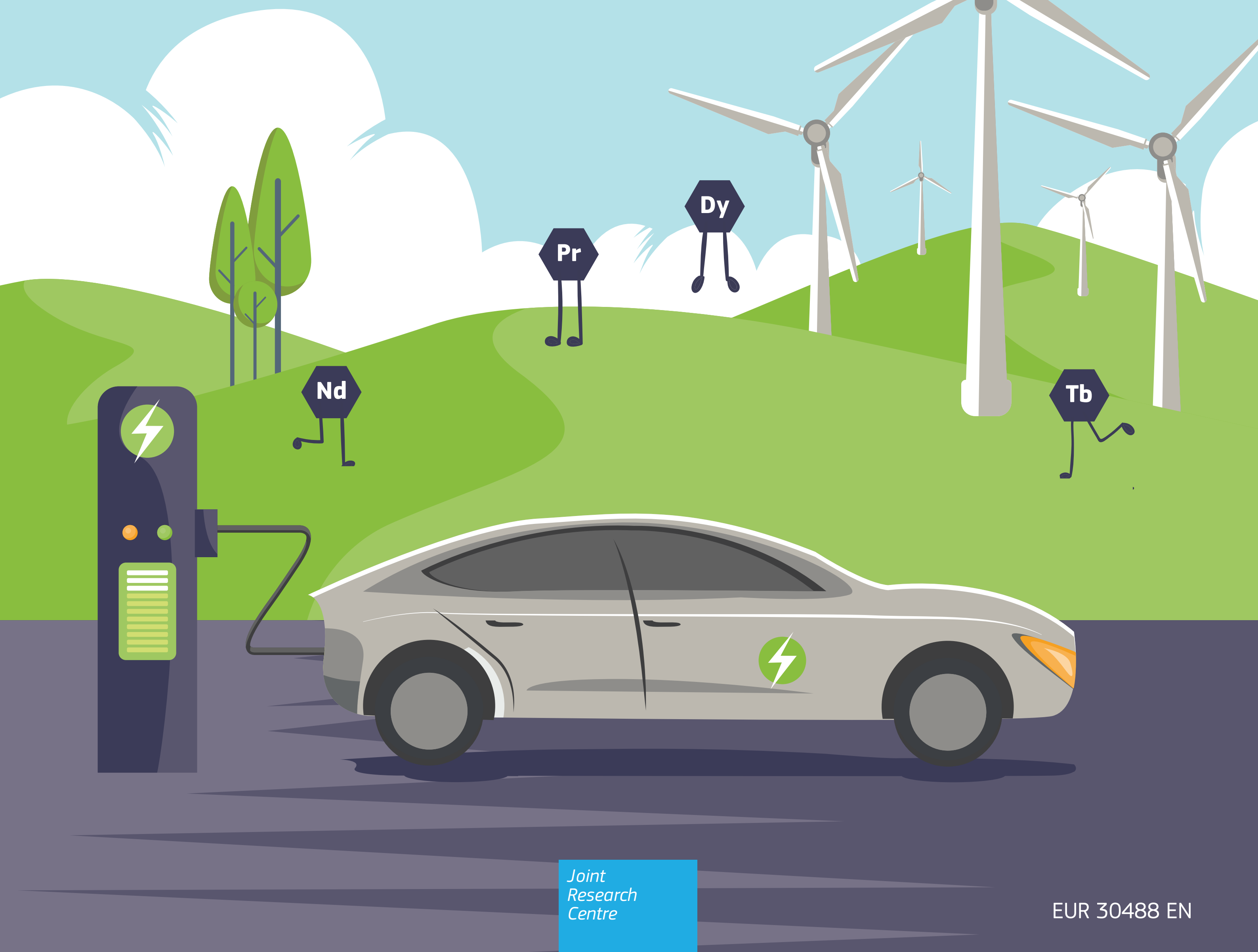
JRC SCIENCE FOR POLICY REPORT

THE ROLE OF RARE EARTH ELEMENTS IN WIND ENERGY AND ELECTRIC MOBILITY

An analysis of future supply/demand balances

ALVES DIAS, P., BOBBA, S., CARRARA, S., PLAZZOTTA, B.



EUR 30488 EN

EU Science Hub
https://ec.europa.eu/jrc

JRC122671

EUR 30488 EN

PDF	ISBN 978-92-76-27016-4	ISSN 1831-9424	doi:10.2760/303258

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Alves Dias, P., Bobba, S., Carrara, S., Plazzotta, B. (2020), The role of rare earth elements in wind energy and electric mobility, EUR 30488 EN, Publication Office of the European Union, Luxembourg, ISBN 978-92-79-27016-4, doi:10.2760/303258, JRC122671.

Contents

Acknowledgements

The authors are grateful to Thomas Telsnig for providing information on past and future developments in wind turbine deployments; Simon Letout for providing information on permanent magnet manufacturers and import/export volumes; Francesco Pasimeni for providing information on permanent magnet patents in the EU; Nicola Magnani for discussion of the results and support for text and visual editing; and colleagues from Joint Research Centre Land Resources Unit for their input and discussion.

Authors

Authors are listed in alphabetical order. Their contributions are as follows:

- Alves Dias, Patricia: supply analysis and forecast,
- Bobba, Silvia: demand and recycling potential analysis for traction motors,
- Carrara, Samuel: demand analysis for wind energy and other sectors, analysis of EU magnet manufacturers,
- Plazzotta, Beatrice: recycling and technological overviews, general coordination and editing.

Executive summary

As the focus on climate change increases, several countries are implementing green strategies and rapidly switching to clean energy technologies. This is leading to an increase in demand for materials used to manufacture key components of such technologies, and the European Commission has already identified several of these components as critical raw materials, which raises concerns about the security of supply. Examples of critical raw materials are the rare earth elements, which are needed for the manufacturing of permanent magnets for wind turbine generators and electric vehicle motors, as well as for several applications in other fields. These elements are currently supplied mainly from China, and with demand increasing at a rapid pace there are fears of supply bottlenecks amid geopolitical tensions. On the other hand, following the rare earth crisis of the early 2010s, increased efforts have been made in terms of geological exploration and the development of alternative technologies, which may mitigate supply risks. This report aims to provide information, data and forecasts that can guide the discussion and put it into context.

Policy context

The rising global demand for rare earths is a matter of concern. China has a leading position among suppliers and uses it both as a negotiating chip in international trade agreements and as leverage to attract advanced stages of the manufacturing supply chain. Both the EU and the United States have therefore flagged these materials as being subject to potential supply risks and both are implementing strategies to mitigate such risks. In particular, in 2020 the EU launched a raw materials alliance that will focus specifically on rare earth elements and permanent magnet manufacturing, and a comprehensive action plan to address potential risks linked to critical raw materials.

Failure to secure access to a stable supply of rare earth elements could curb European plans for a green transition, or increase the costs of this transition. In addition, if the rare earths and permanent magnet value chains remain undeveloped or, worse, move more and more towards non-EU countries, this may have a negative impact on the European economy and on the employment prospects linked to the green transition. Secure access to raw materials is thus an important step towards strategic autonomy.

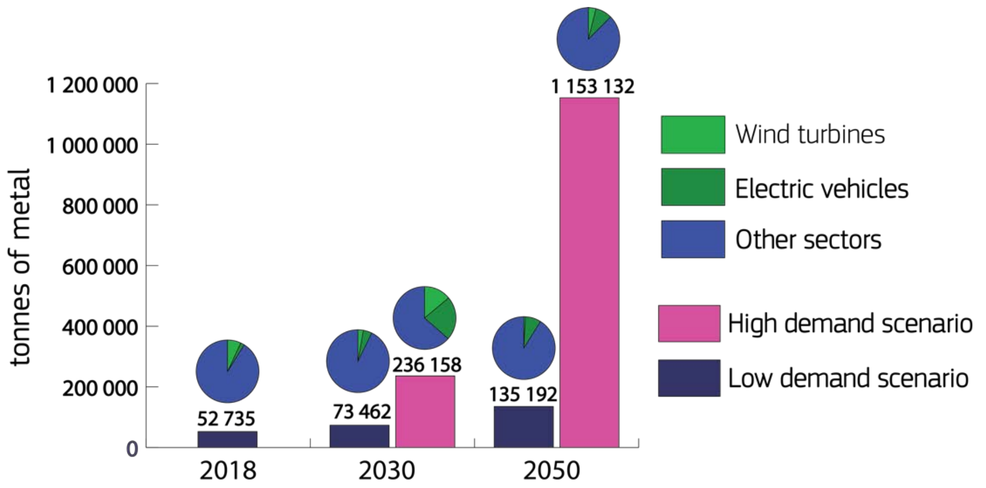
Main findings

Although China is currently the undisputed leader of the poorly diversified, rare earths supply market, there are indications that the situation may be changing. The 2010–2011 rare earth crisis raised global awareness of supply issues and triggered actions and investments. As a result, the global market may diversify, with mines (re)opening in Australia, Canada and the United States. Separation and refining of rare earth oxides is, however, carried out almost exclusively in China, and there are few indications that the situation will change in the future. Thus, even if the supply of ores is expected to diversify, refining is likely to still be relatively concentrated. One can, however, argue that the establishment of a sustainable supply outside China will drag further steps of the value chain outside the country.

As for the EU, its mining projects are located almost exclusively in Greenland and Sweden and are mostly under the control of Australian and Canadian companies. According to our analysis, these mines will provide less than 10 % of the global rare earth supply in the future, even in the best-case scenario. Considerable resources may be found in other European regions (for example in the Balkans) but these areas are relatively underexplored at present. EURARE, a project funded by the European Commission and addressing development prospects for rare earths mining in EU, claims that Europe has the potential to secure its own supply internally, but this would require both further geological exploration and the establishment of a viable exploitation scheme.

The use of the four specific rare earths neodymium, praseodymium, terbium and dysprosium is expected to increase in both low-carbon technologies and for other applications. Future rare earth demand for wind turbines and e-mobility will be driven both by technological advancements and optimisation of material usage and by the political ambitions underlying their development, whereas demand in other sectors, such as for electronics and specialised equipment, will mostly be influenced by market dynamics. This gives rise to a wide range of possible future scenarios (Figure 1).

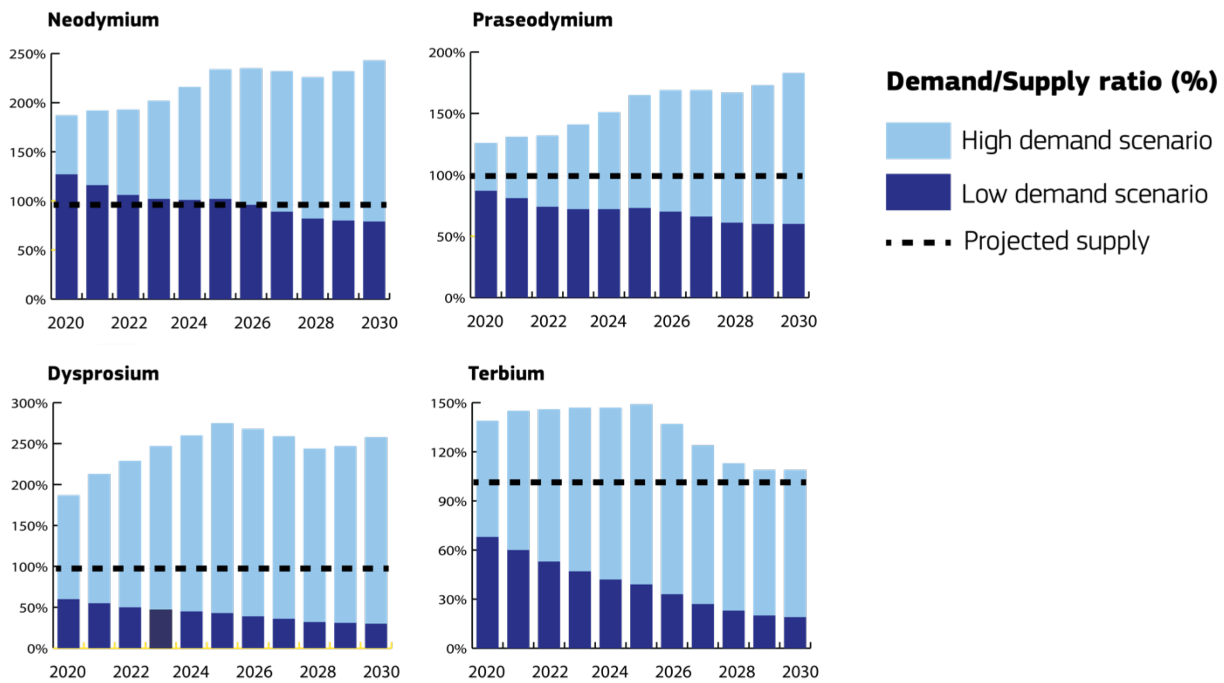
Figure 1: Estimated global demand for neodymium, praseodymium, dysprosium and terbium for wind turbine generators, motors for electric vehicles and other sectors, according to low- and high-demand scenarios.



Source: Joint Research Centre (JRC).

In a low-demand scenario (assuming a maximum increase in temperature of 2.7 °C in accordance with the Paris Agreement, that significant progress occurs in research and innovation and that there is moderate growth in other sectors), supply can generally keep up with demand. At the other extreme, a high-demand scenario (which assumes only minor improvements in technology, a 100 % global reliance on renewables for primary energy production and full EU decarbonisation by 2050, as well as increasing demands from other sectors, such as ICT) anticipates that demand will be significantly above supply. In particular, the demand for neodymium could greatly surpass the anticipated supply in the near future (Figure 2).

Figure 2: Demand/supply ratio for neodymium, praseodymium, dysprosium and terbium, considering all sectors

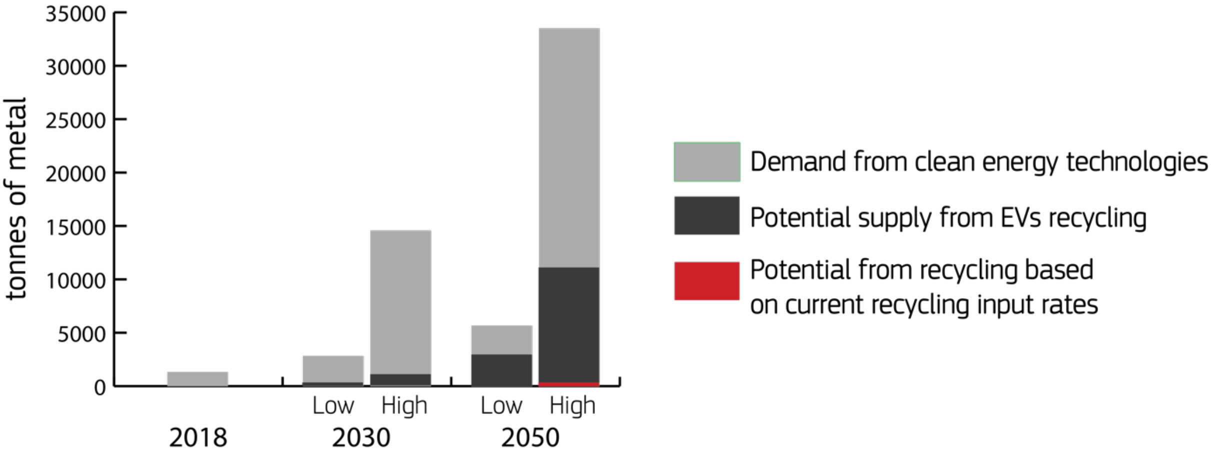


Source: JRC.

In the short term, the situation could be addressed through interventions aimed at reducing demand, such as alternative pathways for achieving policy targets, incentivising rare earth-free technologies and investing in research and innovation. In the long term, actions aimed at boosting supply could also be effective, for example promoting and incentivising geological exploration and mining projects or improving recycling facilities and waste collection.

Recycling is particularly important at the European level as there are limited options for increasing the primary supply. However, recycling systems and infrastructure will need to be significantly upgraded as current recycling input rates for rare earth elements are only around 1 % (Figure 3).

Figure 3: Projected demand for neodymium, praseodymium and dysprosium for clean energy technologies compared with the potential supply from recycling of rare earths from electric vehicles (EVs) (EU-27 and the United Kingdom)



Source: JRC.

1. Introduction

With climate change identified as a major threat to life and societies, many governments are implementing climate plans and agreements, ranging from the United Nations Paris Agreement in 2015 to the more ambitious European Green Deal and its pledge to reach carbon neutrality by 2050. To implement such plans and accomplish their ambitions, the whole world will have to move more and more towards the use of renewables and zero-emission mobility, in particular electric mobility.

In the middle of these efforts, raw materials have been identified as a possible bottleneck to the realisation of the green transition, at least at EU level, as several of the key materials needed for clean energy technologies have been identified as critical raw materials by the European Commission (European Commission, 2020a). Particular attention is currently been paid to the rare earth elements, for which supply risks have been identified by both the EU and the United States (European Commission, 2020b; U. S. Department of Energy, 2020).

Rare earths comprise a group of chemical elements with similar properties that are used in a range of high-tech applications. Among this group, the key elements for clean energy technologies are neodymium, praseodymium, dysprosium and terbium, which are used to manufacture neodymium–iron–boron (NdFeB) permanent magnets. NdFeB permanent magnets are used as components in generators for wind turbines and in traction motors for electric vehicles. They are also used in electronic components and in different kinds of motors. Other rare earths are important in ceramics, as catalysts for air pollution control, as phosphors for illuminated screens, in polishing compounds for optical-quality glass and optical fibre applications.

Although not scarce, these elements tend to be poorly concentrated and thus their mining and extraction is not always profitable. This has led to poor market diversification, with most mines being located in China. China's leading position has reportedly been used as leverage in trade and political negotiations (Business Insider, 2019). In addition, as part of its industrial strategic plan, Made in China 2025, the country has used its dominance in mining and refining as a first step to attract the downstream, high-value segments of production, for example manufacturing of alloys and magnets, thus acquiring global leadership in the entire value chains (Adamas Intelligence, 2019a; Seaman, 2019).

In 2010–2011, the rare earth crisis and the rapid spike and decrease in rare earth prices led to an increase in global attention being paid to the supply of these elements, with several countries backing mining projects and exploration. The awareness of potential issues has also increased, leading to the setting up of several specialised forums and the very first global rare earth industrial association, which was founded in 2019. The availability of rare earths and supply diversification have an impact on technological development, international trade and (de)localisation of manufacturing, and may constitute a bottleneck to the deployment of wind turbines and electric vehicles. Opinions on the topic are varied and range from fear of trade wars to belief in the ability of the market to self-regulate.

Because of their role in the green transition, and also in the digital transition, rare earth element and permanent magnet value chains are considered crucial for European industrial development. If these value chains remain undeveloped or, worse, move more and more towards non-EU countries, this may have an impact on the European economy and on the employment perspectives linked to the green transition.

This report aims to provide information, data and forecasts that can guide the discussion and put it into context. Are rare earth elements critical for our green transition? Why? And to what extent?

Chapter 2 discusses the role of rare earth elements in wind energy and e-mobility, while Chapter 3 presents an overview of the present situation, highlighting current dependencies and issues, as well as current demand levels. Chapter 4 presents our projections for supply and demand, highlighting possible mismatches at the global level and commenting on the situation at the EU level. It also provides insights into recycling and its potential role in the European supply of specific rare earths. Chapter 5 examines the manufacturing steps involved in the production of permanent magnets from rare earth elements, providing an overview of the current situation and some insights into the European landscape. Lastly, Chapter 6 summarises the key messages of the study. Detailed information on the methodology used in the study and key results for each individual element are provided in the annexes, while the data presented in the study are available online in the JRC data catalogue.

2. The role of rare earths in wind energy and e-mobility

With regard to wind energy and e-mobility, rare earth elements are mostly used as raw materials for the manufacturing of permanent magnets, which are used in generators for wind turbines and traction motors for electric vehicles.

Although there are different types of permanent magnets, NdFeB magnets are the most used because of their outstanding properties. In terms of their properties they are equalled only by samarium–cobalt magnets; however, these magnets are significantly more expensive (Lucas et al., 2014; Roskill, 2015).

NdFeB magnets were developed in 1984 by General Motors and Sumitomo Corporation. The two companies developed the magnets independently and through two different manufacturing pathways, producing bonded permanent magnets (General Motors) and sintered permanent magnets (Sumitomo).

These magnets usually contain four different rare earth elements: neodymium, praseodymium, terbium and dysprosium. Neodymium and praseodymium contribute to the magnetic strength, while dysprosium and terbium improve resistance to demagnetisation, particularly at high temperatures.

The exact composition of rare earths within an NdFeB permanent magnet can vary, with different proportions of the different elements leading to different magnetic properties. Neodymium and praseodymium can in principle be substituted by other elements, but this is often limited by the operating condition specifications. In the past few years most research has focused on the optimisation of the use of dysprosium and terbium, which are both costly and poorly available (Roskill, 2018). These two elements are used to improve a magnet's resistance to demagnetisation, allowing for higher working temperatures. The use of terbium is currently limited as it has the same function as dysprosium but is significantly more expensive (Reimer et al., 2018). For wind turbines, an average permanent magnet contains 28.5 % neodymium, 4.4 % dysprosium, 1 % boron and 66 % iron and weighs up to 4 tonnes (Rabe et al., 2017).

Automotive industries are particularly active in researching new compositions for permanent magnets, in an attempt to both reduce production costs and reduce supply risk in the wake of the electric mobility revolution. In early 2018 Toyota Motor Corporation announced the development of a novel neodymium-reduced, heat-resistant magnet. According to the press release, the new magnet does not use either terbium or dysprosium and a significant amount of the neodymium has been replaced with lanthanum and cerium, two rare earths that are currently overproduced and are thus relatively cheap and easily available. The magnet is expected to be deployed in various applications in the first half of the 2020s, and to be further developed for application in high-performance vehicle drive motors by the 2030s (Toyota, 2018).

Progress is also being made to reduce the content of rare earths in permanent magnet generators for wind turbines. Siemens Gamesa Renewable Energy and Goldwind have reduced the content of dysprosium in their generators to below 1 % (Wind Power Monthly, 2018). More radically, GreenSpur Renewables has developed prototypes of ferrite-based permanent magnet generators that do not contain rare earth elements and, after several years of testing, it is carrying out the first steps to commercialise these prototypes (GreenSpur Renewables, 2020). Currently, prototypes have been successfully tested for up to 12-MW generators, with 20-MW generators expected by 2022 (Snieckus, 2019).

While much progress has been made towards reducing the use of the different elements, we are still far from developing viable rare earth-free magnets that can perform competitively (Coey, 2020). The following two sections provide information on potential alternative options for manufacturing generators and motors that do not contain permanent magnets and are thus free of rare earths.

2.1. Use of permanent magnets in electric vehicles

Commercially available electric traction motors are mostly permanent magnet synchronous motors, with market shares reaching up to 90–93 % according to Bloomberg NEF and Adamas Intelligence (Adamas Intelligence, 2019b; Bloomberg NEF, 2020). To date, this kind of motor has been strongly preferred because of its higher efficiency (Demmelmayr et al., 2011). Notable exceptions are the electric vehicles produced by Renault, which use wound rotor motors (Widmer et al., 2015), and the earlier models from Tesla, which used induction motors, which are best suited to high-performing cars (Widmer et al., 2015; Tesla, n.d.). However, since 2019 and the release of the Model 3, Tesla has used permanent magnet switched reluctance motors (Motortrend, 2020).

2.2. Use of permanent magnets in wind turbines

Since 2005 permanent magnet generators have gained popularity, especially in offshore turbines, as they allow for high power density and small size with the highest efficiency at all speeds, offering a high annual production of energy with a low lifetime cost. Most direct-drive turbines are equipped with permanent magnet generators that typically contain neodymium and smaller quantities of dysprosium. The same, although on a different scale, is true for several gearbox designs.

In 2018 generators containing permanent magnets were used in nearly all offshore wind turbines in Europe and in approximately 76 % of offshore wind turbines worldwide (JRC, 2020c). However, it may be possible to replace permanent magnet generators, at least for onshore applications, where the need for powerful generators with a reduced size and weight is not as strict.

Potential alternatives to permanent magnet generators are multipolar synchronous generators, such as those used by ENERCON (Enercon), and squirrel cage induction generators. In the future, alternatives may also include superconductor-based generators, such as those successfully tested in the EcoSwing project (EcoSwing, 2019), which was funded by the EU.

Another option is to use hybrid drive generators, which utilise a smaller permanent magnet than that used in standard systems. This could lead to a reduction in use of neodymium, praseodymium and dysprosium by up to two thirds per turbine (Centre for Sustainable Energy, 2017).

However, although promising, most replacements for permanent magnets are less efficient and less performant and are thus not viable alternatives (Rabe et al., 2017).

3. Current supply and demand

This chapter provides an overview of the current situation in terms of the supply of and demand for rare earth elements, with a focus on the four elements used in permanent magnets: neodymium, praseodymium, terbium and dysprosium.

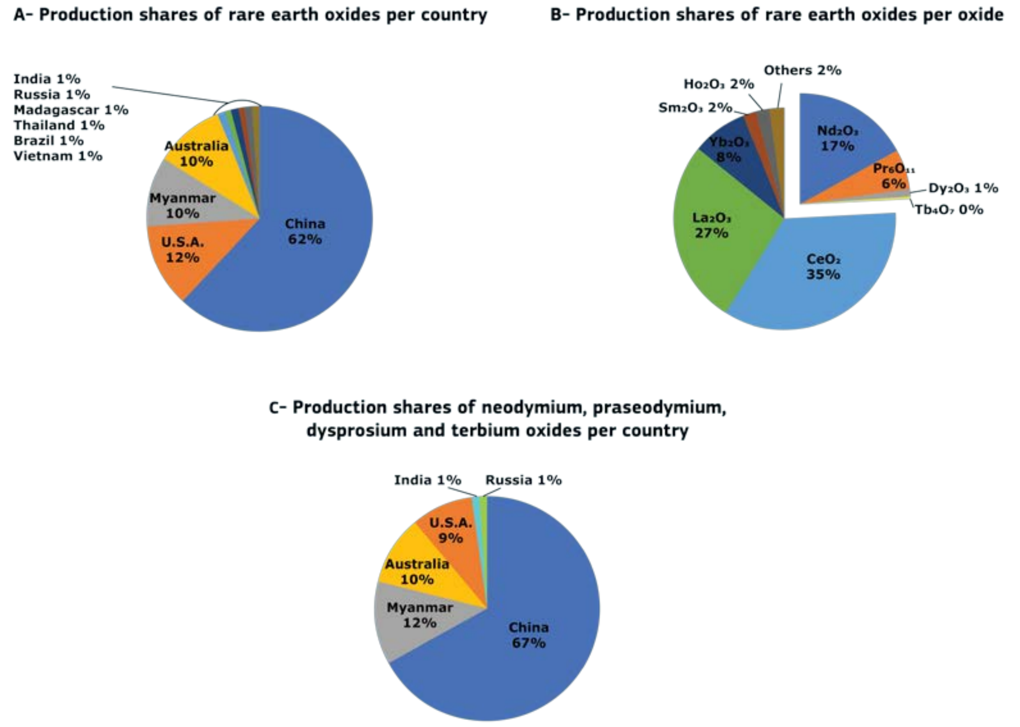
3.1. Supply

Driven by increased demand for technological applications, rare earth oxide production has seen significant growth, with a threefold increase between 1992 and 2017 (BGS, 2020). In 2019, approximately 210 000 tonnes were produced, an increase of 13 % over the previous year (USGS, 2020).

Since the second half of the 1990s, most of the global production of rare earth oxides has been located in China, whose official production currently (2019) accounts for 62 % of the total supply. Other major suppliers are located in the United States (12 % of global production), Myanmar (10 %) and Australia (10 %) (Figure 4A); Mount Weld in Australia and Mountain Pass in the United States are two of the world's largest mines for light rare earth elements and in 2019 they produced 19 737 tonnes and 26 000 tonnes of rare earth oxides, respectively (S&P Global Market Intelligence, 2020; USGS, 2020). On the other hand, production in Myanmar relies on artisanal mining practices, which are largely undocumented; the volume of concentrates delivered to China was reported to contain 22 000 tonnes of rare earth oxides, equivalent to approximately one fifth of China's annual production (USGS, 2020).

Global production shares of individual rare earth elements are largely not available, but can be estimated based on the production of each operating mine and the relative distribution of *in situ* rare earth oxides. Based on such information, the production of neodymium, praseodymium, terbium and dysprosium makes up approximately one quarter of the global production of rare earths. The main producers are China (67 %), Myanmar (12 %), Australia (10 %) and the United States (9 %) (Figure 4C). For specific elements market diversification can be even poorer; this is the case for dysprosium and terbium, which are sourced almost exclusively from China and Myanmar.

Figure 4: Production shares of rare earth oxides per country (A) and per oxide (B), and production shares for rare earths used in permanent magnets per country (C). Undocumented production from China is not taken into account



Sources: (A), USGS (2020); (B) and (C), JRC (see Annex 1 for further information).

However, these estimates do not account for Chinese undocumented production. Several sources have provided information on mines operating without an official licence, especially in the south of China (Kingsnorth D. J., 2018; Packey & Kingsnorth, 2016). Although estimates of undocumented production vary greatly, the volume of undocumented production is likely to be close to that of official production for several elements, including those used in the manufacture of permanent magnets (USGS, 2020). China is reportedly taking action on reducing undocumented production and on minimising the environmental impact of licensed mines (Reuters, 2016; Reuters, 2019; Standaert, 2019), and the volumes of undocumented production are expected to decrease in the coming years.

3.1.1. Issues and uncertainties in rare earth supply

One of the biggest impacts on the cost and economic viability of projects is likely to be the continued overproduction of lanthanum and cerium. As it is not possible to selectively target one specific element of the rare earths group for mining. All rare earths have to be mined together and they are then separated using complex metallurgical processes. As lanthanum and cerium are among the most abundant rare earths, they are extracted in large quantities, much larger than their relatively small market demand, and thus they represent a cost in terms of both extraction and disposal (Barakos et al., 2018).

There are also environmental concerns as rare earth ores often contain thorium and uranium, thus raising the issue of the disposal of radioactive waste. In the past few years this has been a major deterrent to the proliferation of rare earth mines outside China (Seaman, 2019).

The role of China is also causing concerns on many fronts. China has always exerted a strong control on the rare earth market, including introducing stringent export quotas in 2010. Although these quotas were lifted in 2014 following a World Trade Organization ruling, the control of China over the production and export of rare earths has not reduced. Since 2006 the government has been responsible for a strict production quota and since 2016 China has consolidated all official mining and separation companies into six state-owned enterprises: Northern Rare Earth (Group) Hi-Tech (including Baotou), Aluminum Corporation of China (Chinalco), China Minmetals Corporation, Xiamen Tungsten Corporation, China Southern Rare Earth Group and Guangdong Rare Earth Industry Group (Shen et al., 2020).

China also aims to play a major role in the entire value chains for rare earths and permanent magnets and, as the Chinese share of manufacturing increases, so does the internal consumption of minerals. Currently, China already accounts for 70–75 % of the global consumption of rare earths (Kingsnorth D. J., 2018), a share that is increasingly difficult to balance with internal production. In 2017, China's consumption was already higher than the assigned production quota (Shen et al., 2020), with the consequent market gap being filled by the expansion of imports and undocumented mining. Rapid mineral depletion rates in southern China, the region most famous for undocumented mining, might also challenge overall production in the long run (Seaman, 2019), and China may find itself increasingly dependent on other countries such as Myanmar for its rare earth supply, effectively transitioning from being a net exporter to a net importer. This will obviously have a major impact on global prices and market dynamics.

3.1.2 Potential resources and reserves ([1])

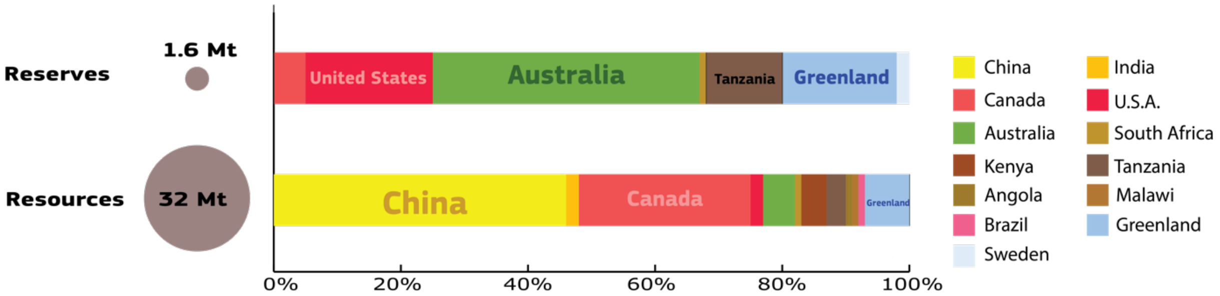
While the current production of rare earths is mostly located in China, several other countries have the potential to develop mining activities. From the information currently available from geological exploration (Figure 5), the resource pool comprises 32 million tonnes of neodymium, praseodymium, dysprosium and terbium, 1.6 million tonnes of which are in compliant reserves outside China. Reserves in China are not reported in Figure 5 as their size is unknown. The list of reserves includes only those that are compliant with national and international reporting systems. All projects are currently still active and reserves were estimated within the last 7 years.

In terms of resources, Canada is a major candidate for the future supply of rare earths, while the reserves reflect the current ambitions of the United States and Australia for stronger positioning in the supply chain. The

([1]) Resources: amounts of minerals in existing deposits; reserves: amounts of minerals in compliant, exploitable deposits.

EU overseas territory of Greenland accounts for almost 20 % of the available reserves and for nearly 10 % of the overall global resources.

Figure 5: Known in situ resources and reserves of neodymium, praseodymium, dysprosium and terbium, and their geographical distribution



Source: JRC, based on S&P Global Market Intelligence (2020).

While the production of rare earths in the EU is negligible, a few projects have begun in Greenland and Sweden, mostly under the control of Canadian and Australian companies. More details are provided in Chapter 4. The EURARE project has, however, identified almost 100 distinct localities of interest for rare earth elements across Europe, notably in Finland and the Balkans (Goodenough, et al., 2016). According to Goodenough et al (2016), Europe has the potential to secure its own supply internally, but there is a need for further geological exploration and the establishment of a viable exploitation scheme.

3.2. Demand

Demand for rare earth elements has been growing rapidly in the last two decades because of their wider deployment in innovative technologies. Permanent magnets are a particularly important driver of the demand for rare earths as they are used in a large number of applications. As described earlier, they are very important components of electric vehicle motors and wind turbine generators; however, they are also used in ICT equipment such as laptops, mobile phones and cameras; electrical appliances and cordless power tools; missile guidance systems and robots; and medical resonance imaging equipment. Combat aircraft and drones also use permanent magnets, which are sometimes referred to as military grade magnets because of their higher content of terbium and dysprosium and their need to withstand particularly harsh conditions.

While dysprosium is used almost exclusively in magnets, neodymium, praseodymium and terbium also have other applications. Neodymium and praseodymium are the most versatile as they are used in batteries, catalysts for cars, specialty glasses and ceramics; praseodymium is also used in polishes for particular types of glass. Terbium green phosphors are largely used in fluorescent lamps and in light-emitting diode (LED) screens for televisions (European Commission, 2020c).

According to our estimates (see Annex 1), in 2018 the global cumulative demand for neodymium, praseodymium, terbium and dysprosium was approximately 50 000 tonnes, while the demand in the EU-27 and the United Kingdom was approximately 15 000 tonnes. This is mostly related to the demand for neodymium, which accounted for 40 000 tonnes of global demand and around 10 000 tonnes of demand in the EU-27 and the United Kingdom in 2018. This was followed by demand for praseodymium (9 238 tonnes globally, 2 697 tonnes in the EU-27 and the United Kingdom), dysprosium (1 442 tonnes globally, 368 tonnes in the EU-27 and the United Kingdom) and terbium (393 tonnes globally, 108 tonnes in the EU-27 and the United Kingdom). The demand at European level should be understood to include the amount of materials needed to manufacture products used in Europe, regardless of where the actual manufacturing takes place.

Clean energy technologies account for different shares of the total demand for the different elements. For praseodymium and neodymium, wind turbines and electric vehicles account for only 7 % and 9 % of the overall demand, respectively, while for dysprosium they account for nearly 37 % and for terbium they account for 30 % of the overall demand. It should be noted that terbium is used in permanent magnet generators for wind turbines only, that is, it is not used in traction motors for electric vehicles.

4. Projections

This chapter addresses our projections for the future supply of and demand for neodymium, praseodymium, dysprosium and terbium. These projections do not take into account the effects of the coronavirus disease 2019 (COVID-19) crisis, as its impacts on the different stages of the value chain are still largely unknown. However, we assume that, while year-by-year projections may be inaccurate, the long-term trends will not be significantly different.

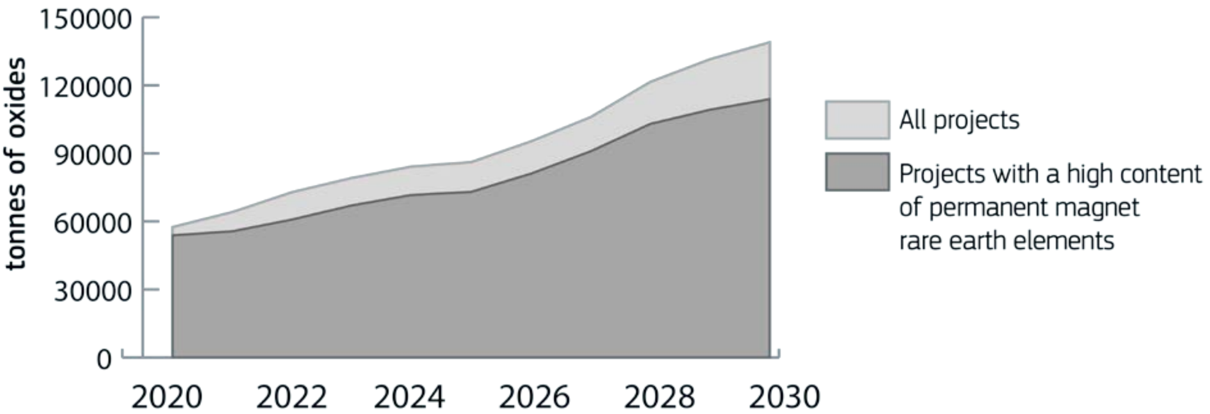
Our supply analysis is based on currently known mining projects and activities and extends until 2030. The demand analysis relies on a mix of market trends, prospects for technological improvements and the projected deployment of technologies in line with global climate ambitions. More details on the methodology and on the parameters used for our estimations can be found in Annex 1.

4.1. Supply

Following the 2010–2011 rare earth crisis and because of concerns over China's dominant role in the rare earths supply chain, several countries have supported geological exploration and mining projects aimed at diversifying supply. Some projects have already come online, such as the reopening of the Mountain Pass mine in the United States and the opening of Mount Weld in Australia, and there are six mines under construction or in pre-production, 12 projects at the feasibility stage and 39 projects at the pre-feasibility and reserves development stages (S&P Global Market Intelligence, 2020). These project are expected to start production in the next few years and thus contribute to a diversification of supply. Although it is impossible to determine a priori which mines will be financially viable and what production rates they will achieve, it is possible to make estimates based on the technical information provided by each project.

Figure 6 provides an overview of the estimated supply, indicating the supply levels that could be reached if all projects prove successful, and the share of supply from projects that yield a high content of rare earth elements used in permanent magnets (above 20 %). These projects were singled out as they may have a higher chance of being viable, given that permanent magnets will be the main demand driver in the coming decades.

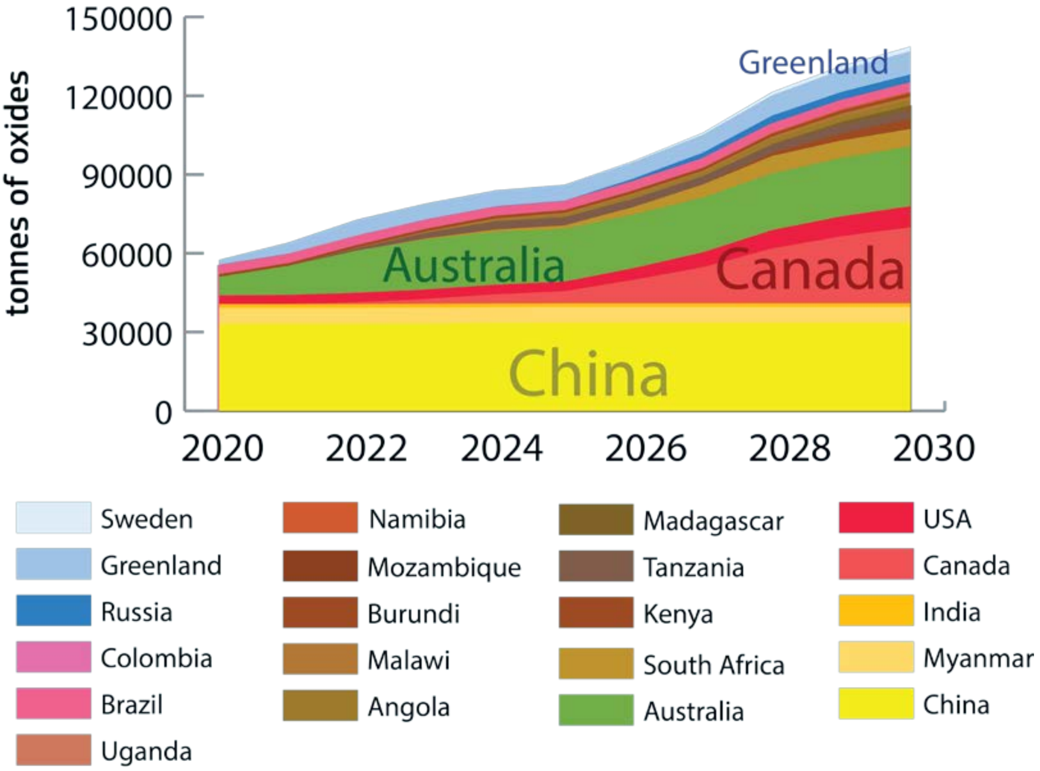
Figure 6: Two scenarios for the evolution of supply up to 2030: cumulative supply of neodymium, praseodymium, dysprosium and terbium



Source: JRC (see Annex 1 for further information).

Both scenarios show an increase in future supply, as more mines will go into production than will discontinue or reduce production. The two scenarios produce similar results as most projects produce a high yield of rare earths used in permanent magnets. Figure 7 shows the geographical distribution of production considering all projects. Based on current projects, the market is expected to diversify markedly, with Australia playing a significant role in the next few years and Canada establishing itself as a major producer starting from the second half of the 2020s.

Figure 7: Geographical distribution for all projects up to 2030: cumulative supply of neodymium, praseodymium, dysprosium and terbium. As upcoming production from China is unknown, its contribution throughout the period analysed is considered to be equal to the 2019 production quota



Source: JRC (see Annex 1 for further information).

Contributions from Myanmar and China are considered to be constant over time. In the case of Myanmar, this is because mining is artisanal and undocumented and thus production is difficult to estimate, while for China production is considered to be equal to the current official production quota. China introduced quotas on mine production in 2006 (Shen et al., 2020), which are aimed at gaining increased control of the internal market, tackling undocumented production and ensuring that the country maintains its position in the international market.

In the EU, rare earth supplies are expected in the short term from the Kvanefjeld site (Greenland), which will consist of a mine, a concentrator and a refinery. Other projects in the EU are at least 6 years away from production. Norra Kärr (Sweden) and Karrat (Greenland) are at the pre-feasibility/scoping stage, while Olserum (Sweden) and Sarfartoq (Greenland) are undergoing reserves development. It is interesting to note that the projects are not led by European companies but rather by companies with headquarters in Canada (Norra Kärr, Sarfartoq, Olserum) and Australia (Kvanefjeld), with occasional participation from Chinese companies (Kvanefjeld). The exception is Karrat, which is a project managed by a British company.

On a global perspective, Chinese companies are increasingly acquiring minority shares in foreign rare earth mines, allowing them to obtain information on major developments happening worldwide. For example, Shenghe Resources owns minority shares in both the Kvanefjeld project in Greenland and the Mountain Pass mine in the United States. In the United States, particularly, this has created additional tensions as questions have been asked about whether or not the government should fund technical projects in which information is fed directly to Chinese competitors (Financial Times, 2020).

It is important to note that the projections refer to potential mining only. The extracted ores will contain different elements and oxides and will need to be further separated and refined down to their individual oxide and metal forms. Currently, this separation is carried out almost exclusively in China and there are few indications that this will change in the future. Thus, even if the supply of ores is expected to diversify, refining is likely to remain relatively concentrated. One can, however, argue that the establishment of a sustainable supply outside China will drag further steps of the value chain outside the country.

According to Adamas Intelligence (Adamas Intelligence, 2019), China is responsible for the production of 85 % of rare earth oxides and 90 % of rare earth metals globally. Other sites known to refine rare earths to oxides are the Lynas Advanced Materials Plant in Malaysia, which processes rare earth concentrates from Mount Weld (Australia), the Molycorp Silmet facility in Estonia and some further refining sites in Laos (S&P Global Market Intelligence, 2020). The production of rare earth metals and alloys in Europe takes place at the following sites: Rhodia in France, Molycorp Silmet in Estonia, Treibacher in Austria and Less Common Metals in the United Kingdom. Outside Europe, production is carried out at the Magnetic Materials and Alloys facility in the United States and by a few Japanese companies such as Hitachi Metals, Santoku Corporation, Showa Denku K. K., Shin-Etsu Chemical Co. and Nippon Yttrium Co. (Barakos et al., 2018).

4.2. Demand

Demand for rare earth elements has long been forecast to increase, with earlier assessments expecting growth of 6–7 % per year until 2025 (Kingsnorth D. J., 2018). More recent assessments predict a more moderate increase of 3.3 % per year by 2024, slowing to 2.1 % annually between 2024 and 2029, with permanent magnets forecast to exceed one third of total demand by 2025, thus changing the focus of rare earth producers and processors (Roskill, 2019).

In this study, demand scenarios were produced taking into account three separate categories: demand for wind turbines, demand for electric vehicles and demand for all other sectors (ICT, defence, healthcare, etc.). As the 'other sectors' are more established and their market is more stable, their scenarios were developed as forecasts based on historical market trends (Kingsnorth D. J., 2018).

On the other hand, wind turbines and electric vehicles are emerging sectors for which there are no established trends. They are also closely linked to climate actions and ambitions and their deployment is likely to be influenced as much by policy decisions as by market dynamics. Scenarios for these two sectors were thus developed using a backcasting method based on different levels of political ambition and technological improvement.

4.2.1 Clean energy technologies

The two scenarios for clean energy technologies are meant as reasonable extremes within the global green transition, with future trends likely to fall in between them.

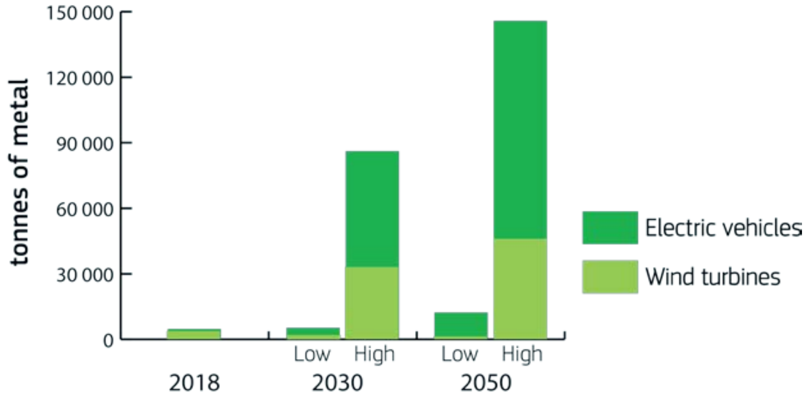
In particular, the low-demand scenario assumes a maximum increase in temperature of 2.7 °C with respect to pre-industrial levels, as pledged by all countries under the Paris Agreement, and considers the EU 2030 binding targets on climate change. It also assumes that research and innovation will lead to a significant increase in the lifetime of wind turbines and electric vehicles, as well as significant optimisation with regard to material usage. Alternative technologies are also assumed to have significant shares of the market, especially for wind turbine generators.

The high-demand scenario considers stronger political ambitions, leading to a maximum temperature increase of 1.5 °C, 100 % renewable primary energy by 2050 and complete EU decarbonisation by 2050. Research and innovation is assumed to bring minor improvements only, and permanent magnet products are assumed to have stable or increasing market shares, with little space for alternative technologies.

In both extremes the overall demand for rare earths is expected to increase, although at very different rates (Figure 8). Demand for wind turbines may decrease in the low-demand scenario, mostly because of the positive impact of technological developments, but this decrease will be overshadowed by the large increase in demand for electric vehicles, a sector that is expected to experience a boom in any scenario. Even in the high-demand scenario, in which there is a significant increase in demand for wind turbines, the biggest demand is for electric vehicles.

Interestingly, while the difference in supply levels between the high- and low-demand scenarios is quite moderate, the difference in demand levels between the two scenarios is more than 10-fold. This indicates that the future is still very uncertain and that there is the potential to influence future demand trends through the (re)definition of climate ambitions, investments in research and innovation and incentives that promote the uptake of alternative technologies as soon as they are available.

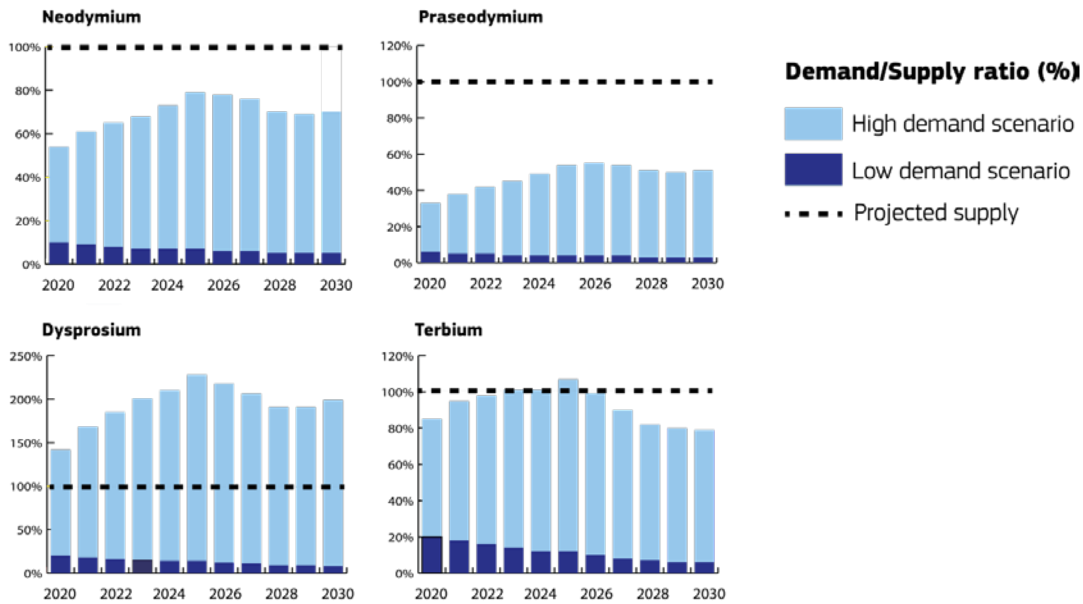
Figure 8: Estimated global demand for neodymium, praseodymium, dysprosium and terbium metals from clean energy technologies according to the low- and high-demand scenarios



Source: JRC.

To better gauge the potential impact of increasing demand, demand was compared with supply. It was assumed that there is no loss of materials during manufacturing, as closed-loop recycling of manufacturing scraps is increasingly being implemented and is increasingly effective (Seaman, 2019). As shown in Figure 9, the low-demand scenario for clean energy technologies corresponds to approximately 5–20 % of the supply depending on the element. The high-demand scenario accounts for a larger share of the supply: nearly 100 % for terbium and significantly over the supply threshold for dysprosium.

Figure 9: Demand/supply ratio for neodymium, praseodymium, dysprosium and terbium metals, considering clean energy technologies only (worldwide)



Source: JRC.

This section has provided an indication of the impact of clean energy technologies and decarbonisation plans on the rare earth market. However, this is just a partial overview as it does not take into account all other sectors, which as seen in Chapter 3 account for between 60 % and 90 % of the present demand for neodymium, praseodymium, dysprosium and terbium.

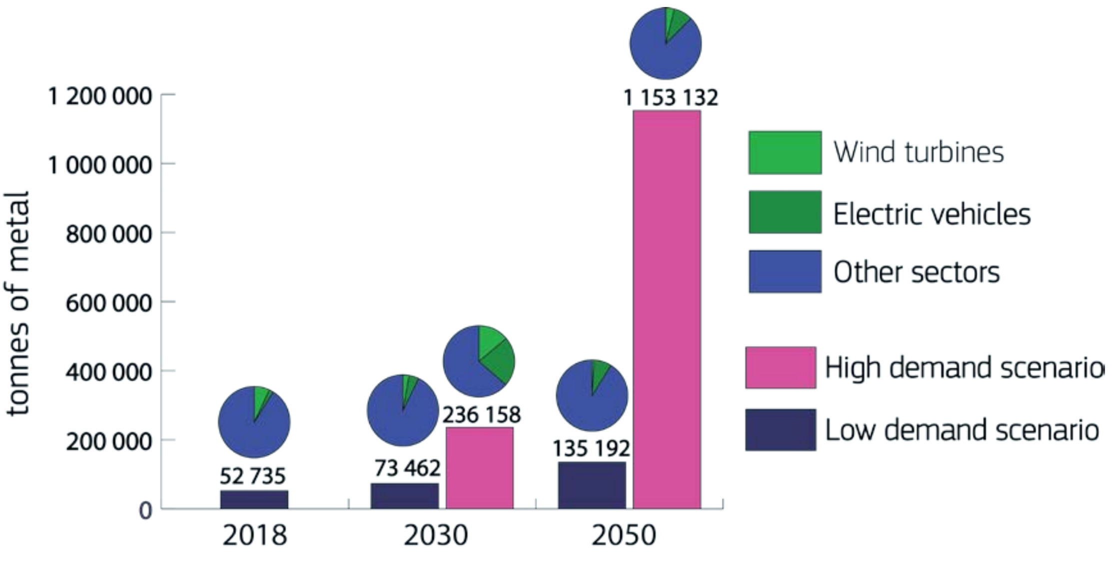
4.2.2 All applications

Regardless of the scenario considered, sectors other than wind turbines and electric vehicles, such as ICT, healthcare and defence, will remain predominant in the demand for neodymium, praseodymium, dysprosium and terbium. However, although in the long term there is not expected to be any significant change in the ratio between clean energy technologies and other sectors, the situation in the short and medium term could be quite different.

While the growth in demand in other sectors is mainly regulated by market dynamics, and it is assumed to range between 3 % and 10 % on 2018 values depending on the scenario, for clean energy technologies there are strong public commitments at the political level that should be taken into account and that may have a high impact on demand, particularly within the next decade. In the low-demand scenario technological improvements and moderate ambitions may lead to a lower demand share for clean energy technologies, while in the high-demand scenario the ambitious targets set for 2030 may lead to a strong acceleration in the deployment of wind turbines and electric vehicles, which coupled with poor technological developments will lead to a large relative increase in demand for clean energy technologies. In this scenario clean energy technologies could account for over one third of the overall demand for neodymium, praseodymium, dysprosium and terbium in 2030 (Figure 10).

Europe will account for approximately one third of the demand in all scenarios considered, with a distribution of demand across sectors that is in line with the global distribution.

Figure 10: Estimated global demand for neodymium, praseodymium, dysprosium and terbium metals for wind turbine generators, motors for electric vehicles and other sectors, according to the low- and high-demand scenarios.

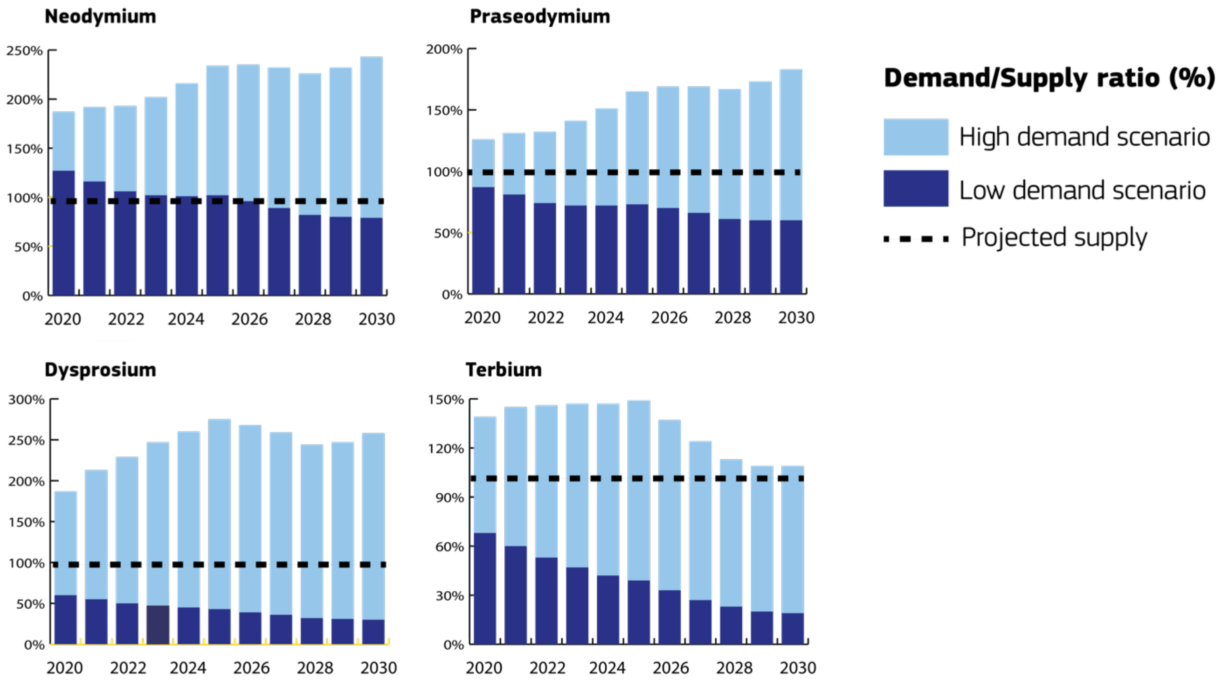


h: JRC.

Again, it is important to put demand into context by comparing it with supply (Figure 11). Demand in the low-demand scenario is very much in line with supply projections for praseodymium and neodymium, and significantly below supply projections for dysprosium and terbium. However, looking at the high-demand scenario the situation is very different: demand may reach up to 3.5 times the volume of the projected supply. The only element that will not face significant challenges in the high-demand scenario is terbium, which is already being replaced in most applications because of its excessive cost and the development of alternative technologies.

In practice this means that the high-demand scenario is not realistic, as the projected supply is not sufficient to meet the anticipated increase in demand. To complete the green transition and achieve our climate ambitions, it is paramount that material usage in existing applications is improved and that alternative technologies are developed that do not rely on rare earth elements. These changes can and will be driven by the market, but could also be planned ahead and influenced by appropriate political actions at the global level. A steered process may be the best approach, as this could allow for targeted innovations in material usage and technological uptake without sacrificing performance.

Figure 11: Demand/supply ratio for neodymium, praseodymium, dysprosium and terbium metals, considering all sectors



Source: JRC.

While in the short term curbing demand is the easiest strategy to implement, in the long term it could be valuable to increase supply. This could be achieved both by promoting and incentivising geological exploration and mining projects and through recycling. The latter is seen as a particularly appealing option for Europe, which has few resources on its territory and where new mining activities are often subject to harsh public debate. The next section will provide an overview of the current situation in terms of recycling and possible future perspectives.

4.3. Secondary raw materials, reuse and reprocessing

In principle, the recycling of rare earths for use in permanent magnets is possible and could be economically viable, and several projects and start-ups are setting up pilots for scaling up recycling processes. However, these projects are not yet mature enough to be widely deployed.

In the EU, the most advanced project in this field appears to be REE4EU. The project was funded under Horizon 2020 with the aim of developing an efficient and cost-effective method for the recycling of rare earth elements for magnet production. The project was positively concluded in autumn 2019 with a successful pilot at industrial scale, bringing the technology to a technology readiness level of 7 out of 9 (ree4eu, 2019).

Outside the EU, the biggest developments have been seen in Japan, with Santoku being the most active company in the recycling of neodymium and dysprosium for use in permanent magnets. In early 2018 the company was acquired as a subsidiary of Hitachi Metals, with the explicit am of having a branch that would focus on the recycling of rare earth elements (Hitachi Metals, 2018). However, even though plans for the recycling of rare earths have been mentioned by both companies for most of the last decade, there is no information available on successful implementation of recycling.

In addition, both in the EU and elsewhere there is no effective system for the collection and separation of rare earth element-containing products. With the exception of fluorescent lamps, rare earths from end-of-life products are either used as landfill or non-functionally recycled in the steel and cement industry (Bio Intelligence Service, 2015). It is therefore unlikely that the recycling of dysprosium, neodymium, praseodymium and terbium from end-of-life products will contribute significantly to their supply in the next decade.

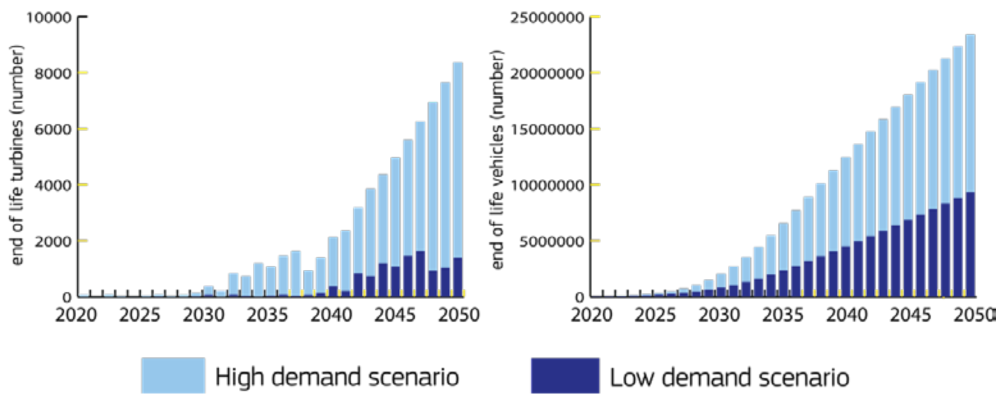
Potential alternatives to the recycling of individual elements are the reuse of permanent magnets, the reprocessing of permanent magnets into rare earth alloys or, in general, the remanufacturing of motors and generators (Bobba et al., 2020).

On one hand, reuse is a particularly attractive option as in ideal conditions permanent magnets have a lifetime of up to 300 years (Busch et al., 2014), several time longer than the lifetimes of traction motors and wind turbines. On the other hand, reuse may be hindered by innovation cycles and limitations in product architecture, especially given the high rate of technological improvements in clean energy technologies (Goldner & Regett, 2017).

An additional issue is that turbine drives and traction motors are rarely designed to be dismantled, with permanent magnets deeply embedded in the systems and sometimes glued (Akil et al., 2017) onto the other components. In addition, to be safely extracted the magnets should be demagnetised, a non-trivial step that poses technical difficulties and may reduce the quality of the magnets to be reused (Li, Kedous-Lebouc, Dubus, Garbuio, & Personnaz, 2019). This poses issues not only for the recovery of whole permanent magnets for reuse, but also for their direct recycling, with scraps and powders used as a basis for the production of new permanent magnets. Improved designs for disassembly are currently under study, especially in the automotive sector (JRC, 2020a). In addition, the EU has included the identification and reuse of rare earths in permanent magnet motors as one of the key areas to be addressed in the next review of Commission Regulation (EU) 2019/1781 laying down ecodesign requirements for electric motors and variable speed drives, which is expected in 2023.

Although still underdeveloped, recycling could prove to be an interesting source of rare earth elements in the EU. Based on historical data and on the deployment trends used to calculate demand, it was possible to estimate the number of end-of-life turbines and electric vehicles that will become available for recycling in the future (Figure 12). The more wind turbines and electric vehicles that are deployed (high-demand scenario), the more end-of-life products will be available.

Figure 12: Number of wind turbines using permanent magnet generators (left) and electric vehicles using permanent magnet motors (right) reaching their end of life each year up to 2050 (EU-27 and the United Kingdom)

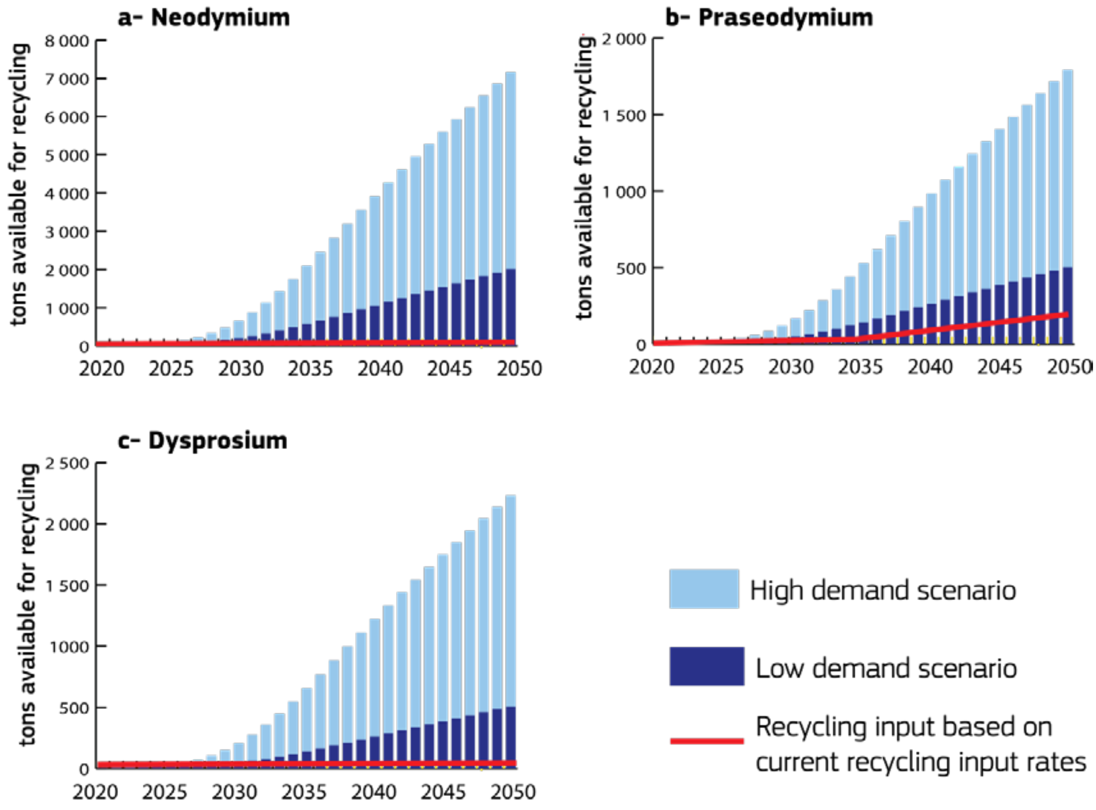


Source: JRC.

Due to their long lifetime (25–35 years) and their limited deployment to date, wind turbines using permanent magnet synchronous generators will reach the end of their life only in the second half of the 2040s, and their contribution would be anyway limited. For this reason, and because of difficulties in estimating the exact composition and size of the turbines that have already been deployed, the equivalent content of rare earth elements was not calculated.

Electric vehicles are instead more interesting as they have a shorter lifetime (9–13 years) and will be extensively deployed in the near future. Thus, even in the low-demand scenario there will already be a significant number of end-of-life vehicles in the 2030s. These projections were used to calculate the equivalent amounts of dysprosium, praseodymium and neodymium that could become available for recycling and reprocessing (Figure 13).

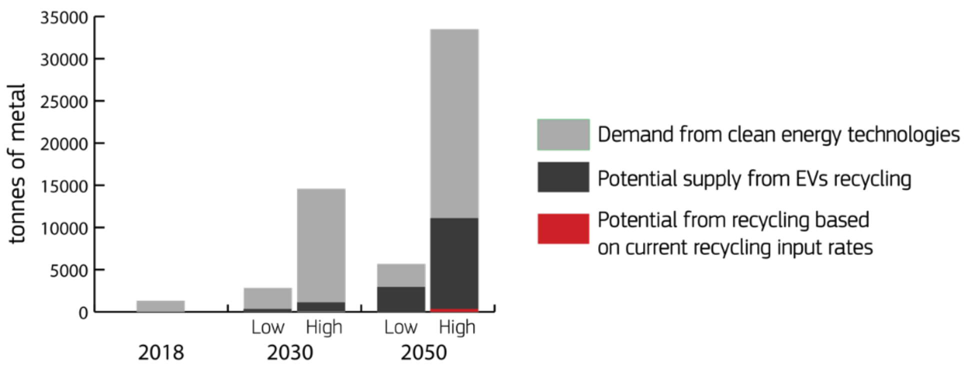
Figure 13: Tonnes of (a) neodymium, (b) praseodymium and (c) dysprosium potentially available for recycling up to 2050 (EU-27 and the United Kingdom) and the maximum expected recycling inputs based on current recycling input rates



Source: JRC.

In the long term, recycling could supply up to half the demand for rare earth elements for electric traction motors, and nearly one third of the demand for clean energy technologies in general (wind turbines and electric vehicles). As highlighted in Figure 14, however, this will happen only in the long term and only if the recycling system is significantly improved. If the current recycling input rates of less than 1 % for neodymium and dysprosium and less than 5 % for praseodymium (European Commission, 2020c) are not improved, this potential will remain completely untapped.

Figure 14: Projected demand for neodymium, praseodymium and dysprosium for clean energy technologies compared with the potential supply from the recycling of rare earths from electric vehicles (EVs) (EU-27 and the United Kingdom)



Source: JRC.

5. Manufacturing of permanent magnets

As mentioned previously, the main application of rare earth elements in clean energy technologies is in NdFeB permanent magnets. Once ores containing neodymium, praseodymium, dysprosium and terbium are extracted, they are sent to a refinery for separation and refining of the different elements into individual oxides or metals, which are then used in different manufacturing processes.

In the case of permanent magnets, the metals are melted together under a vacuum to obtain an alloy, which is then often reduced to a powder. There are two methods available for producing magnets from the powder, discovered by General Motors and Sumitomo.

In the first method the alloy powder is mixed with polymers to create a mouldable putty (bonded magnets), whereas in the second method the powder is pressed together under a specific heat profile (sintered magnets). In both cases, magnetisation can be induced either during the treatment of the powder or in a separate phase of the manufacturing process. The magnets are then often arranged into arrays for specific applications. Sintered magnets are usually more compact and have better magnetic properties and as such constitute over 90 % of NdFeB magnet production (Roskill, 2015).

Both processes have been patented. Sumitomo's patent for sintered magnets is now owned by Hitachi Metals, while General Motors' patent for bonded magnets was acquired by Magnequench International, which was formerly an American company and is currently a Chinese company.

Although the master patent used for the vast majority of magnets is held by a Japanese company, China is the most prominent manufacturer of alloys and permanent magnets.

In the past few years, and in line with its industrial strategic plan, Made in China 2025, China has progressively increased its shares in the permanent magnet manufacturing supply chain, thus advancing its control of the high-value steps of all related value chains. In 2014 China already accounted for approximately 80 % of the global permanent magnet manufacturing supply chain, while today it accounts for approximately 90 % (Adamas Intelligence, 2019). Production capacities have also expanded accordingly. In 2014 the total Chinese production capacity was reported to be 130 000 tonnes per year across more than 130 production sites (Roskill, 2015), while in 2018 capacity was approximately 300 000 tonnes, with actual production of 160 000 tonnes of magnets (Bloomberg, 2019).

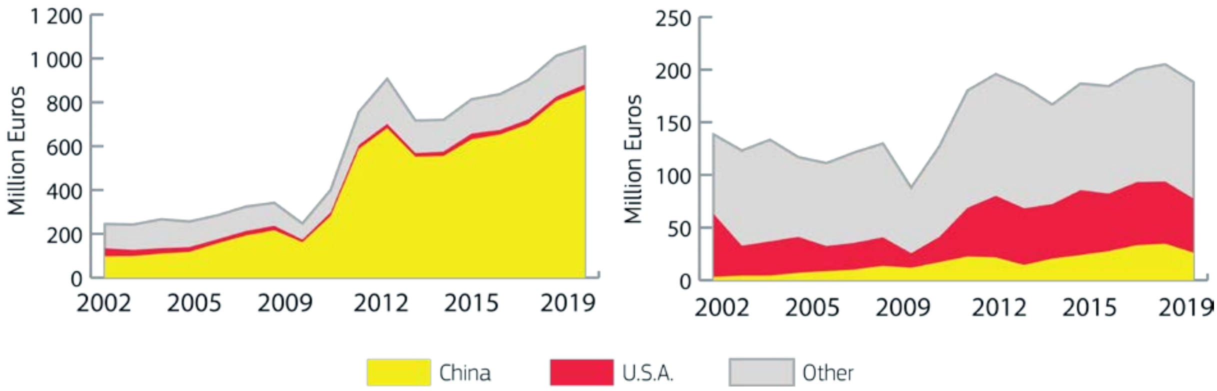
This increase is partially the result of an expansion of Chinese companies and partially the result of non-Chinese manufacturers moving to China, attracted by lower labour costs and closer access to rare earth suppliers (Roskill, 2015).

Similarly to what happened with extraction and refining companies, a consolidation phase for permanent magnet manufacturers in China is currently taking place, leading to a few major companies dominating the production landscape. While rare earth mines are mostly concentrated in the north and south of China, permanent magnet producers are mostly located on the east coast of the country, closer to its major ports.

In monetary terms, the value of the global production of NdFeB permanent magnets was estimated to be USD 7.1 billion (EUR 6 billion) in 2013 (Roskill, 2015) and more than USD 10 billion (EUR 8.4 billion) in 2018 (Bloomberg, 2019). According to data from Eurostat, at the EU level the value of sold production of permanent magnets has been roughly constant over the past decade, at around EUR 400 million.

In the EU, nearly half of sales are intra-EU sales, with the remaining sales being to non-EU countries. As shown in Figure 15, the volume of exports has been nearly constant over the past 20 years, while import volumes have increased nearly fivefold. As expected, most imports are from China, with its market share increasing steadily since 2010.

Figure 15: Net imports (left) and exports (right) of permanent magnets to and from the EU-27 and the United Kingdom



Sources: Eurostat and Comext.

Considering the EU manufacturing situation, information was extracted from the corporate websites of different companies and from the Orbis and PitchBook databases. This analysis revealed that there are eight known European manufacturers of permanent magnets, two of which are ultimately owned by American companies. The remaining six all have European ownership, although in one case minority shares are held by a Chinese company. All of the companies were established a few decades ago and none has seen changes in ownership in the recent past. Their turnover and number of employees have also been relatively constant over time, indicating a very stable market that is poorly influenced by global dynamics. The known levels of research and innovation in the field of permanent magnets are also relatively low, with few or no patents filed specifically on permanent magnets; only four of the companies participating in EU-funded projects have filed patents.

6. Conclusions

Rare earth elements, and specifically neodymium, praseodymium, neodymium and terbium, will play a role in the future of climate actions and the green transition. Although wind turbines and electric vehicles account for only 10 % of the total demand for these elements, they can greatly influence future supply/demand balances, especially as they are key to many political strategies. Thus, future trends will not be based only on market dynamics.

While the whole world is currently dependent on China for the extraction and processing of rare earths, this could change in the near future, with Canada and Australia emerging as alternative locations for mining. This may lead to positive diversification of the market and in the long term could help to establish more and more steps of the value chain outside China.

Demand is also expected to increase in all possible scenarios, and so will supply. However, while supply projections show few differences between high and low supply prospects, there is over a 10-fold difference between the low- and high-demand scenarios. This is mainly because of the complex dynamics behind demand, which is strongly influenced not only by market dynamics, but also by technological developments and climate and political ambitions.

In a low-demand scenario taking into account a maximum increase in temperature of 2.7 °C and a positive outlook in terms of research and innovation impact, no supply issues are expected. However, assuming more ambitious decarbonisation plans and few or no improvements in material usage and the lifetimes of products, supply may quickly fall behind demand. The difficulty of replacing rare earth elements in permanent magnets will not make the situation easier, even though there are many research activities in the area, and even more is done to develop alternative technologies.

In the short term the most effective way to ensure a balance between supply and demand is to curb demand, taking advantage of the wide range of possible scenarios and steering the future accordingly. This could be achieved by promoting research and innovation, by taking into account alternative green technologies in the realisation of climate ambitions and by pushing the market towards products containing smaller amounts of rare earth elements. The last is, however, a potentially risky move, as it may lead to market distortions in a business that is already poorly diversified.

In the long term, it remains important to invest in supply, especially from a European perspective. At the moment the EU has little to no direct access to rare earths, and the only territory that is expected to make significant contributions to supply is Greenland. However, all operations in this area are controlled by non-EU companies. Strengthening supply could come from two separate streams of actions. On the one hand, geological exploration and mining projects should be incentivised. On the other hand, it will be important to develop an effective recycling system, investing not only in the development of recycling technologies but also in dedicated infrastructure for the collection, dismantling and separation of products containing rare earths.

References

Adamas Intelligence (2019a), *Rare Earth Elements: Market issues and outlook*.

Adamas Intelligence (2019b), *Electric Growth: EVs, motors and motor materials*.

Barakos, G., Mischo, H. and Gutzmer, J. (2018), 'A forward look into the US rare-earth industry; How potential mines can connect to the global REE market', *Mining Engineering*, Vol. 70, Issue 8, pp. 30–37.

BGS (British Geological Survey) (2020), 'World mineral statistics data' (https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS).

Bio Intelligence Service (2015), *Study on data for a raw material system analysis: Roadmap and test of the fully operational MSA for raw materials – Final report,* DG Internal Market, Industry, Entrepreneurship and SMEs, European Commission, Brussels.

Bloomberg NEF (2020), *Rare-earth Demand in Clean Energy.*

Bloomberg News (2019), 'Chinese rare-earth magnet producer to expand as EV demand booms', 24 June (https://www.bloomberg.com/news/articles/2019-06-24/chinese-rare-earth-magnet-producer-to-expand-as-ev-demand-booms).

Bobba, S., Tecchio, P., Ardente, F., Mathieux, F., Marques dos Santos. F. and Pekar, F. (2020), 'Analysing the contribution of automotive remanufacturing to the circularity of materials', 27th CIRP Life Cycle Engineering Conference, Grenoble, France, 13–15 May.

Business Insider (2019), 'Xi Jinping may have shown how he plans to cripple US tech and defense giants in the trade war with a visit to a Chinese magnet factory', 21 May (https://www.businessinsider.in/Xi-Jinping-may-have-showed-how-he-plans-to-cripple-US-tech-and-defense-giants-in-the-trade-war-with-a-visit-to-a-Chinese-magnet-factory/articleshow/69430293.cms).

Centre for Sustainable Energy (2017), *Common Concerns about Wind Power* (2nd edition), Centre for Sustainable Energy, Bristol.

Coey, J. (2020), 'Perspective and prospects for rare earth permanent magnets', *Engineering*, Vol. 6, Issue 2, pp. 119–131.

Demmelmayr, F., Troyer, M. and Schroedl, M. (2011), 'Advantages of PM-machines compared to induction machines in terms of efficiency and sensorless control in traction applications', IECON 2011 – 37th Annual Conference of the IEEE Industrial Electronics Society, pp. 2762–2768.

EcoSwing (2019), *Report on the successful turbine testing of the EcoSwing HTS generator on Envision's GC-1 turbine.*

Eggert, R., Wadia, C., Bauer, D., Fields, F., Meinert, L. and Taylor, P. (2016), 'Rare earths: Market disruption, innovation, and global supply chains', *Annual Review of Environment and Resources*, Vol. 41, pp. 199–222.

ENERCON (n.d.), 'WEC components – Constant innovation' (https://www.enercon.de/en/technology/wec-components/).

European Commission (2018), Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank – A Clean Planet for All – A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, COM(2018) 733 final, 28.11.2018, Brussels

European Commission (2020a), *Critical raw materials for strategic technologies and sectors in the EU – A foresight study*, Publications Office of the European Union, Luxembourg.

European Commission (2020b), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Critical Raw Materials Resilience: Charting a path towards greater security and sustainability, COM(2020) 474 final, 3.9.2020, Brussels.

European Commission (2020c), *Study on the list of critical raw materials – Critical raw materials factsheets*, .

Financial Times (2020), 'US-China: Washington revives plans for its rare earths industry', 14 September (https://www.ft.com/content/5104d84d-a78f-4648-b695-bd7e14c135d6).

Goldner, D. and Regett, A. (2017), 'Circular approaches for permanent magnets from wind turbines', poster, Life Cycle Management Conference, 3–6 September, Luxemburg.

Goodenough, K. M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E. A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D. G., Shaw, R. A., Thrane, K. and Keulen, N. (2016), 'Europe's rare earth element resource potential: An overview of REE metallogenetic provinces and their geodynamic setting', *Ore Geology Reviews*, Vol. 72, Part 1, pp. 838–856.

GreenSpur Renewables (2020), 'GreenSpur showcases its generator to potential customers', 11 February (https://www.greenspur.co.uk/media/2020/2/11/3kayws5rsp2hymxgbuumynb8fc9rat).

Hitachi Metals (2018), 'Notice concerning acquisition of a consolidated subsidiary (Santoku Corporation)', 25 May (https://www.hitachi-metals.co.jp/e/ir/ir-news/20180525en.pdf).

IEA (International Energy Agency) (2017), *Energy Technology Perspective 2017*, IEA, Paris.

JRC (2020a), *Sustainable use of Materials through Automotive Remanufacturing to boost resource efficiency in the road Transport system (SMART*), JRC Exploratory Research Project final report, under publication.

JRC (2020b), *Clean Energy Technologies Synergies and Issues*, JRC119072, Publication Office of the European Union, Luxembourg.

JRC (2020c), *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*, EUR 30095 EN, Publications Office of the European Union, Luxembourg.

Kingsnorth, D. J. (2018), *The Rare Earths Market in 2018, Driven by e-Mobility*, Curtin University and Industrial Minerals Company of Australia, Perth, WA.

Li, Z., Kedous-Lebouc, A., Dubus, J.-M., Garbuio, L. and Personnaz, S. (2019), 'Direct reuse strategies of rare earth permanent magnets for PM electrical machines – An overview study', *European Physical Journal Applied Physics*, Vol. 86, 20901.

Lucas, J., Lucas, P., Le Mercier, T., Rollat, A. and Davenport, W. (2014), *Rare Earths: Science, technology, production and use*, Elsevier, Amsterdam.

Motortrend (2020, February 19), 'What Is the Tesla Raven Powertrain?', 19 February (https://www.motortrend.com/news/tesla-raven-powertrain/).

Packey, D. J. and Kingsnorth, D. (2016), 'The impact of unregulated ionic clay rare earth mining in China', *Resources Policy*, Vol. 48, pp. 112–116.

Rabe, W., Kostka, G, and Smith Stegen, K. (2017), 'China's supply of critical raw materials: Risks for Europe's solar and wind industries?', *Energy Policy*, Vol. 101, pp. 692–699.

ree4eu (2019), 'REE4EU project' (https://www.ree4eu.eu).

Reimer, M. V., Schenk-Mathes, H. Y., Hoffmann, M. F. and Elwert, T. (2018), 'Recycling decisions in 2020, 2030, and 2040 – When can substantial NdFeB extraction be expected in the EU?', *Metals*, Vol. 8, Issue 11, p. 867.

Reuters (2016), 'China to boost crackdown on illegal rare earth mining', 2 February (https://uk.reuters.com/article/rareearths-china/china-to-boost-crackdown-on-illegal-rare-earth-mining-idUSL3N15D278).

Reuters (2019), 'China to step up crackdown on rare earth sector', 4 January (https://www.reuters.com/article/us-china-rareearths-idUSKCN1OY0R3).

Roskill (2015), *Rare Earths: Market outlook to 2020* (15th edition), Roskill, London.

Roskill (2018), 'Rare earths: Changing magnet compositions to manage supply availability', 22 November (https://roskill.com/news/rare-earths-changing-magnet-compositions-to-manage-supply-availability/).

Roskill (2019), *Rare Earths: Market outlook to 2029* (19th edition), Roskill, London.

S&P Global Market Intelligence (2020), SNL Metals & Mining database (retrieved April 2020).

Seaman, J. (2019). *Rare earths and China: A review of changing criticality in the new economy*, Notes de l'Ifri, Ifri, Paris.

Shen, Y., Moomy, R. and Eggert, R. (2020), 'China's public policies toward rare earths, 1975–2018', *Mineral Economics*, Vol. 33, pp. 127–151.

Snieckus, D. (2019), 'Offshore wind turbine 20MW generator ready "within three years" ', 22 November (https://www.rechargenews.com/).

Standaert, M. (2019), 'China wrestles with the toxic aftermath of rare earth mining', 2 July (https://e360.yale.edu/features/china-wrestles-with-the-toxic-aftermath-of-rare-earth-mining).

Statista (2014), 'Total terbium oxide demand worldwide excluding China from 2009 to 2025', 17 November (https://www.statista.com/statistics/450121/global-reo-terbium-oxide-demand-outside-of-china-forecast/).

Teske, S. (2019), *Achieving the Paris climate agreement goals – Global and regional 100 % renewable energy scenarios with non-energy GHG pathways for +1.5 °C and +2 °C*, Institute for Sustainable Futures, University of Technology Sydney, Sydney.

Tesla (n.d.), 'Induction versus DC brushless motors' (https://www.tesla.com/blog/induction-versus-dc-brushless-motors).

Toyota Europe Newsroom (2018), 'Toyota develops new magnet for electric motors aiming to reduce use of critical rare-earth element by up to 50 %', 20 February (https://newsroom.toyota.eu/toyota-develops-new-magnet-for-electric-motors-aiming-to-reduce-use-of-critical-rare-earth-element-by-up-to-50/).

US Department of Energy (2020), *Critical materials rare earths supply chains: A situational white paper*.

USGS (US Geological Survey) (2020), *Mineral Commodity Summaries 2020*, USGS, Reston, VA.

Widmer, J. D., Martin, R. and Kimiabeigi, M. (2015), 'Electric vehicle traction motors without rare earth magnets', *Sustainable Materials and Technologies*, Vol. 3, pp. 7–13.

Wind Power Monthly (2018), 'Rethinking the use of rare-earth elements', 30 November (https://www.windpowermonthly.com/article/1519221/rethinking-use-rare-earth-elements).

List of abbreviations

JRC	Joint Research Centre
NdFeB	Neodymium–iron–boron
EVs	Electric Vehicles

List of figures

Annexes

Annex 1. Methodological notes

This annex presents information on the methods used for estimating the projected supply and demand.

Supply analysis

The baseline used for the supply forecast was the 2019 production rate for each rare earth element, which was estimated based on the production of each operating mine and the relative distribution of *in situ* rare earth oxides. The main source of information was the SNL Metals & Mining database from S&P Global Market Intelligence, as retrieved in April 2020. Additional sources of information used to consolidate the assessment are listed in Table 1.

Table 1: Sources of information used to estimate 2019 production rates

Main sources for mine production:
S&P Global Market Intelligence (2020), SNL Metals & Mining database
USGS (US Geological Survey) (2020), *Mineral Commodity Summaries 2020*, USGS, Reston, VA
Kingsnorth, D. J. (2018), *The Rare Earth Market in 2018, Driven by e-Mobility*, Curtin University and Industrial Minerals Company of Australia, Perth, WA
China Water Risk (2016), Rare earths: shades of grey. Can China continue to fuel our global clean & smart future, China Water Risk, Hong Kong
Shen, Y., Moomy, R. and Eggert, R. G. (2020), 'China's public policies toward rare earths, 1975–2018', *Mineral Economics*, Vol. 33, pp. 127–151
Packey, D. J. and Kingsnorth, D. (2016), 'The impact of unregulated ionic clay rare earth mining in China', *Resources Policy*, Vol. 48, pp. 112–116
Zhou, B., Li, Z. and Chen, C. (2017), 'Global potential of rare earth resources and rare earth demand from clean technologies', *Minerals*, Vol. 7, 203
Main sources for the relative distribution of *in situ* rare earth oxides:

S&P Global Market Intelligence (2020), SNL Metals & Mining database
TMR (Technology Metals Research) (2014), *TMR Advanced Rare-earth Projects Index*
Roskill (2015), *Rare Earths: Market outlook to 2020* (15th edition), Roskill, London
Van Gosen, B. S., Verplanck, P. L., Seal, R. R., II, Long, K. R., and Gambogi, J. (2017), 'Rare-earth elements', in Schulz, K. J., DeYoung, J. H., Jr., Seal, R. R., II, and Bradley, D. C. (eds), *Critical mineral resources of the United States – Economic and environmental geology and prospects for future supply*, US Geological Survey Professional Paper 1802, US Geological Survey, Reston, VA, pp. O1–O31
Ganguli, R. and Cook, D. R. (2018), 'Rare earths: A review of the landscape', *MRS Energy & Sustainability*, Vol. 5, p. E9
Zhou, B., Li, Z. and Chen, C. (2017), 'Global potential of rare earth resources and rare earth demand from clean technologies', *Minerals*, Vol. 7, 203
Rainbow Rare Earths (2016), *JORC competent person's report for the Gakara REE Project, Bujumbura Province, Western Burundi*, prepared by the MSA Group (Pty) Ltd for Rainbow Rare Earths Ltd, 3 October
Kumari, A., Panda, R., Kumar Jha, M., Kumar, J.R. and Young Lee, J. (2015), 'Process development to recover rare earth metals from monazite mineral: A review', *Minerals Engineering*, Vol. 79, pp. 102–115
Appia Energy Corp. (2013), 'Appia Energy files technical report on Elliot Lake uranium-rare earth property', 14 August (http://www.appiaenergy.ca/_resources/news/nr_20130814.pdf)
Tasman Metals Ltd (2013), Preliminary economic Assessment N1 43–101. Technical report for the Norra Kärr (REE-Y-Zr) Deposit Gränna, Sweden
Other sources of information:
Rainbow Rare Earths (2016), *JORC competent person's report for the Gakara REE Project, Bujumbura Province, Western Burundi*, prepared by the MSA Group (Pty) Ltd for Rainbow Rare Earths Ltd, 3 October
Kumari, A., Panda, R., Kumar Jha, M., Kumar, J.R. and Young Lee, J. (2015), 'Process development to recover rare earth metals from monazite mineral: A review', *Mineral Engineering*, Vol. 79, pp. 102–115
Met-Chem/DRA (2018), Projet de terres rares Kwyjibo – Évaluation économique préliminaire
U308 Corp. (n.d.), Company website (http://www.u3o8corp.com/projects/colombia/berlin-project/)
Appia Energy Corp. (2013), 'Appia Energy files technical report on Elliot Lake uranium-rare earth property', 14 August (http://www.appiaenergy.ca/_resources/news/nr_20130814.pdf)

Source: JRC.

Mine production capacities – the nominal levels of output based on the mine designs – are the underlying data that were used to develop projections of future mine supply. Mine supply projections were calculated by simulating idealised, life-of-mine production profiles. This was carried out using a declining resources method to estimate the number of production years the reported resources could theoretically support at full capacity. To calculate the remaining years of production, resource figures were adjusted to an average metallurgical recovery of 65 % (Kingsnorth D. J., 2018). Most information on production capacities was retrieved from S&P Global Market Intelligence. To overcome data gaps, we used statistical assumptions based on log-linear regressions between rare earth elements resources and production capacities.

The start-up dates for developing projects were established based on the declared development stage (Table 2). In addition, as planned production capacities are rarely attained quickly after start-up, capacity profiles for mines expected to come online in the future were calculated assuming a ramp-up trajectory over the first 2 years (30 % in the first year and 70 % in the second year), with each mine reaching full capacity in the third year. Overall reported capacities were disaggregated into individual rare earth oxide production capacities by using distribution profiles of *in situ* rare earth oxides.

Table 2: Assumed start-up dates for developing projects, based on their development stage in 2019

Development stage	Assumed start of production
Pre-production, under construction	2021
Feasibility stage (started and completed)	Between 2022 and 2024
Pre-feasibility stage	2026
Reserves development	2028

Source: JRC.

Demand analysis

Estimation of future demand for rare earths for wind turbines and electric vehicles was based on expected deployments according to political ambitions, the average lifetimes of wind turbines / electric vehicles and the amounts of materials used in manufacturing, which may vary over time as a result of technological improvements. For wind turbines we also considered the forecast market shares for the different generator designs and sub-technologies, as the deployment scenarios used did not include this information.

The **low-demand scenario** was built considering the commitments made by countries to limit greenhouse gas emissions and improve energy efficiency under the Paris Agreement, leading to a maximum temperature increase of 2.7 °C. For the EU it considers legally binding 2030 targets and aims to achieve a 64 % reduction in greenhouse gas emissions by 2050. It also assumes that research and innovation will lead to a significant increase in the lifetime of wind turbines and electric vehicles, as well as reduced usage of the different materials, and that generators not relying on permanent magnets will have an important share of the market, thus limiting the demand for magnets and rare earths.

The **high-demand scenario** was built considering strong political ambitions worldwide, leading to a maximum temperature increase of 1.5 °C, 100 % renewable primary energy by 2050 and, for the EU analysis, complete decarbonisation by 2050. Developments in research and innovation are assumed to be incremental, with no real technological breakthroughs; thus, wind turbine and electric vehicle lifetimes and material usage are only slightly improved. In this scenario, alternative designs for generators struggle to keep up with market demand, and permanent magnet products see their market shares increase.

For the other sectors, current demand for dysprosium, neodymium and praseodymium was indirectly assessed using a two-stage process, starting from the demand for wind power and e-mobility, considering – for each element – first the share of wind power and e-mobility within the magnet sector and then the magnet sector share within the overall market, based on data from the literature. For terbium, the demand from other sectors was calculated by subtracting the demand for wind power and e-mobility from the overall demand estimated using data from the literature (Statista, 2014; Kingsnorth D. J., 2018).

Future demand was extrapolated based on historical market trends (Kingsnorth D. J., 2018), assuming that in the low-demand and high-demand scenarios market sales of rare earth-containing products will rise according to the slowest and fastest growth rates historically recorded, respectively. As technologies used in other sectors are well established, no contributions of research and innovation to technology lifetimes and material usage were considered. Data and demand for wind turbines were taken from a study on raw materials for wind turbines and solar panels (JRC, 2020c), while data and demand for traction motors for passenger cars in the EU were taken from a study on materials for strategic sectors and technologies in the EU (European Commission, 2020a). Table 3 summarises the parameters used in the estimations. Demand for traction motors includes all light duty vehicles, for both commercial and private use, but does not include projections for electric bikes or heavy duty vehicles.

Table 3: Parameters used in the estimation of the future demand for neodymium, praseodymium, dysprosium and terbium

Low-demand scenario	
Deployment according to political commitments	World: International Energy Agency energy technology perspective reference technology scenario (IEA, 2017) EU: Long-term strategy baseline scenario (European Commission, 2018)
Lifetimes	30 years for onshore wind turbines 35 years for offshore wind turbines Linear increase from 9 to 13 years between 2015 and 2050 for electric vehicles
Material intensities	Wind turbines: 6–17 t/GW for dysprosium with a 12 % annual reduction up to 2050 1–7 t/GW for terbium with a 5 % annual reduction up to 2050 51–180 t/GW for neodymium with a 5 % annual reduction up to 2050 4–35 t/GW for praseodymium with a 5 % annual reduction up to 2050 Electric vehicles: 112.5 g/motor for dysprosium with a 66 % reduction by 2030 and a 75 % reduction by 2050 151.2 g/motor for neodymium with a 30 % reduction by 2030 and a 40 % reduction by 2050 90 g/motor for praseodymium with a 30 % reduction by 2030 and a 40 % reduction by 2050
Market shares for permanent magnet generators	EU:

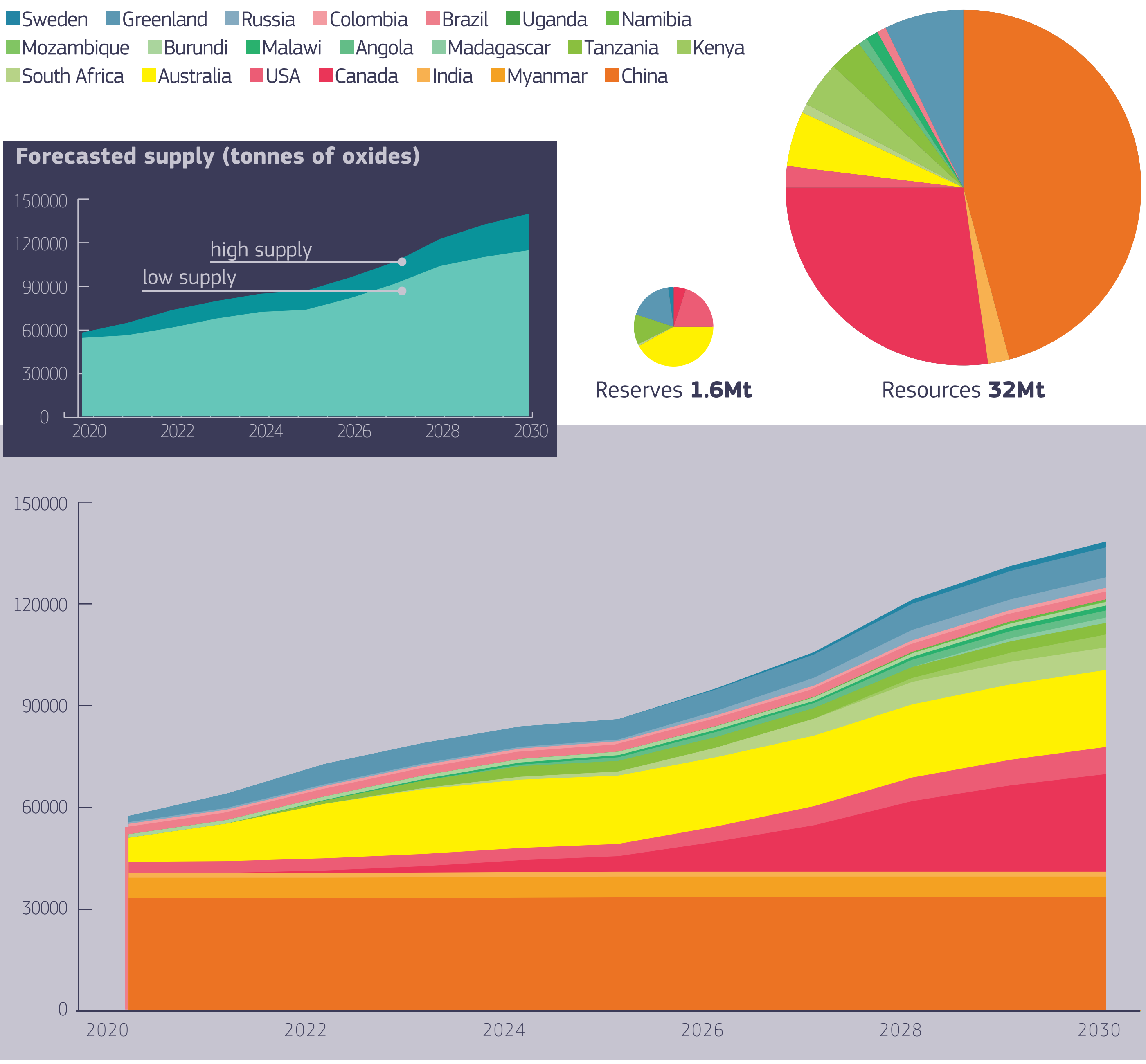
	From 30 % (2018) to 41 % (2030) to 52 % (2050) for onshore turbines From 100 % (2018) to 48 % (2030) to 44 % (2050) for offshore turbines Global: From 32 % (2018) to 32 % (2030) to 40 % (2050) for onshore turbines From 76 % (2018) to 44 % (2030) to 41 % (2050) for offshore turbines
Annual growth rate in other sectors	3 % for neodymium, praseodymium and dysprosium 6 % reduction for terbium in the EU; 4.5 % reduction for terbium globally
High-demand scenario	
Deployment according to political commitments	World: Institute for Sustainable Futures 1.5 °C 2019 scenario (Teske, 2019) EU: JRC-EU-TIMES zero carbon scenario (JRC, 2020b)
Lifetimes	20 years for onshore wind turbines 25 years for offshore wind turbines Linear increase from 9 to 11 years between 2015 and 2050 for electric vehicles
Material intensities	Wind turbines: 6–17 t/GW for dysprosium with 2 % annual reduction up to 2050 1–7 t/GW for terbium with no reduction over time 51–180 t/GW for neodymium with no reduction over time 4–35 t/GW for praseodymium with no reduction over time Electric vehicles: 112.5 g/motor for dysprosium with a 40 % reduction by 2050 151.2 g/motor for neodymium with a 10 % reduction by 2030 and a 15 % reduction by 2050 90 g/motor for praseodymium with a 10 % reduction by 2030 and a 15 % reduction by 2050
Market shares for permanent magnet generators in wind turbines	EU: From 30 % (2018) to 52 % (2030) to 65 % (2050) for onshore turbines

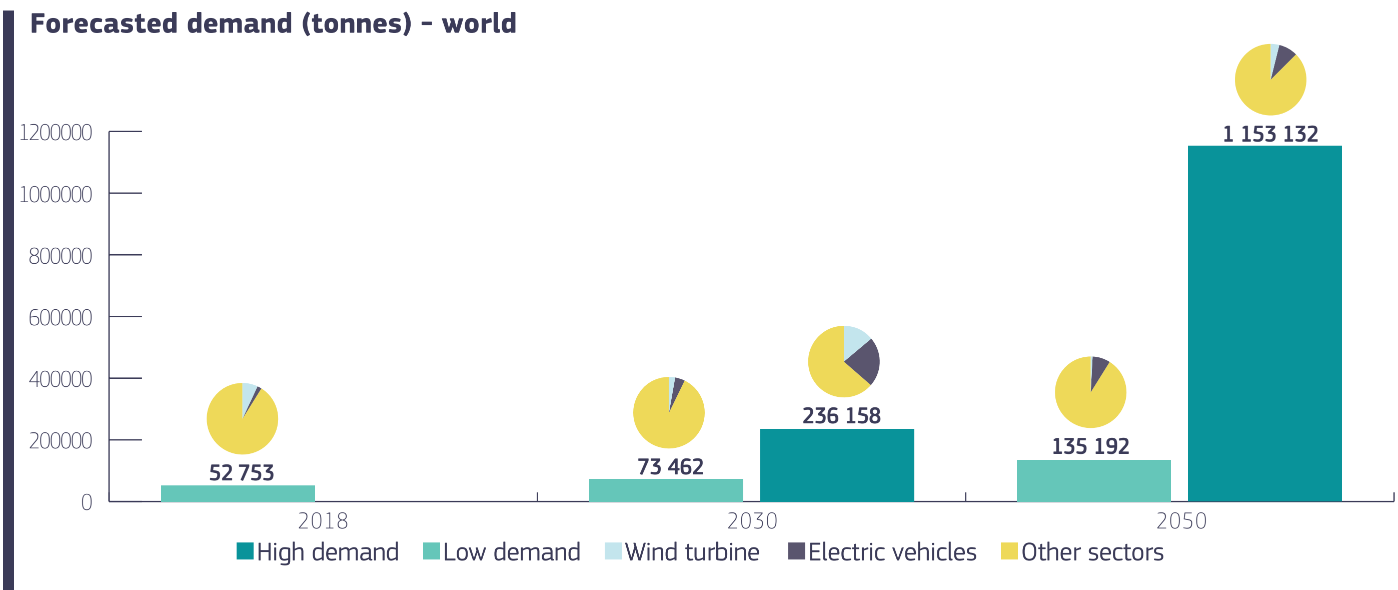
	From 100 % (2018) to 95 % (2030) to 95 % (2050) for offshore turbines Global: From 32 % (2018) to 46 % (2030) to 68 % (2050) for onshore turbines 76 % for all years for onshore turbines
Annual growth rate in other sectors	10 % for neodymium, praseodymium and dysprosium No change for terbium in the EU; 1.5 % reduction for terbium globally

Source: JRC.

Annex 2. Overview of the results for individual elements

CUMULATIVE *dysprosium, terbium, neodymium, praseodymium*



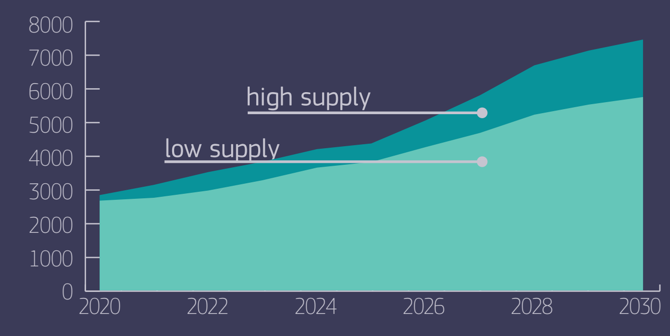


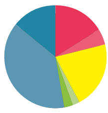
Source: JRC, 2020

DYSPROSIUM

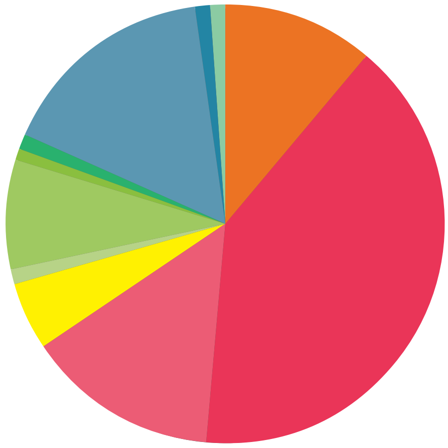
Sweden · Greenland · Russia · Colombia · Brazil · Uganda · Namibia · Mozambique · Burundi · Malawi · Angola · Madagascar · Tanzania · Kenya · South Africa · Australia · USA · Canada · India · Myanmar · China

Forecasted supply (tonnes of oxides)

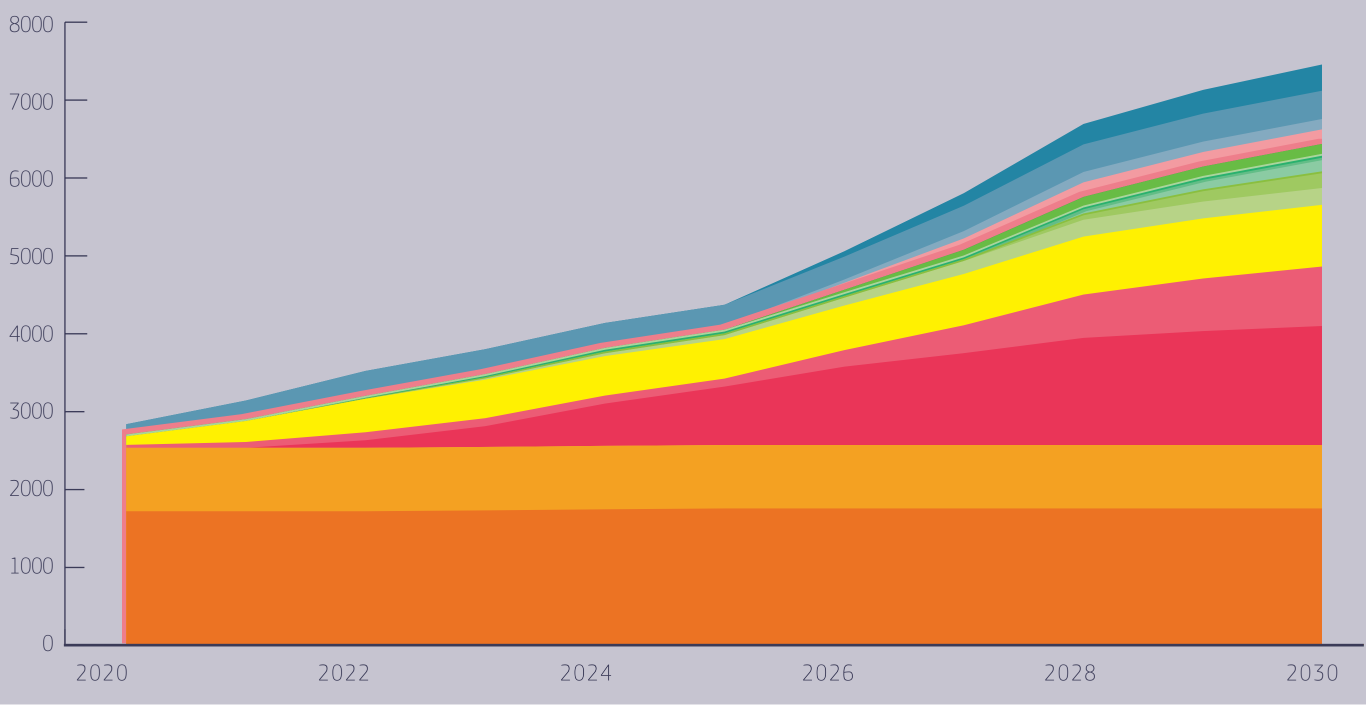




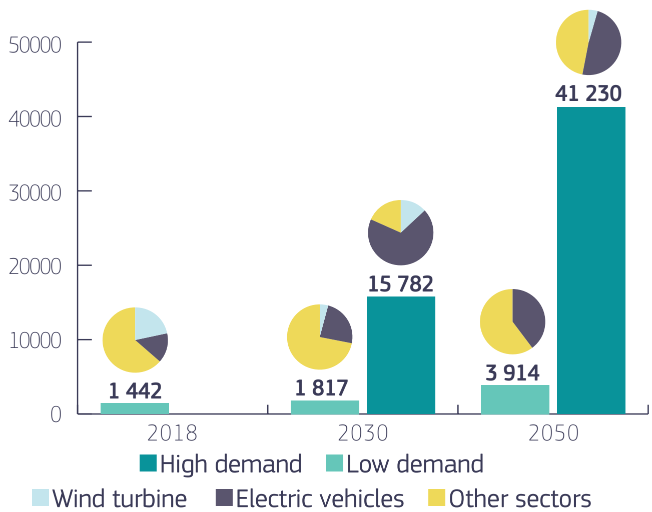
Reserves **44Kt**



Resources **800kt**



Forecasted demand (tonnes) - world

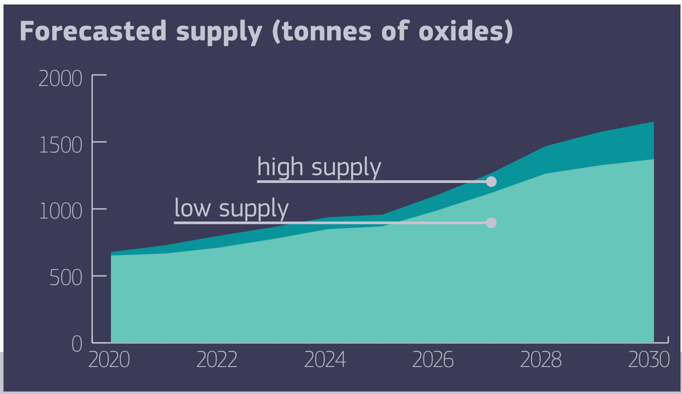


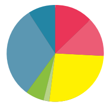
Demand/Supply ratio

Source: JRC, 2020

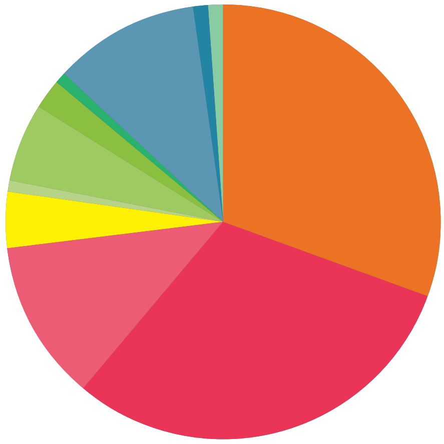
TERBIUM

Sweden Greenland Russia Colombia Brazil Uganda Namibia
Mozambique Burundi Malawi Angola Madagascar Tanzania Kenya
South Africa Australia USA Canada India Myanmar China

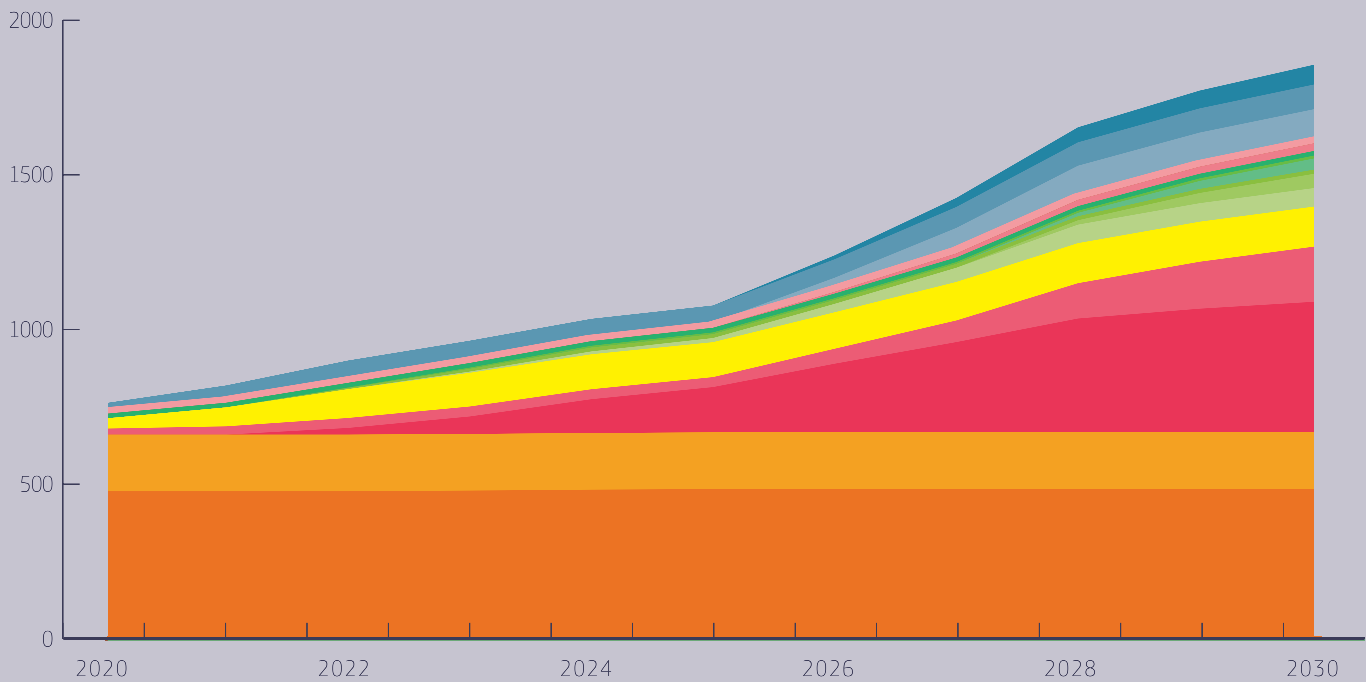


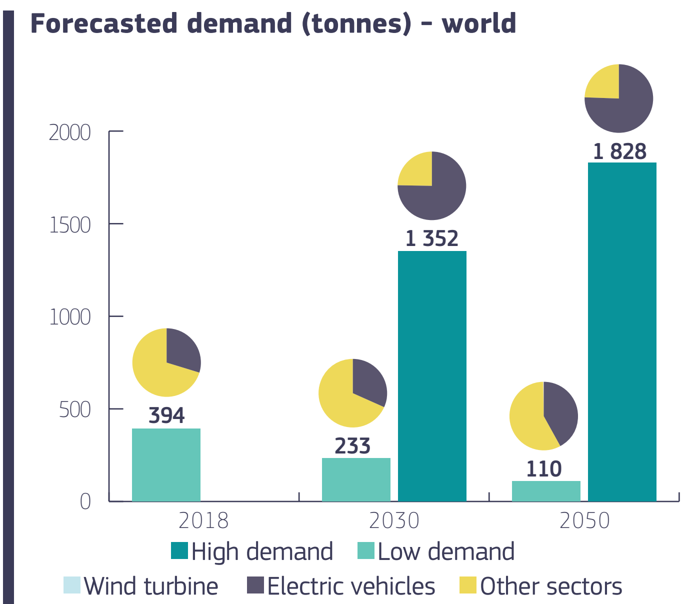


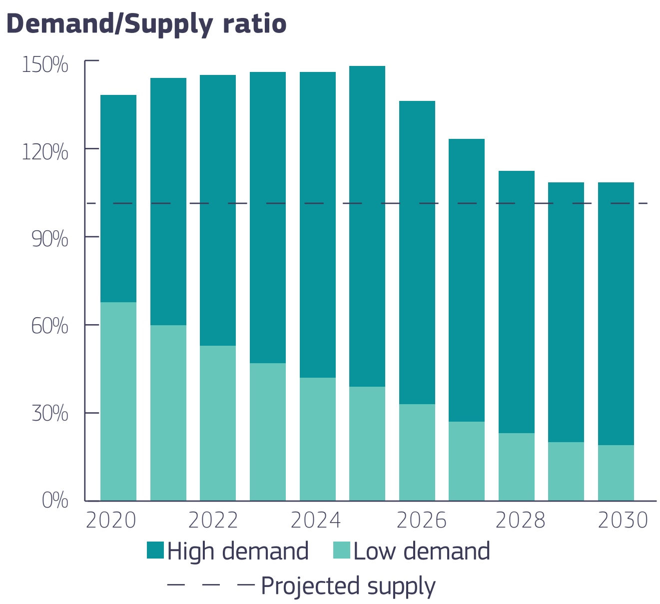
Reserves **10Kt**



Resources **200Kt**





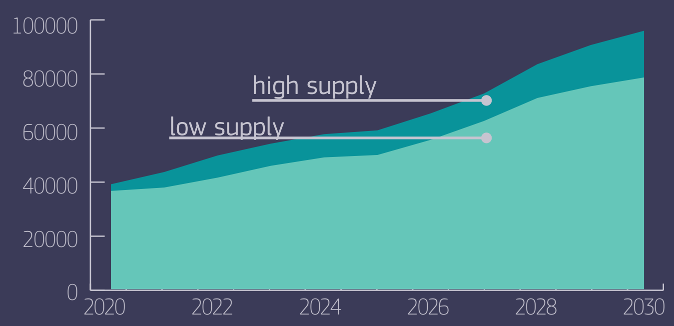


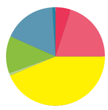
Source: JRC, 2020

NEODYMIUM

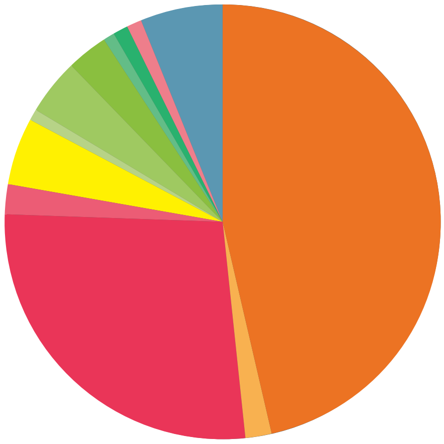
Sweden Greenland Russia Colombia Brazil Uganda Namibia
Mozambique Burundi Malawi Angola Madagascar Tanzania Kenya
South Africa Australia USA Canada India Myanmar China

Forecasted supply (tonnes of oxides)

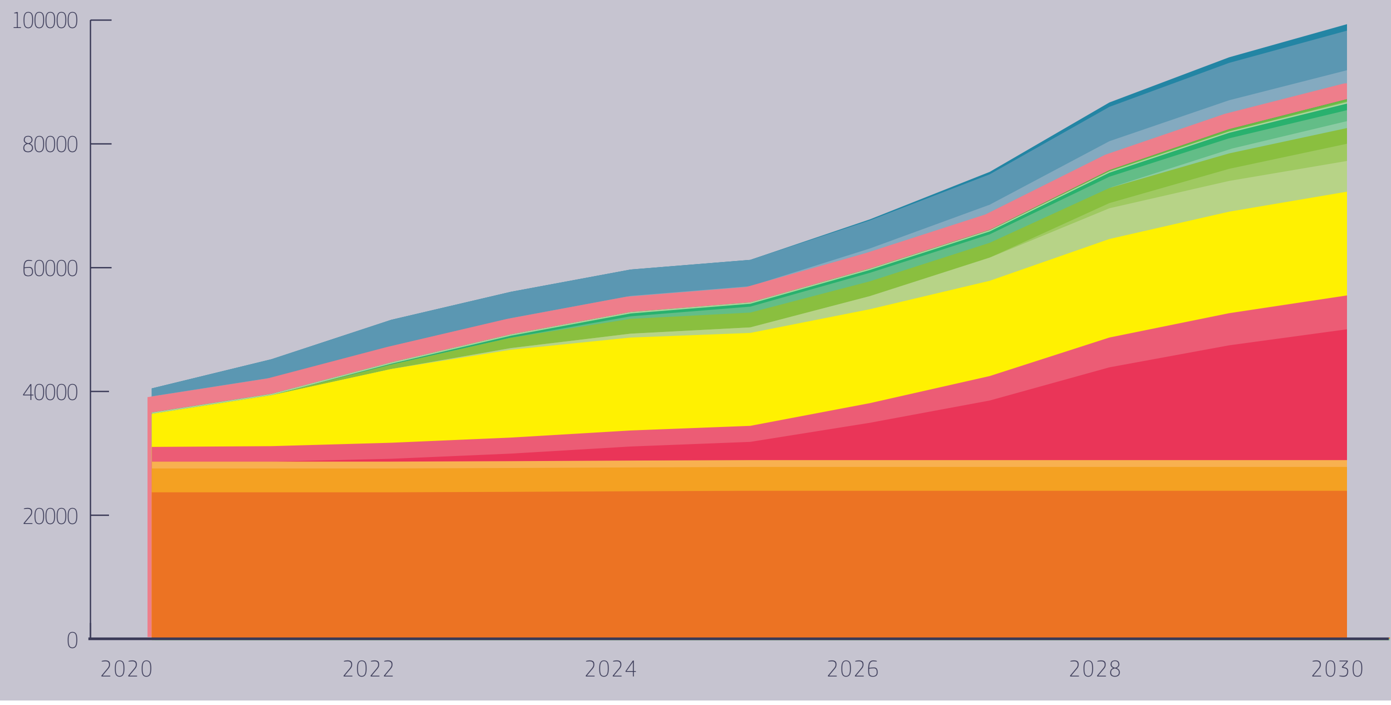




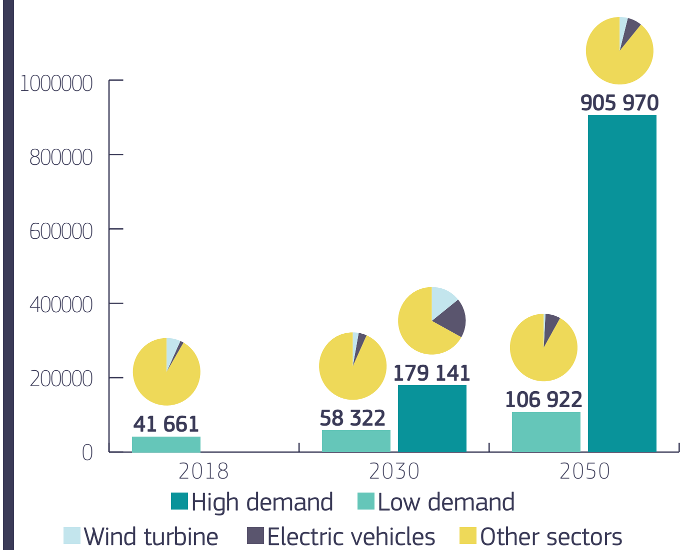
Reserves **1.2Mt**



Resources **23.6Mt**



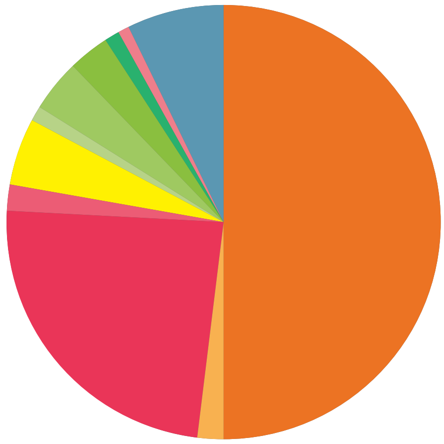
Forecasted demand (tonnes) - world



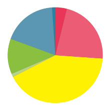
Demand/Supply ratio

Source: JRC, 2020

PRASEODYMIUM

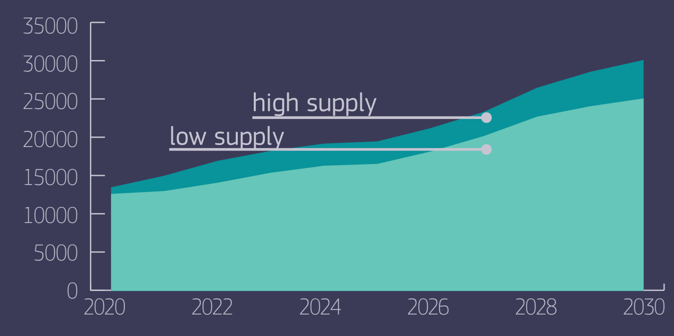


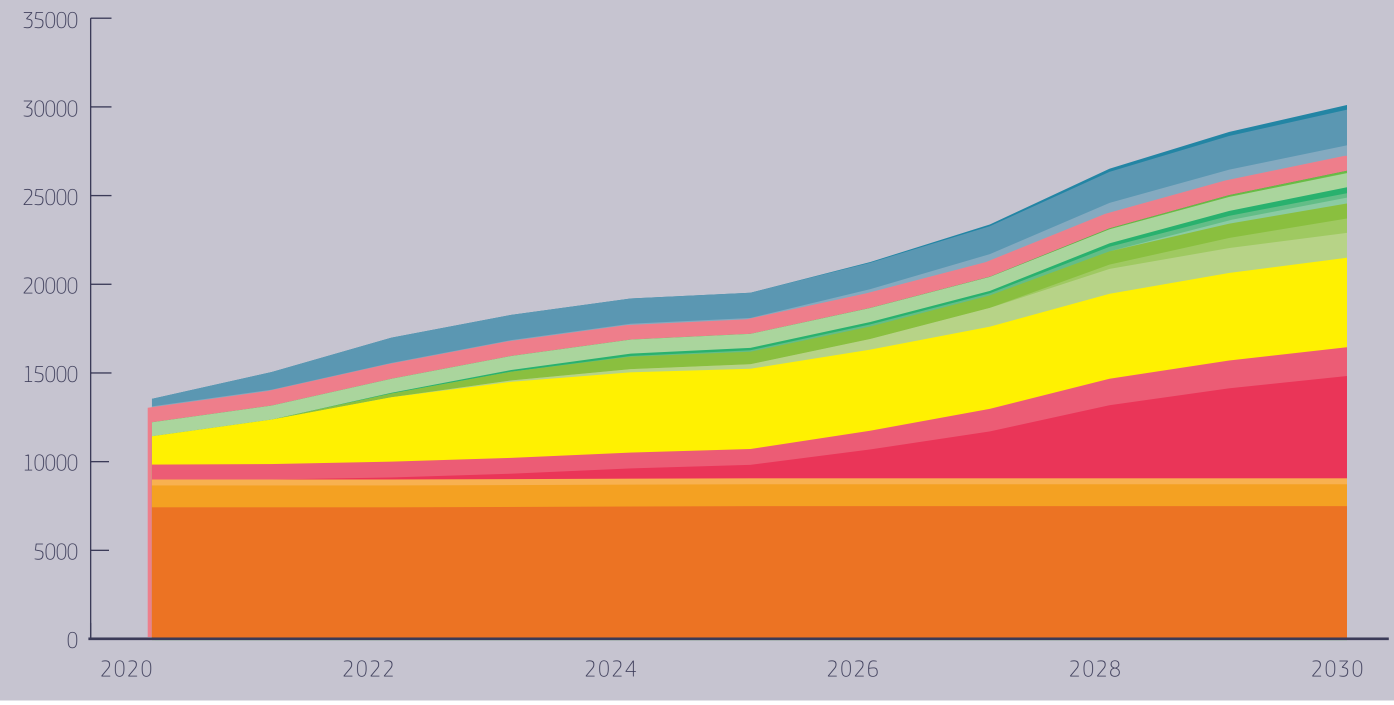
Resources **7.3Mt**



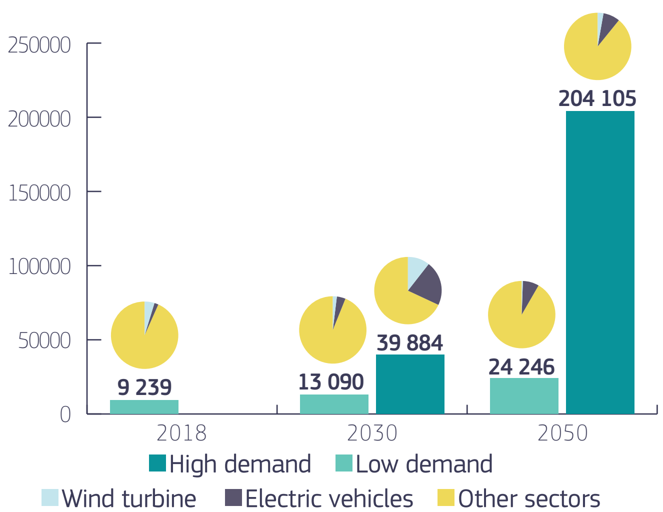
Reserves **370Kt**

Forecasted supply (tonnes of oxides)





Forecasted demand (tonnes) - world



Demand/Supply ratio

Source: JRC, 2020

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

KJ-NA-30488-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office
of the European Union

doi:10.2760/303258

ISBN 978-92-76-27016-4