persist. This prospect once more emphasizes the need for alternatives or material intensity improvements with regard to Nd-Fe-B permanent magnets (USDE 2010).

In general, it takes 5 to 10 years for newly designed technologies to mature while the time lag between the planning of new mining projects and their start of production ranges from 5 to 15 years (Behrendt et al. 2007; London 2010; Milmo 2010; USDE 2010). This means that supply adjustment can theoretically keep pace with changing demand-side patterns if technological developments can be anticipated (Behrendt et al. 2007), which does not seem to be the case in practice. The reasons for the considerable time lag between the identification of mineable deposits and their exploitation are various. They include difficulties with raising investment capital (EC 2008) - sometimes a mining company must even manage

[23] This is a highly improbable assumption, but it is necessary to ensure comparability of different points of time.

[24] As 2006 is taken as a base year in both references, “current production” in the fraction’s denominator also refers to the value from 2006.

[25] It is remarkable that despite the data from both sources differ considerably, they are both consistent with the EC (2010)’s prediction that neodymium demand from emerging technologies will rise to 700% of current levels by 2030.

to find potential purchasers for the mine's output and bind them contractually before production can actually start (USDE 2010). Besides, planning and legal permit phases vary depending on the location, but can take several years. In some cases the existing infrastructure is not sufficient and has to be expanded first. Further possible bottlenecks are delays in equipment delivery or a lack of skilled staff (EC 2008). Finally, overall experience with REE mining projects is quite limited outside China (London 2010).

In spite of these barriers, global expenditure for the exploration of new mines has continuously increased since 2002 (EC 2008). In order to reduce their import dependency, many countries now pursue their own REE mining projects. In the USA the reopening of Mountain Pass is currently being planned. In Australia the Mount Weld deposit is being prepared for REE production (Angerer et al. 2009). Further locations anticipated to start REE mining in the next years include Canada, Malawi (Cordier 2011b), India (Liedtke and Elsner 2009), Vietnam (USDE 2010), South Africa, Greenland, Kyrgyzstan, and Namibia (Walters and Lusty 2010). A gradual diversification of supply can therefore be expected by the end of this decade, although REO reserves at most sites and hence their REE production potential are relatively small compared to Chinese conditions. Moreover, the circumstances of REE production are more favourable in China than in other places, especially regarding competitiveness, as the processing of deposits there is associated with particularly low costs. Out of the alternative deposits listed here, Mountain Pass is the only location mined exclusively for REEs. The other sites target different ores as main products and process REEs as by-products only (Haxel et al. 2002; Walters and Lusty 2010). All these factors contribute to the appraisal that China's market power will probably be reduced to a small extent, but it will nevertheless retain a dominating position in the medium term.

Nonetheless, it is still beneficial for mitigation of excess demand to search for alternative mineral sources because further options, like substitution, recycling, efficiency increases, or intelligent demand management, will take years to develop and implement (Aston 2010; EC 2010). Meanwhile, REE mining outside China will become more economic if continued REE production and export restrictions as well as rising domestic demand within China yield further price increases on the world market (Cordier 2011a).

Regarding future pricing, it is anticipated that long-term agreements will lose their importance due to rising uncertainty resulting from more volatile currency and energy cost developments. Outstandingly high prices are expected for materials that are demanded by emerging technology industries and whose supply is already beginning to show tightness, predominantly neodymium, dysprosium, terbium, yttrium and europium (London 2010; Walters and Lusty 2010).

When switching to a long-term assessment, uncertainty becomes even more apparent. Since market power, its influences on international trade, and resulting price volatility are rather short- to medium-term phenomena, REE criticality can then be evaluated by reserve availability (although this concept also involves several weaknesses, as described earlier in this chapter) (Behrendt et al. 2007). The fact that this indicator did not point to the occurrence of scarcity in the past does not justify the assumption that this will remain valid in the future (Tietenberg 2006). However, reserve figures are not the only data sources to rely on: developments of geopolitics and economic circumstances are equally important (EC 2010). These trends are even more difficult to predict, but play a crucial role, e.g. when policies target the deployment of clean energy technologies and thus induce a positive shock on REE demand (USDE 2010). The relevance and possible directions of policy interventions can also be retraced in Figure 3.10, which additionally provides a graphic summary of this chapter, illustrating the supply chain of critical materials with its associated problems and potential solutions.

As a result from the analysis conducted so far, it can be concluded that REE shortages and further price increases are likely to occur, but accurate predictions are impossible (USDE 2010). However, the consequences of further wind power deployment for REE demand have not been investigated up to now. Hence, Chapter 4 analyses possible pathways and their respective implications.

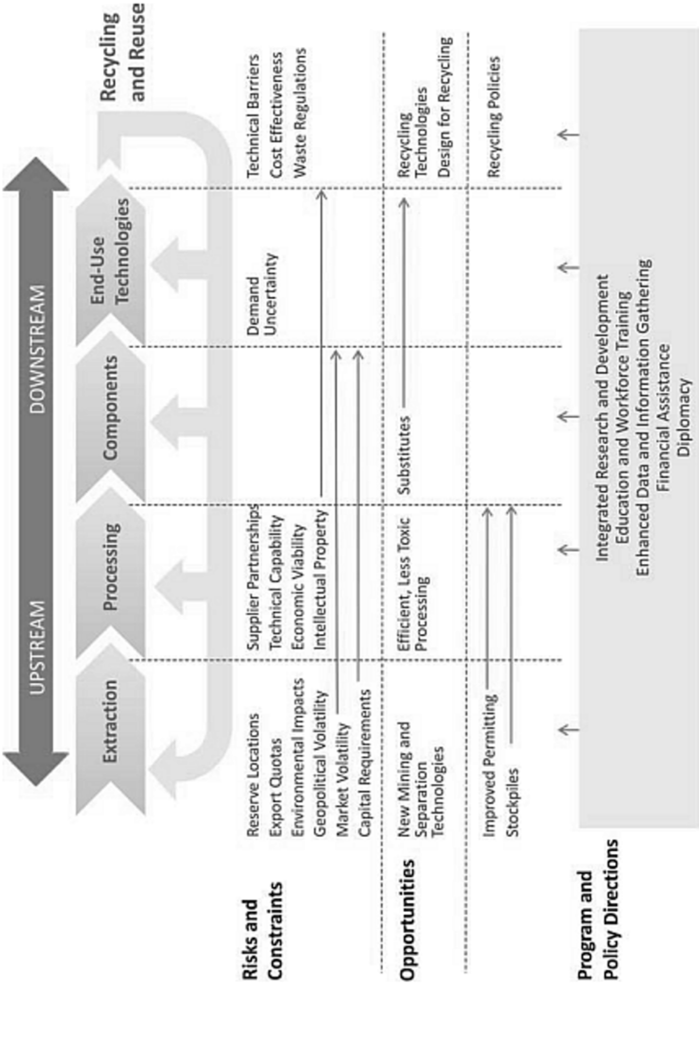

Figure 3.10: Supply chain of critical materials. Source: USDE (2010).

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