Rare Earths in the Wind Industry

OCTOBER 2020

EXECUTIVE SUMMARY

Rare Earth Elements (REE) are used by the wind turbine industry in permanent magnet generators. This research note focuses on the demand and supply of REE and Rare Earth Oxides (REO)[1] for the wind turbine industry.

After discussing the global situation in the supply and demand side, this note analyses the role of REO in the wind power industry. Taking into consideration the different aspects of the REO market worldwide and the development of wind power, the following conclusions are drawn:

- Permanent magnet generators (PMSG) allow a lighter and more compact wind turbine design and require lower maintenance costs.
- The actual (2018) EU market share of PMSG turbines is 34% for onshore and 100% for offshore. The Joint Research Council (JRC) scenarios suggest an increase of the EU market share to between 52% and 65% for onshore and a decrease of the EU market share to between 44% and 95% for offshore in 2050.
- The supply chain of REE entirely depends on non-EU countries, in particular China.
- The deployment of wind turbines according to EU plans would require most of the Dysprosium, Neodymium, Praseodymium and Terbium currently available for the EU at global level.
- Substitution strategies are hardly applicable for Neodymium but more promising for Dysprosium.
- Recycling technologies are 5-10 years away from commercialisation (Yang et al, 2017).
- Increased material efficiency could reduce REE content in PMSG turbines from 29% to 20% in 2030.

RECOMMENDATIONS

- Expand **EU Research Development and Innovation (RD&I)** for neodymium and dysprosium substitutes, most urgently for dysprosium;
- Examine low-cost opportunities for **small-quantity recycling**;
- Strengthen the **Raw Materials Initiative**;
- Further examine **mining options within the EU**, in particular considering strict EU environmental legislation, addressing possible local and national public resistance and investigating possibilities for stop-and-go mining;
- Strengthen **multilateral and bilateral trade policy** efforts to balance the market power of China as a near-monopoly supplier of neodymium and dysprosium;
- Expand trade relations with neodymium and dysprosium suppliers other than China;
- Consider stockpiling of neodymium and dysprosium, but only as a last resort option to reduce current dependencies.

[1] Oxide: a chemical compound that consists of one or more oxygen atoms and at least one element atom. REO are therefore the chemical compounds that occur after combining the REE with oxygen.

INTRODUCTION

Rare earth elements (REE) belong in a group of 17 chemical elements with similar catalytic, magnetic, optical and other properties, which are a part of our daily high-technology and modern equipment. The Oxides of the rare earth elements (Rare Earth Oxides, REO) are present in appliances from LCD screens to hybrid cars and wind turbine generators.

La	lantanum	**Tb**	terbium
Ce	cerium	**Dy**	dysprosium
Pr	praseodymium	**Ho**	holmium
Nd	neodymium	**Er**	erbium
Pm	promethium	**Tm**	thulium
Sm	samarium	**Yb**	ytterbium
Eu	europium	**Lu**	lutetium
Gd	gadolinium	**Y**	yttrium

Figure 1: Names and Symbols of Rare Earth Elements

Owing to their unique magnetic, optical, and catalytic properties, REEs can be used in a wide variety of products and technologies, including computing and defence systems and clean energy technologies (Gupta and Krishnamurthy 2015).

Light rare earths (underlined in Figure 1) are those elements with an atomic number between 57 and 62. Elements with atomic numbers from 63 to 71 make up the heavy rare earths. Yttrium (Y) is a heavy rare earth even though its atomic number is 39. Scientists place it in the heavy group because its properties resemble those found in the heavy rare earth elements.

Rare earths are relatively abundant in the Earth's crust, but minable concentrations are less common than for most other minerals. Resources are primarily in four geologic environments: carbonatites, alkaline igneous systems, ion-adsorption clay deposits, and monazite-xenotime-bearing placer deposits. Carbonatites and placer deposits are the leading sources of light rare-earth elements. Ion-adsorption clays are the leading source of heavy rare-earth elements. Light rare earths are generally more abundant than heavy rare earths (ERECON, 2014).

Table 1 shows the main applications of REE and the share in the global consumption:

Table 1: Summary of REE Usage. Source: Zhou B. et al. 2016

REE Main Use - Percentage		
Ce	Catalytic converters, metal production, refining crude oils	**40.2%**
La	Petroleum cracking and catalyst, camera lenses, battery electrodes	**27.8%**
Nd	**Permanent magnets, metal production improver**	**17.6%**

REE Main Use - Percentage		
Y	Television and computer screen, CFLs, and LED lights	6.8%
Pr	**Permanent magnets, glass and ceramics colorant, lasers**	4.4%
Gd	Magnetic refrigeration, metal production, optical glass	0.9%
Dy	**Permanent magnet additive, luminescent material**	0.7%
Sm	Sm-co permanent magnet, X-ray lasers	0.5%
Ho	Laser glass, glass coloring, metal halide lamp, dielectric ceramic	
Er	Signal amplification in fiber optic cables, laser glass	
Tm	Fiber amplifier, laser glass	
Yb	Laser glass, fiber amplifier	
Lu	Medical isotope radiation therapy	
Eu	Color television screens, LED lights, X ray intensifying screens	0.4%
Tb	**Permanent magnet additive, giant magnetostrictive material**	0.2%
Pm	Isotope luminescent materials	NA
Sc	Aerospace framework, special alloy, neutron generator NA	NA

The REEs used in the production of permanent magnets (PM) are neodymium (Nd), terbium (Tb), dysprosium (Dy) and praseodymium (Pr) – in bold in Table 1. Neodymium–iron–boron ($Nd_2Fe_{14}B$) magnets are used in wind turbines and other electricity generators. Back in 2015, these magnets typically contained 29% of neodymium (Nd) and 2-4% of dysprosium (Dy) as additive (Smith Stegen 2015). Nowadays, Dy content is closer to 1-1.5%.

GLOBAL DEMAND AND SUPPLY OF REE

In 2015, estimations of the global consumption of rare earths varied significantly and generally ranged from about 120,000 to 150,000 tonnes (t) (Adamas Intelligence 2016). The amount and specific REEs used varies significantly by market sector and application. Figure 2 summarises the demand per REE element Consumption in the **magnet sector** varies by the type of permanent magnet. The share of the magnet sector in 2015 is shown in Figure 3.

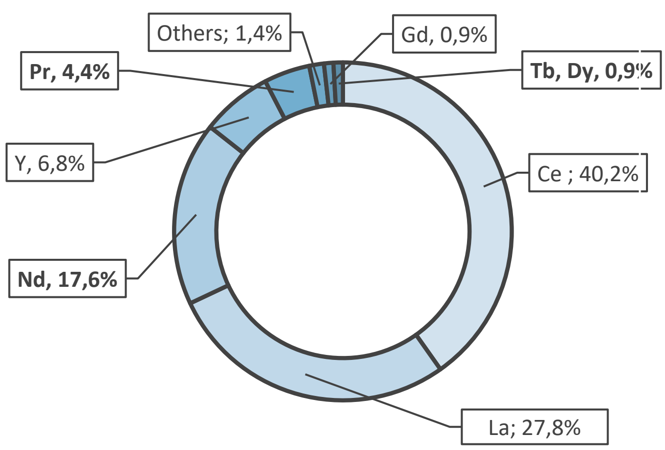


Figure 2: REE Demand per Element. (Source: Zhou et al. 2016)

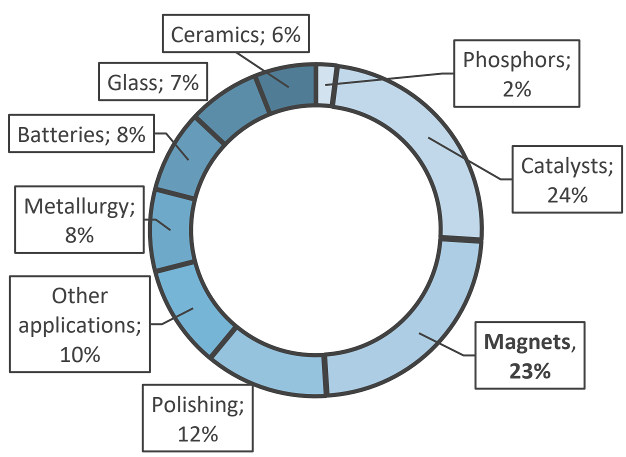


Figure 3: REE Demand per Sector (Source: Roskill 2016)

By 2018, the market share increased to 35% by volume and 91% by value thus becoming the leading sector (Adamas Intelligence 2019). Global annual growth in REE consumption in this sector is expected to exceed 5% through 2020 (USGS 2019). The consumption of magnets is expected to dominate the overall availability of REEs. Increased demand for magnets may cause an oversupply of some REEs not used in magnets (BCC Research 2015, Roskill Information Services Ltd. 2016 and USGS 2018). Adamas Intelligence (2019) forecasts that prices of high-demand elements, like Nd, Pr, Dy and Tb, will rise accordingly to pay for the losses that producers are incurring by over-producing the other unsaleable surplus rare earths.

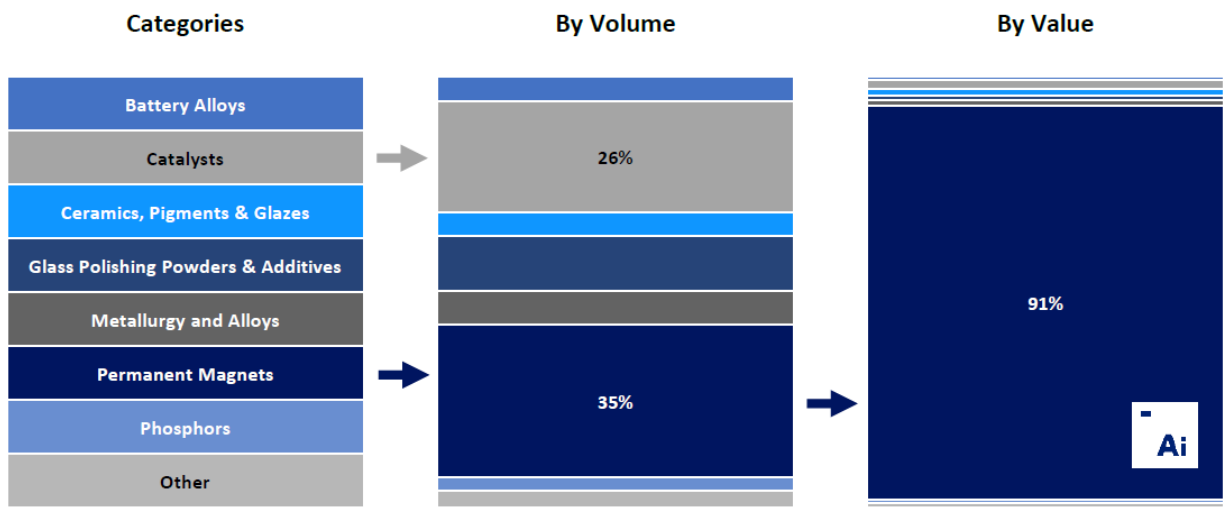


Figure 4: Permanent magnets are the leading users of REEs. Source: Adamas Intelligence, 2019.

In 2018 and 2019, the US Geological Survey estimated a total mine production of, respectively, 190,000 and 210,000 t (USGS 2020). As the leading producer and consumer of rare-earth minerals and most downstream products, China is expected to continue to dominate the global markets for rare-earth compounds and metal alloys.

Table 2: World REE Mine Production. Source: USGS 2020.

Country	2018 (t)	2019 (t)	2019 (%)
US	18,000	26,000	12
Australia	21,000	21,000	10
Brazil	1,100	1,000	0,5
Burma (Myanmar)	19,000	22,000	10,5
Burundi	630	600	0
China	**120,000**	**132,000**	**62**
India	2,900	3,000	1,5
Madaga-scar	2,000	2,000	1
Russia	2,700	2,700	1
Thailand	1,000	1,800	1
Vietnam	920	900	0,5

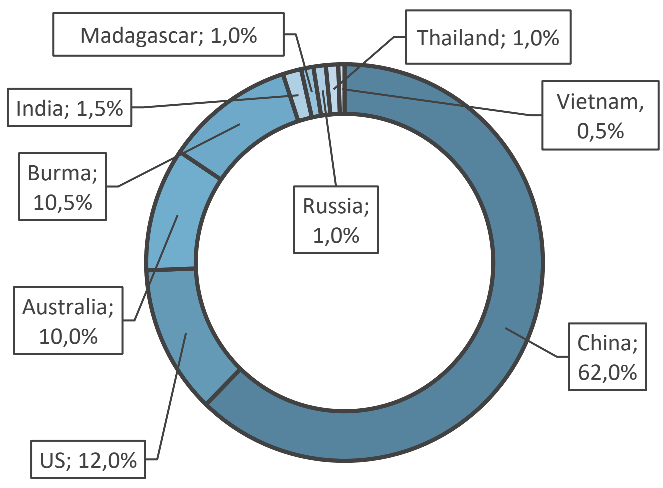


Figure 5: REE Mine Production by Country in 2019.

Other countries	60	-	-
TOTAL	**190,000**	**210,000**	**100**

China dominates the mining, processing and manufacturing of REE. Whilst, China's share of global rare earth mine production has fallen from over 95% in 2010 (USGS 2011) to 62% in 2019 (USGS 2020), its supply monopoly for heavy rare earths remains largely intact (ERECON 2014). Furthermore, China's share of downstream value-adding capacity to convert rare earth mine outputs has continuously expanded reaching 85% for oxides and 90% for metals, alloys and magnets (Adamas Intelligence 2019). Fluctuation in China's supply of rare earths is strictly dependent on the country's export policies.

There are currently 120 million tonnes of REEs estimated reserves globally (Table 3), of which 38% is located in China. Sizeable deposits are also found in Brazil, Vietnam, Russia, India and Australia (Figure 5). A new important deposit of REO with an estimated 1.2 million tonnes was recently discovered in the western North-Pacific Ocean near Minamitorishima Island, Japan. The increased effectiveness of the mineral processing is expected to make this deposit exploitable in the future (Takaya et al. 2018).

Table 3: World REE Reserves in 2019
Source: USGS 2020.

Country	Reserves (t)
United States	1,400,000
Australia	3,300,000
Brazil	22,000,000
Burma (Myanmar)	NA
Burundi	NA
Canada	830,000
China	44,000,000
Greenland	1,500,000
India	6,900,000
Madagascar	NA
Russia	12,000,000
South Africa	790,000
Tanzania	890,000
Thailand	NA
Vietnam	22,000,000
Other countries	310,000
TOTAL	**120,000,000**

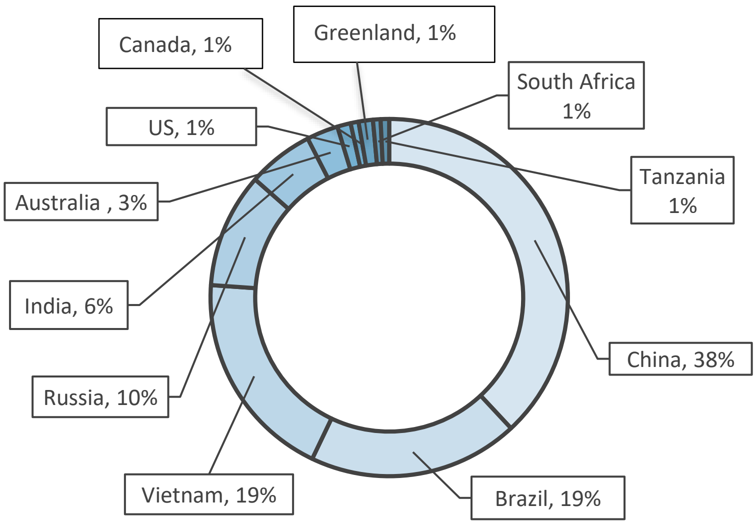


Figure 6: World REE Reserves in 2020 – Percentages Extracted from Table 3.

From 2010, China tightened export restrictions and banned any REE export to Japan, creating an alarming speculation which led REE prices to increase significantly. The price increase was amplified in Europe due to quotas and exportation taxes. This led REE users to explore alternative sites for extraction of REE while other sectors began a substitution effort, intensifying recycling and technological development to compensate for the shortage of these materials. In addition, from 2008, China started pursuing sustainability goals in REE extraction such as fighting illegal mining, regulating exportation, improving the environmental practices and boosting internal processing industries.

As a result, global REE supply diversified, with some major mining projects starting in Australia and in the United States. The demand for China's REE significantly dropped and consequently, prices started to fall after the price spike in 2011. On a percentage basis, the largest declines in REE prices were led by europium (-59%), samarium (-57%), and yttrium (-50%) (USGS 2018). Figure 6 presents the price variation for Tb, Dy, Nd and Pr between 2005 and 2015.

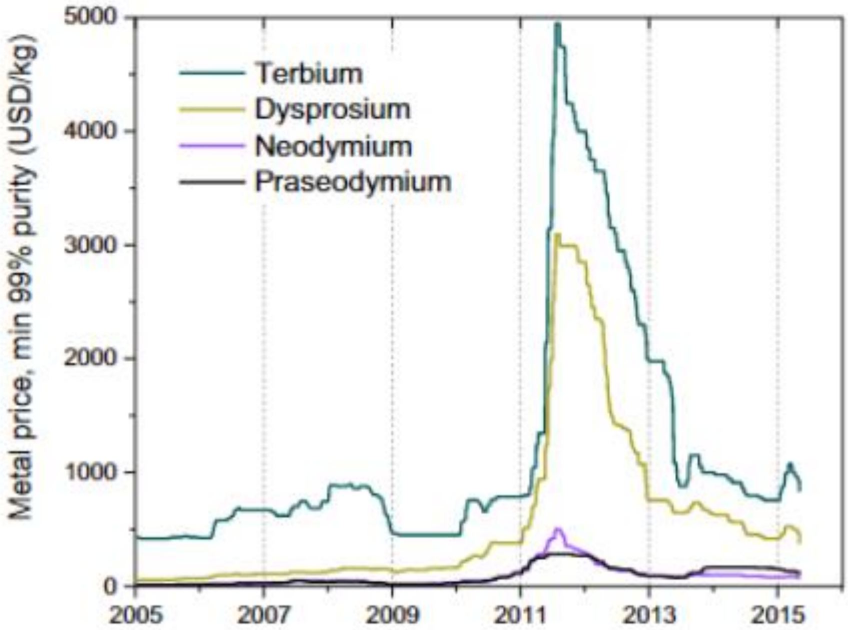


Figure 7: Price Variation of Tb, Dy, Nd and Pr, 2005-2015. (Source: Pavel et al. 2017)

Excess inventory and production capacity in China are expected to limit increased prices and the expansion of mine production outside of China through 2020. Beyond 2020, increased demand, industry consolidation in China, tighter enforcement of environmental compliance, and reductions in illegal mining are expected to result in higher prices for some REE materials. This scenario may accelerate the development of mining and processing projects outside of China as already happened after 2010 (BCC Research 2015 and Roskill 2016).

Due to the potential diversification of supply sources and a greater EU mine production, the resilience situation regarding the supply of Nd, Pr and Dy is likely to improve (Blagoeva et al. 2016). To foster the resilience of the supply of those elements, substitution, technological development and higher recycling rates will also play a fundamental role. For example, the Government of Sweden is currently investigating the abundance of critical minerals in the country and the possibilities for the development of an entire Swedish production chain from extraction to finished product, including recycling. Current barriers include market risks due to Chinese dominance and permission processes (Growth Analysis 2017 and Geological Survey of Sweden 2018). Another example is that of Siemens Gamesa Renewable Energy investigating recycling and recovery opportunities (Danish Environmental Protection Agency, 2018). Likewise the EU projects REE4EU (http://www.ree4eu.eu/) and SUSMAGPRO (https://www.susmagpro.eu/) are also investigating recycling solutions. Finally, Greenspur, a UK-based company, has developed permanent magnet generators free of rare earths (https://www.greenspur.co.uk).

SUSTAINABILITY OF RE

Discussions regarding the sustainability of RE may be broadly classified into three categories: a) geological reserves and availability; b) environmental and social impacts of RE production and c) environmental benefits of utilisation (McLellan, 2014).

From the perspective of securing supply, RE are relatively abundant, geologically speaking, however not necessarily in concentrations that make economic extraction possible. Moreover, with the policy drive to utilise energy efficient and low carbon energy technologies, and with growing global demand for electronics, demand will likely outstrip production in the future (McLellan, 2014). Adams Intelligence (2019) forecasts that global annual demand for Nd and Dy will substantially exceed global annual production by 2030. Until recently, there was limited economic benefit in recycling RE, due to the small quantities and concentrations contained in consumer products and the difficulty in collection and processing (Binnemans et al. 2013). However, as demand-supply balance shifts, increasing the price of RE in the market, recycling becomes more attractive.

Many environmental and social issues are associated with REE production. Nearly all RE deposits under exploration contain the radioactive elements thorium (Th) and uranium (U) and their decay products (Zhou at al. 2016). Much of the public health concerns around RE come from thorium containing wastes as a source of radiation. As much of the processing in China has not been undertaken with publicly available monitoring, the epidemiological evidence of the impact of REE mining is limited. The only detailed study of RE health-related toxicity was carried out in the early 1990s by Hirano and Suzuki and provides data similar to that of heavy metals toxicity concerns (Ali 2014). Ongoing monitoring of radioactivity levels as well as health monitoring around plants is crucial to ensure there are no health impacts.

In addition, large amounts of chemical reagents are required in the production of REs with the potential for environmental contamination and associated and health risks. Strict environmental monitoring and mitigation measures already used in many large industrial operations are required, particularly regarding wastewater treatment systems and controls of emissions of dust, sulphur compounds and fluoride. This can be an obstacle for the spread of mining and processing of RE in countries like Europe and USA where environmental restrictions are tighter than, for example, China. The latter may further lead to concerns over environmental justice, as projects are more likely to be located in developing countries (Ali 2014).

Roskill (2019) highlights that the Chinese industry has continued to introduce legislation to ‘clean-up’ their domestic rare earth industry, tackling the environmental, social and governmental impact of historical production. Despite its dominance of the global industry, China’s production of mined rare earths has been impacted in recent years by the introduction of environmental legislation and industry consolidation. Environmental legislation has led to many operations, predominantly in southern Chinese provinces, suspending production. As a result, Chinese processors have looked to alternative sources of rare earth raw materials, creating opportunities for producers both in the Chinese domestic market and in the rest-of-world. For example recycled rare earth materials have been imported and processed by facilities in China, to meet growing demand for rare earth products. Illegal production remains a significant source of raw materials in China, though efforts by local and central government have reduced illegal production by almost 50% since 2016.

RE contribution towards developing a “green energy” can be cited as a potential positive impact. Social perceptions of the risk at the site level thus need to be balanced against broader national priorities towards low carbon technology development. With rises in RE market price and concerns over environmental impact and supply security, recycling and substitution technologies will play a fundamental role (Ali 2014 and McLellan et al. 2014).

WIND ENERGY TECHNOLOGY AND REE

Wind energy is one of the most cost-effective technologies for climate-change mitigation and is a growing sector in the EU industrial base. Further penetration of wind technology in the EU and global markets will influence the global demand for rare earths based on the latest techno-economic developments and trends.

Depending on the technology for the generation of electricity and the configuration of its components, wind turbines require substantially different amounts of rare earths elements.

GENERATOR

The main component of a wind turbine is the generator, which converts the mechanical energy input from the blades into electrical energy. The choice of generator varies based on the fluctuation of the material cost over time and on the location of the installed wind turbine. In addition, generators have to meet grid connection requirements for the quality and form in which the power is delivered to the grid system.

There are two main generator types: the asynchronous and the synchronous. The asynchronous generator needs to use electricity from the grid to start its operation. The variable speed systems **doubly-fed induction generators (DFIG)** are widespread on the onshore market. Vestas V120-2.2, Siemens-Gamesa 2.1-114 and General Electric Cypress Platform are some representative models of this configuration.

For synchronous generators, the use of a moving magnet generates the electricity. These magnets could be either electromagnets (**Electrically Excited Synchronous Generators - EESG**) or permanent magnets (**Permanent Magnets Synchronous Generation – PMSG**). Electromagnets are rare earths free and need some electricity in order to start operating and create the necessary magnetic field. On the other hand, permanent magnets consist of rare earth elements which have strong magnetic properties by nature and therefore do not need any electricity to start operating. Siemens-Gamesa 8.0-167 DD, Vestas V162-5.6 and General Electric Haliade-X 12MW are some examples of permanent magnet generators.

Permanent magnet generators take advantage of the important magnetic properties of REOs to generate electricity with high efficiency. One of the main advantages of using permanent magnet generators is the higher power density, which results in a lighter and more compact generator. This is particularly advantageous for larger wind turbines (>5MW) allowing to reduce weight and other mechanical constraints. In addition, it performs with higher efficiency even at low wind speeds due to self-excitation. It finally enhances grid compatibility by the use of a full power converter. On the other hand, the cost of full power converters is relatively high, adding to the overall cost of the wind turbine.

DRIVE TRAIN CONFIGURATION

Wind turbines are categorised according to the drive train configuration. The drive train connects the blade hub to the generator and different configurations are required for different rotational blade speeds.

In **Geared Drive Train** turbines, the blades are connected to the generator through a compact gearbox (medium speed turbines, ≥ 80 rpm) or a full-sized transmission system (high speed turbines, ≥ 900 rpm). Geared Drive Train turbines can be equipped with PMSG low in magnet content or electromagnet generators (mainly Doubly-Fed Induction Generators (DFIG) but also well Squirrel Caged Induction Generators (SCIG) and Wound-Rotor Induction Generators (WRIG)) which do not require permanent magnets.

As it is heavy and requires maintenance, the gearbox design is less competitive in larger plants and offshore solutions (Carrara et al. 2020).

In **Direct Drive (DD)** turbines, the blades are directly connected to the generator. These turbines run at low speed (10-30 rotation per minute (rpm)) and can be equipped with both PMSGs and EESGs. Manufacturers like Enercon and Mtorres, among others, use large electromagnets (EESGs) benefiting from the absence of gearboxes in their drive train. Enercon is the dominant manufacturer in DD wind turbines based on EESGs.

A key advantage of DD permanent magnets is that by eliminating the gearbox they enable a reduction in size, and thus a reduction in the turbine's overall weight, increasing its attractiveness in offshore applications. In addition, by replacing the mechanical failure-prone gearbox with permanent magnets, direct drive turbines utilise a simple, more reliable design that allows them to operate at lower speeds, be more efficient and requires less maintenance (Carrara et al. 2020).

In the future, DD turbines could additionally be based on high temperature super conductors (HTS). (Carrara et al. 2020). Gains associated with this technology include improvements in performance owing to a decrease in weight and savings in terms of neodymium and dysprosium consumption. However, moving towards this option, in particular at offshore locations where it can be most beneficial, continues to depend on cost reductions and further technological progress (Månberger and Stenqvist 2018).

Table 4: Overview of wind turbine technologies
Source: Carrara et al. 2020.

Type of generator	Type of turbine	Application
Direct Drive	*High temperature Superconductors (HTS)*	*Offshore*
Direct Drive	Electrically Excited Synchronous Generators (EESG)	Onshore

Type of generator	Type of turbine	Application
Geared Drive Train	Electrically Excited Synchronous Generators (EESG)	Onshore
Direct Drive	Permanent Magnets Synchronous Generation (PMSG)	Onshore and Offshore
Geared Drive Train	Permanent Magnets Synchronous Generation (PMSG)	Onshore and Offshore
Geared Drive Train	Doubly-Fed Induction Generators (DFIG)	Onshore and Offshore
Geared Drive Train	Squirrel Caged Induction Generators (SCIG) – without full converter	Onshore
Geared Drive Train	Squirrel Caged Induction Generators (SCIG) – with full converter	Offshore
Geared Drive Train	Wound-Rotor Induction Generators (WRIG)	Onshore

Note: Technologies which are no longer relevant but that were widely adapted in previous decades are highlighted in dark blue. HTS technology in italics is not yet marketed.

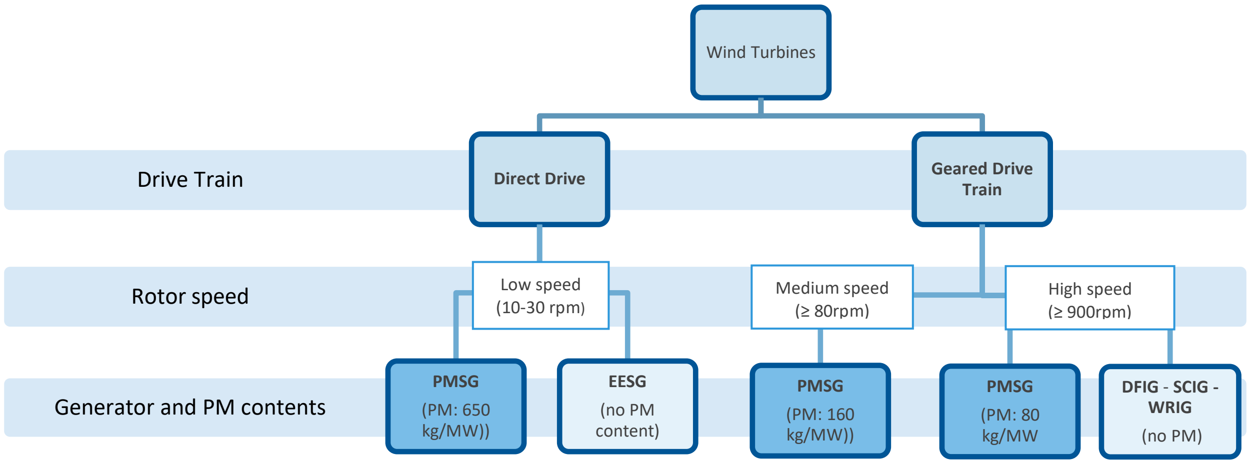


Figure 8: Wind Turbine Configuration and Permanent Magnets (PM) Content (Source: Pavel et al. 2017a)

DRIVE TRAIN TECHNOLOGY TRENDS

In 2018, permanent magnet turbines accounted for the totality of the European offshore market and 76% of the global market. The direct drive low speed PMSG configuration in particular was most widely adopted. In the onshore market, turbines were largely based on the traditional the geared high speed DFIG technology, which accounted for 34% and 52% of the EU and global installed capacities, respectively. Permanent magnets have been gaining market shares, but they are still less widespread, accounting for 30% and 32% of the EU and global markets, respectively (JRC wind database).

The offshore market has been characterised by distinct phases, common to both the EU and global level. From the beginning of the 1990s to the beginning of the 21st century, the market was monopolised by the geared high speed SCIG turbines. These were abruptly replaced by geared high speed DFIG turbines, which were in turn displaced due to the widespread adoption of geared high speed SCIG turbines around

2007. These turbines are themselves now being replaced by permanent magnet turbines (Carrara et al. 2020).

On the other hand, technology adoption developed gradually in the onshore sector leading to a better balanced mix of technologies. Geared high speed SCIG and geared high speed WRIG turbines were progressively phased out over the years, as geared high speed DFIG gradually gained market shares (51% on average since the beginning of the century at EU level, 57% at global level), and is now itself being challenged by the rise of permanent magnet turbines (Carrara et al. 2020).

Figures 9 and 10 show the EU28 trend of installed capacity per wind turbine type for onshore and offshore respectively.

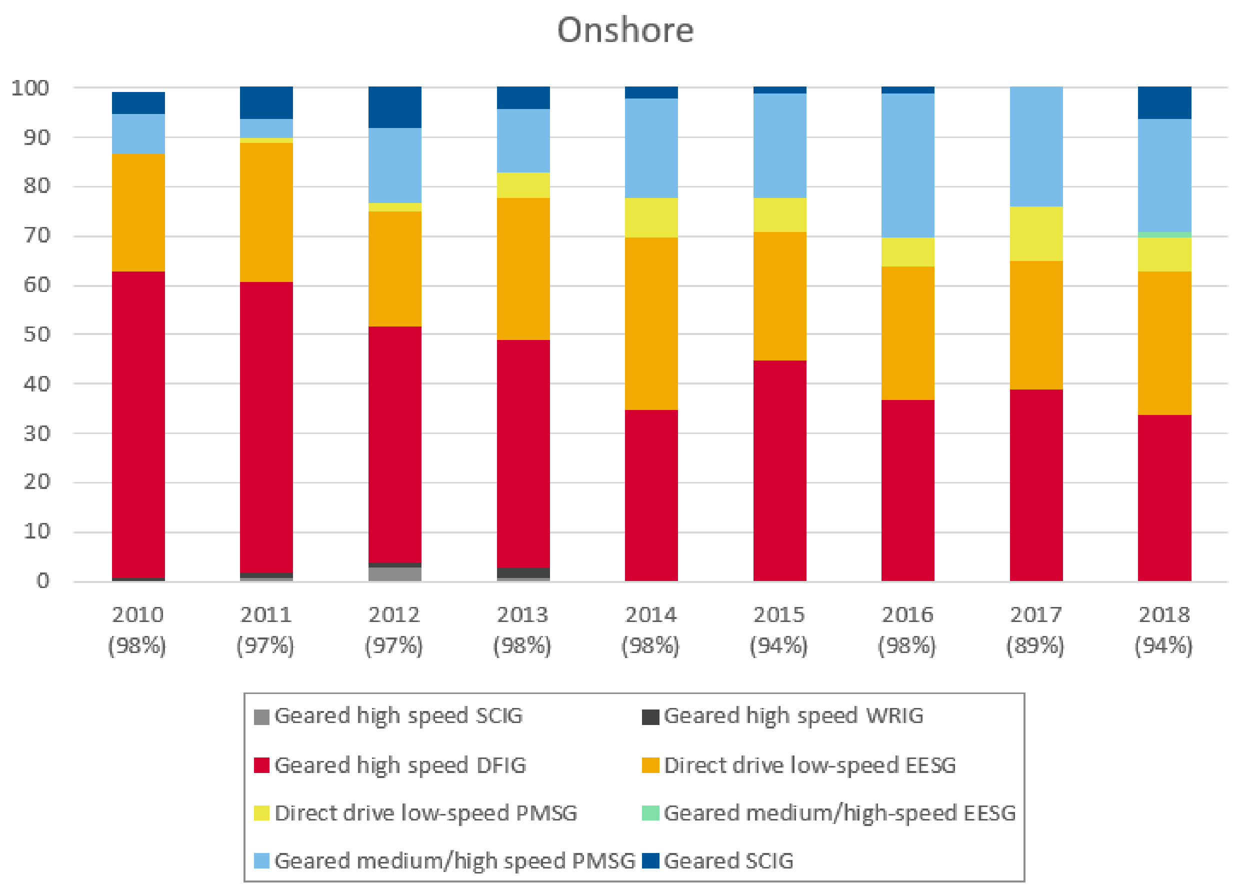


Figure 9: Share of Installed Capacity in Onshore Wind Turbines in EU28 by Drive Train Configuration. In brackets, for each year, the value for data completeness. Source: JRC database

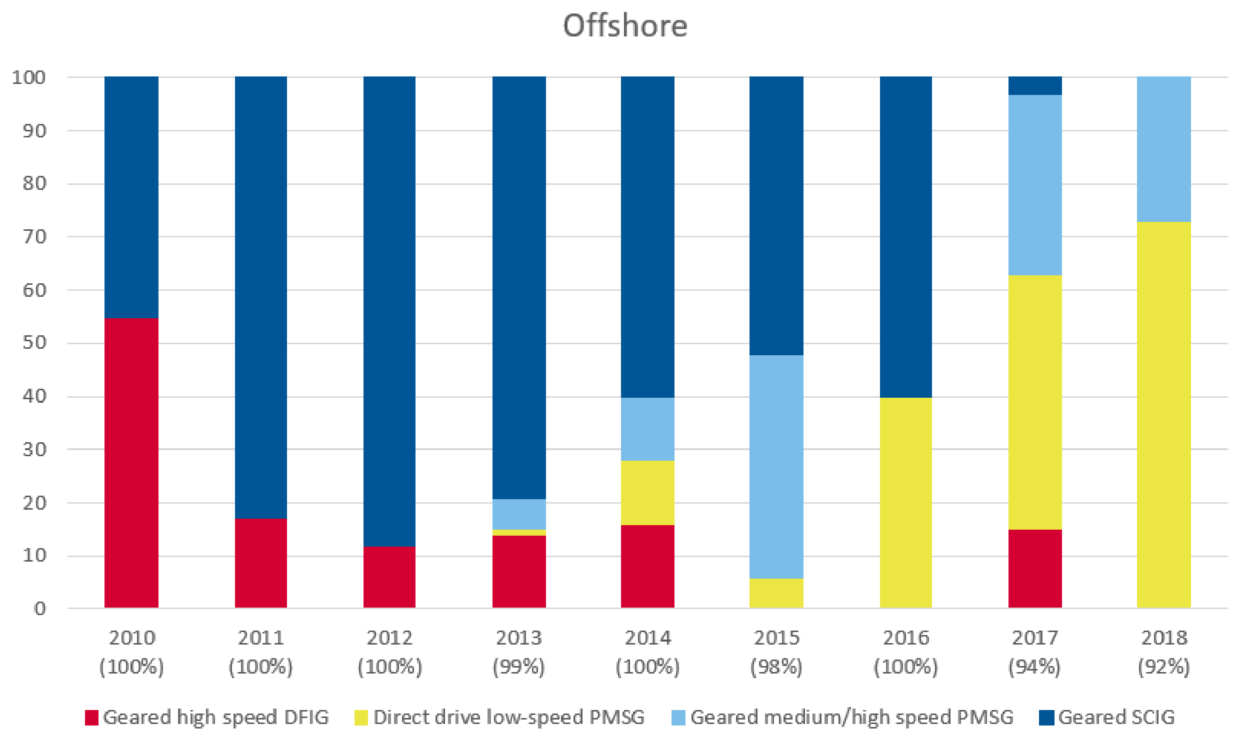


Figure 10: Share of Installed Capacity in Offshore Wind Turbines in EU28 by Drive Train Configuration. In brackets, for each year, the value for data completeness. Source: JRC database

Wind turbines equipped with PM generators faced a substantial increase in their application in the last years. In 2009 the global market share of wind turbine using PM generators was 1% while the projections foreseen the share to grow up to 20% by 2030 following a linear increase. This figure has been proven wrong as PM generators spread much faster.

Tables 5 and 6 present the EU market share of DD-PMSG and geared PMSG for onshore and offshore wind in 2018, 2030 and 2050 as estimated by the Joint Research Centre (JRC) of the European Commission (Carrara et al. 2020).

Table 5: EU Market Share of PM-based Wind Turbines – Onshore (JRC scenarios)

		2018 (%)	2030 (%)	2050 (%)
DD - PMSG	**LDS***	7%	10%	13%
	MDS**	7%	15%	20%
	HDS***	7%	21%	26%
Geared PMSG (high and medium-speed)	**LDS**	23%	31%	39%
	MDS	23%	31%	39%
	HDS	23%	31%	39%

Table 6: EU Market Share of PM-based Wind Turbines – Offshore (JRC scenarios)

		2018 (%)	2030 (%)	2050 (%)
DD - PMSG	LDS	73%	36%	32%
	MDS	73%	58%	56%
	HDS	73%	87%	87%
Geared PMSG (high and medium-speed)	LDS	27%	12%	12%
	MDS	27%	12%	12%
	HDS	27%	8%	8%

Notes on Tables 5 and 6: The methodology used to develop each scenario is as follows:

- **Low Demand Scenario (LDS): Extrapolation based on historical time series (focusing on the period post 2000) with an uptake of offshore HTS generator.*
- ***Medium Demand Scenario (MDS): Extrapolation based on historical time series (same period as above) modified to accommodate a higher penetration of generators with permanent magnets (notably direct drive) in the offshore sector and, to a lesser extent, in the onshore sector.*
- ****High Demand Scenario (HDS): For the offshore, mixes of sub-technologies in future energy scenarios are assumed to substantially mimic's today's average values at global level. For the onshore, technology replacement rates are based on historical time series (same as above) modified to accommodate a higher deployment of turbines with permanent magnets (again, notably direct drive).*

FUTURE DEMAND OF REE FROM THE WIND INDUSTRY IN THE EU

To assess the future demand of REE from the wind industry, the JRC used three scenarios considering four factors: power generation capacities, plant lifetime, sub-technology market shares and material intensity as detailed in Table 7.

Table 7: JRC EU scenarios (Carrara et al. 2020)

	Low Demand Scenario (LDS)	Medium Demand Scenario (MDS)	High Demand Scenario (HDS)
Power generation capacities	EU long term strategy (LTS) Baseline Scenario - Considers the EU legally binding 2030 targets and aims to achieve a 64% reduction in GHG emissions by 2050.	EU LTS 1.5 °C Technical Scenario - Considers the EU legally binding 2030 targets (hence it is identical to the LTS Baseline Scenario until that time) and aims to	JRC-EU-TIMES Zero Carbon Scenario - Considers almost complete decarbonisation by 2050 and greater decarbonisation by 2030 than the LTS, in line with the 55% objective laid out in the European Green Deal.

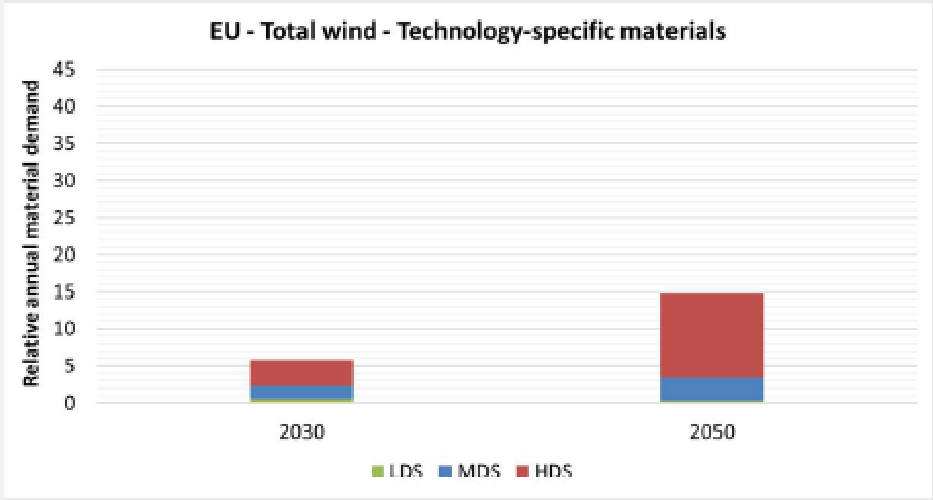
		achieve a 100% reduction in GHG emissions by 2050.	
Plant lifetime	30 years for onshore 35 years for offshore	25 years for onshore 30 years for offshore	20 years for onshore 25 years for offshore
Sub-technology market shares	As per Tables 5 and 6	As per Tables 5 and 6	As per Tables 5 and 6
Material intensity	An annual 5% reduction	An annual 2% reduction	A constant level of material intensity

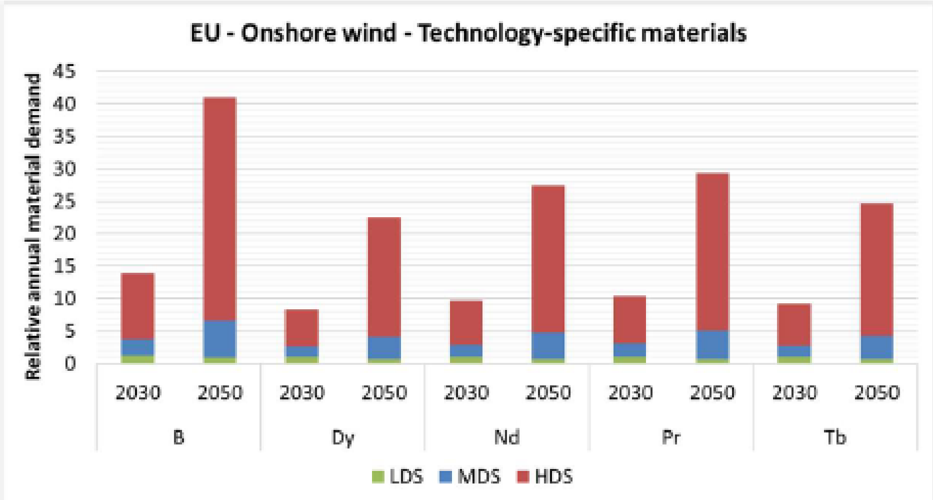
In terms of material intensity, current research (Pavel et al. 2016) indicates that the quantity of neodymium and praseodymium needed to produce NdFeB permanent magnets might decrease in the future. This might be reached by a common effort in research and new developments in material efficiency (reduction in the average size of the permanent magnets) and substitution strategies (reduction of the REE share in permanent magnets). Lacal-Arántegui (2015) estimate the neodymium/praseodymium content in NdFeB permanent magnets at equal magnetic density might fall from 29 % in 2015 **down to 20 % by 2030**. The JRC considered the following hypothetical situations: an annual 5% reduction in the LDS, an annual 2% reduction in the MDS and a constant level of material intensity in the HDS. The following breakdown of materials was applied for the baseline year (2018): 29% for neodymium, 4% for dysprosium, 1% for boron and 66% for iron of the weight of a rare-earth permanent magnet.

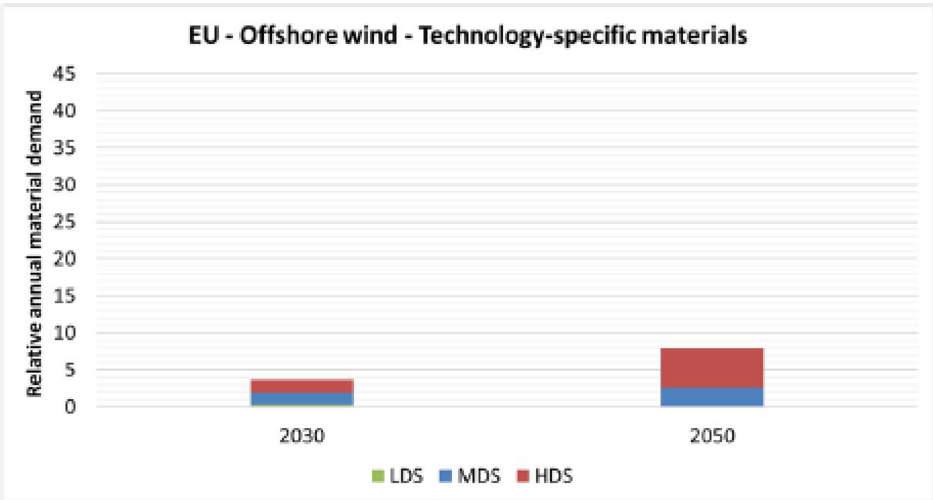
Figure 15 of the JRC report (Carrara et al. 2020 - reproduced below), presents the annual demand of rare earths materials (and boron) for wind energy in the EU. The data is presented both as aggregated wind demand and as individual onshore and offshore contributions. Data for 2030 and 2050 are shown in terms of a scale factor of the current (2018) demand, with the exact value of the current demand reported in the table.

Figure 15. Annual EU demand for technology-specific materials in 2018 in t/year (table, left) and relative demand in 2030 and 2050 as a ratio of current demand (charts, right) for total (top), onshore (middle) and offshore (bottom) wind

B	Total	23
	Onshore	5
	Offshore	18
Dy	Total	95
	Onshore	42
	Offshore	53
Nd	Total	857
	Onshore	305
	Offshore	552
Pr	Total	150
	Onshore	49
	Offshore	101
Tb	Total	32
	Onshore	12
	Offshore	20







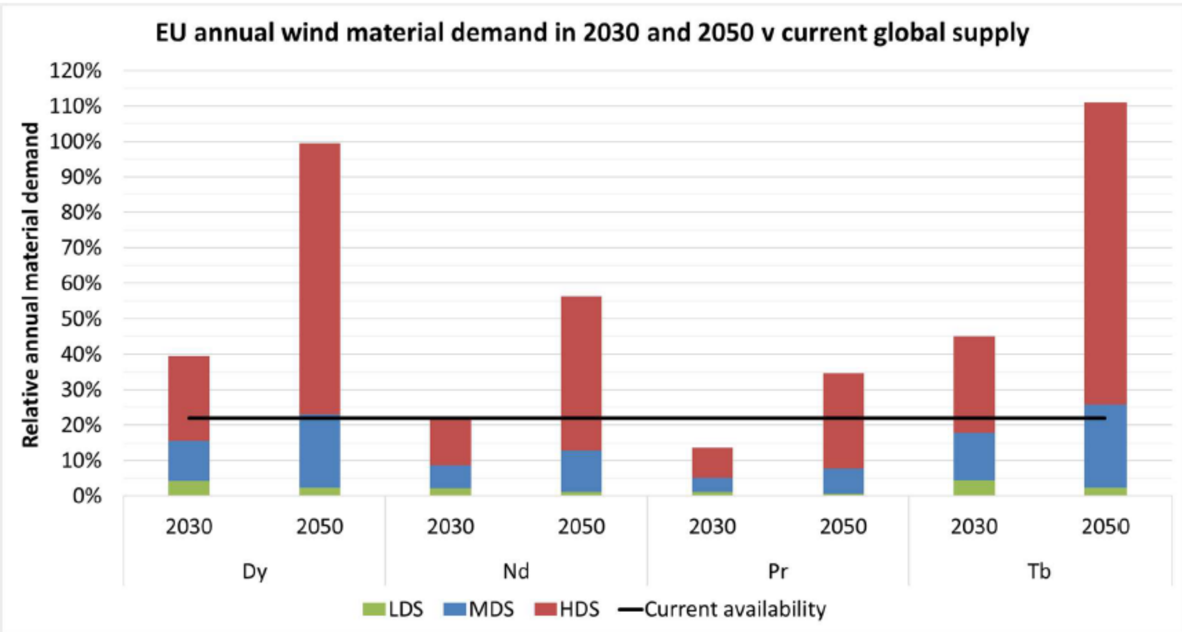
Source: JRC analysis.

To evaluate the potential for supply risks, the JRC plotted the predicted wind material demands as a proportion of the current global supply (Figure 16 of the JRC report, reproduced below). The aggregated wind material demands are split based on the ratio of demand to current supply.

The potential for supply risk is assessed by comparing the relative demand with an indicative availability threshold. A reference value of 22% was taken as the threshold, assuming that the EU's access to the supply market for raw materials or components is proportional to its share of the global gross domestic product. Although this assumption is likely to be incorrect, it provides a general idea of whether a material could be subject to supply risks or not.

The estimated increase in demand for Dy, Nd, Pr and Tb is above or close to the current supply levels, with Dy and Tb overcoming the availability threshold in the MDS in 2050. Pr poses the least supply risks. In these results, the threshold is indicative of the current supply for all technologies, not just wind energy. The JRC therefore concludes that the deployment of wind turbines according to EU plans alone would require most of the Dy, Nd, Pr and Tb currently available for the EU at global level.

Figure 16. EU wind demand-to-global supply ratio for 2030 and 2050 – levels of demand close to current availability

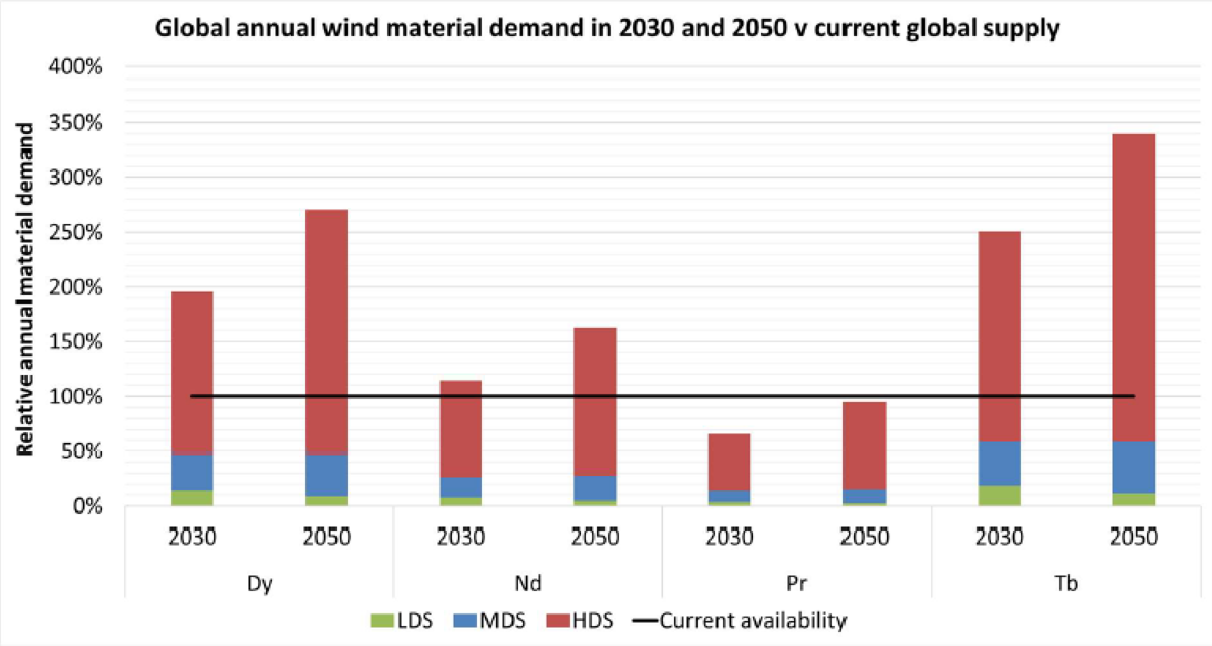


Source: JRC analysis.

FUTURE DEMAND OF REE FROM THE WIND INDUSTRY AT GLOBAL LEVEL

The JRC did a similar analysis for global demand of REE. The current global supply, equivalent to 100% in the figure below, was used as the indicative availability threshold. As with the EU, the estimated increase in demand for Dy, Nd, Pr and Tb is above or close to the current supply levels. However, the MDS demand level is far from the availability threshold in both 2030 and 2050. Still, considering that only the needs of wind technologies are compared with the whole global supply, the deployment of the predicted number of wind farms (in the global MDS) alone may require up to half of the current global supply.

Figure 20. Global wind demand-to-global supply ratio in 2030 and 2050 – levels of demand close to current availability



Source: JRC analysis.

OTHER MARKETS

The markets for wind power, electric vehicles, NiMH batteries, and catalytic converters will face continuous growth to a different degree. Nd and Dy oxides will play an increasingly more important role in the development of clean energy in the future.

Regarding the **automotive sector**, PM synchronous-traction motors is the most common technology. An electric vehicle for personal transportation needs between 1 and 2 kg of NdFeB, depending on the model (Speirs et al. 2013). In 2015, about 550,000 cars were sold, requiring up to 1,100 t of NdFeB. To meet the global deployment target of 7.2 million electric vehicle sales in 2020 (IEA, 2013), the industry will require between 7,200 and 14,400 t of NdFeB in 2020. This translates into an increase of PM demand from the car sector up to 14 times in only 5 years. Hybrid electric vehicles (HEV) will also play an important role. Pavel et al. (2017b) estimated that in 2020 the HEV market will require 2,650 t of NdFeB magnets (3.15 million vehicles). In total, including also electric bikes, **11,500 to 34,500 t of NdFeB magnets** might be required globally for electric road transport in 2020 (over two times the amount required in 2015), representing up to **30% of expected global NdFeB supply in 2020** (Pavel et al. 2017b). Dy poses the highest risk as up to 75% of its 2020 supply might be required to meet the global electric road transport demand. Substitution strategies are very important in the sector, allowing a potential reduction of REE required by up to 75% for Nd and 80% for Dy.

EU CRITICAL RAW MATERIALS ACTION PLAN

In September 2020, the EU updated its critical raw materials list (Table 8). This list is a factual tool to support EU policy development, in particular: trade policy, research & innovation (e.g. support for new mining technologies, substitution and recycling), and industrial policy. Two criteria determine a material's inclusion in the list a) economic importance and b) supply risk. As shown on Figure 11, Dy, Nd, Pr and Tb are considered to be at very high supply risk and medium to high economic importance.

In September 2020, the European Commission (EC) also launched its [Critical Raw Materials Action Plan](). It identifies 10 actions to:

- support resilient value chains for EU industrial ecosystems;
- reduce dependency through circularity and substitution;
- strengthen responsible extraction and processing of raw materials in the EU – with a focus on reorienting coal mining regions to other mining activities; and
- diversify third country suppliers.

The full list is provided below. Importantly, Action 1 announces a new **European Raw Materials Alliance, which will initially focus on increasing EU resilience in the rare earths and magnets value chain**.

Table 8: EU List of Critical Raw Materials 2020

EU List of Critical Raw Materials		
Strontium*	Titanium*	Bauxite*
Lithium*	Antimony	Light rare earth elements*
Phosphorous	Baryte	Gallium
Magnesium	Scandium	Beryllium
Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber
Tantalum	Borate*	Niobium
Tungsten	Cobalt*	Heavy rare earth elements*
Platinum group metals	Vanadium	Coking coal
Indium	Phosphate rock	Fluorspar

* New in 2020, in addition to 2017 list *Present in wind turbines

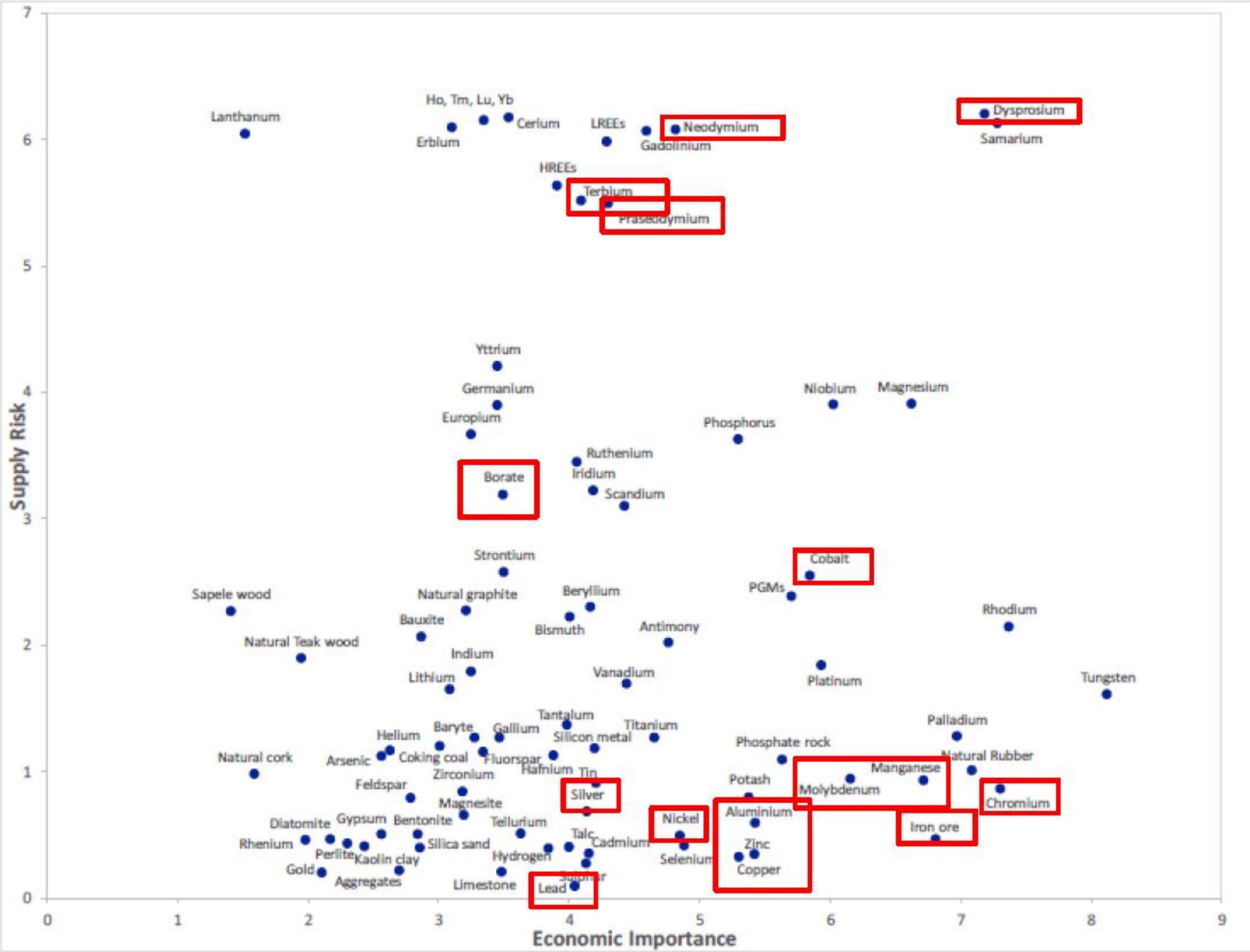


Figure 11: Supply risk and economic importance results for all individual and grouped materials. Those present in wind turbines are highlighted in red. Source: EC, 2020

EU CRITICAL RAW MATERIALS ACTION PLAN

Action 1 – Launch an **industry-driven European Raw Materials Alliance** in Q3 2020, initially to build resilience and open strategic autonomy for the rare earths and magnets value chain, before extending to other raw material areas (industry, Commission, investors, European Investment Bank, stakeholders, Member States, regions).

Action 2 – **Develop sustainable financing criteria for the mining, extractive and processing sectors** in Delegated Acts on Taxonomy by end 2021 (Platform on Sustainable Finance, Commission).

Action 3- Launch **critical raw materials research and innovation in 2021 on waste processing, advanced materials and substitution**, using Horizon Europe, the European Regional Development Fund and national R&I programmes (Commission, Member States, regions, R&I Community).

Action 4 - **Map the potential supply of secondary critical raw materials from EU stocks and wastes** and identify viable recovery projects by 2022 (Commission, EIT Raw Materials).

Action 5 - **Identify mining and processing projects and investment needs and related financing opportunities** for critical raw materials in the EU that can be operational by 2025, with priority for coal-mining regions (Commission, Member States, regions, stakeholders);

Action 6 – **Develop expertise and skills in mining, extraction and processing** technologies, as part of a balanced **transition strategy** in regions in transition from 2022 onwards (Commission, industry, trade unions, Member States and regions);

Action 7 - Deploy **Earth-observation programmes and remote sensing** for resource exploration, operations and post-closure environmental management (Commission, industry).

Action 8 – Develop **Horizon Europe R&I projects on processes for exploitation and processing of critical raw materials** to reduce environmental impacts starting in 2021 (Commission, R&I community).

Action 9 – Develop **strategic international partnerships** and associated funding to secure a diversified and sustainable supply of critical raw materials, including through undistorted trade and investment conditions, starting with pilot partnerships with Canada, interested countries in Africa and the EU's neighbourhood in 2021 (Commission, Member States, industry and third country counterparts).

Action 10 - **Promote responsible mining practices** for critical raw materials through the EU regulatory framework (proposals in 2020-2021) and relevant international cooperation (Commission, Member States, industry, civil society organisations).

FUTURE SUPPLY AND TECHNOLOGIES

It is clear REE demand is likely to increase in the coming years. Still, projections are subject to a margin of uncertainty. The spread of new technologies and improvements in material design for the automotive, renewables and storage sectors (among others) will be dependent on regulatory frameworks (import/export quotas, improvement in mining practices) as well as performance, cost and consumer preferences related to the single products.

The technological improvements on substitution and recycling will decrease the supply and mining activities of rare earths. From a policy perspective, the elimination of export regulations, including export quotas and export taxes, does have a negative impact on China's future domestic supply of rare earths.

REE known reserves could sustain the global REE production at the current pace for more than a hundred years. Nd and Dy demand will strongly influence the exploration of new REE projects and clean technologies in the next decades.

Zhou et al. (2017):

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

Superconducting generators may potentially be an alternative to permanent magnet generators i.e. a substitution strategy. Indeed, superconductors exhibit virtually zero resistance, allowing the circulating current in the windings to be increased as well as achieving higher air-gap flux densities. In this case, the volume of the machine can be reduced by a factor of two to three compared with traditional machines. Despite the attractive advantages offered by superconductors, there are also substantial uncertainties and challenges, mainly related to the necessary cooling systems and costs.

Recycling, is a source for many critical materials. Recycling REEs from primary ores, end-of-life consumer products, landfills, and scrap formed in rare earth oxides, metals, and material production are recognised as valuable ways to bring REE markets into balance (Binnemans et al. 2013; Binnemans and Jones 2015) and thus as positive and effective techniques for reducing the harmful environmental effects of REE mining. REE recycling is therefore receiving more and more attention from governments and businesses as a solution to potential future supply constraints and a way of reducing environmental impacts.

At present no commercial operation has been identified for recycling end-of-life NdFeB permanent magnets and the recovery of the associated REE content. Most of the processing methods are still at various research and development stages. Yang et al. (2017) estimate that approximately 5-10 years are required for commercialisation of recycling technologies. In addition, they note that secondary supply from recycling would only likely meet 50 % of the global demand by 2100. A brief summary of the key existing recycling routes for REE identified by Yang et al. (2017) is provided below.

Direct Alloy Recycling Routes

If a clean, nonoxidized form of scrap NdFeB magnets can be separated from the end of life products, in the form of a hydrogenated powder, or as a solid magnet, then it is possible to reprocess the material directly from the alloy using the following routes: resintering of the powder; melt spinning; hydrogenation disproportionation desorption and recombination (HDDR) processing or recasting back into a master alloy. These direct alloy recycling routes are used in the primary production of magnets but require some modification to handle secondary materials. It should be noted that these routes are not suitable for shredded material as the contamination levels of the hydrogenated powder will be very high.

Metallurgical Extraction and Separation

Except for the large NdFeB magnets used in wind turbines and electric motors of electric vehicles, direct alloy recycling will be difficult and impractical for the rest of applications (e.g. home electrical appliances and consumer electronics) due to their small size and mix of different magnet types (ferrites, SmCo and NdFeB). Metallurgical processes such as hydrometallurgical, pyrometallurgical or electrochemical, or combinations of these techniques are being investigated instead. Studies so far have focused on the highly concentrated and relatively clean waste magnets from manufacturing scrap (production waste) and not of waste magnets from end-of-life products. Pre-dismantling and up-concentration through physical processing will be critical for viable metallurgical extraction from end-of-life products.

REFERENCES

Adamas Intelligence 2016, 'Rare earth market outlook—Supply, demand, and pricing from 2016 through 2025', *Adamas Intelligence Publications*. Available from https://metalevents.com/rare-earths-community/rare-earth-market-outlook-supply-demand-and-pricing-from-2016-through-2025-from-adamas-intelligence [09 August 2019].

Adamas Intelligence 2019, 'Rare Earth Elements: Market Issues and Outlook". *Adamas Intelligence Publications.*

Ali, SH, 2014, 'Social and Environmental Impact of the Rare Earth Industries', *Resources,* vol. 3, pp. 123-134.

BCC Research, 2015, 'Rare earths: Worldwide markets, applications, technologies', *BCC Research Report: AVM018H*, pp. 244 plus appendices. Available from: https://www.bccresearch.com/market-research/advanced-materials/rare-earths-markets-applications-technologies-report.html [09 August 2019].

Benecki WT 2013, 'The permanent magnet market – 2015' PowerPoint presentation at the Magnetics 2013 Conference [7-8 February 2013]. Available from: http://www.waltbenecki.com/uploads/Magnetics_2013_Benecki_Presentation.pdf [09 August 2019].

Binnemans, K, Jones, PT, Blanpain, B, Van Gervern, T, Yang, Y, Walton, A & Buchert, M 2013, 'Recycling of rare earths: a critical review', *Journal of Cleaner Production*, vol. 51, pp. 1-22.

Binnemans, K & Jones, PT 2015, 'Rare earths and the balance problem', *Journal of Sustainable Metallurgy*, vol 1, pp. 29-38.

Blagoeva, DT, Alves Dias, P, Marmier, A & Pavel, CC 2016, 'Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030', *Joint Research Centre (JRC) of the European Commission*, EUR 28192 EN, doi:10.2790/08169.

Carrara, S, Alves Dias, P, Plazzota, B, Pavel, CC 2020, 'Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system', *Joint Research Centre (JRC) of the European Commission*, EUR 30095 EN, doi:10.2760/160859.

Danish Environmental Protection Agency, 2018, 'Designing out waste – Chapter 13: Circularity and rare earth elements in the wind industry' Available from: https://www2.mst.dk/Udgiv/publications/2018/10/978-87-93710-90-0.pdf [13 August 2019].

EC, 2020, 'Study on the EU's list of Critical Raw Materials'. Available from: file:///C:/Users/Marylise.Schmid/Downloads/CRM%20list%202020_Final%20Report.pdf

ERECON 2014, 'Strengthening the European rare earths supply-chains: Challenges and policy options', Kooroshy, JG, Tiess, A & Walton A (eds). Available from: https://reinhardbuetikofer.eu/wp-content/uploads/2015/03/ERECON_Report_v05.pdf [01 October 2019]

EURARE 2013, 'EURARE: Development of a sustainable exploitation scheme for Europe's REE ore deposits', PowerPoint presentation. Available from: http://promine.gtk.fi/documents_news/promine_final_conference/8_50_PASPALIARIS_EURARE_project_promine.pdf. [09 August 2019].

Geological Survey of Sweden, 2018, 'Mapping of innovation-critical metals and minerals'. Available from https://www.sgu.se/en/about-sgu/news/2018/december/mapping-of-innovation-critical-metals-and-minerals/ [13 August 2019].

Global Wind Energy Council (GWEC), 2016, 'Global Wind Energy Outlook 2016', Available from https://gwec.net/publications/global-wind-energy-outlook/global-wind-energy-outlook-2016/ [09 August 2019].

Global Wind Energy Council (GWEC), 2017, 'Global Wind Statistics 2016', Available from https://gwec.net/wp-content/uploads/vip/GWEC_PRstats2016_EN_WEB.pdf [09 August 2019].

Growth Analysis, 2017, 'Innovation-critical metals & minerals from extraction to final product – how can the state support their development?', *Growth Analysis Publications*. Available from https://www.tillvaxtanalys.se/in-english/publications/reports/reports/2017-11-23-innovation-critical-metals--minerals-from-extraction-to-final-product---how-can-the-state-support-their-development.html [13 August 2019].

Gupta, CK, & Krishnamurthy, N 2015, *Extractive Metallurgy of Rare Earths*, Taylor & Francis, Abingdon.

Gutfleisch, O, Willard, MA, Brück, E, Chen, CH, Sankar, SG & Liu JP, 2011, 'Magnetic materials and devices for the 21st century: Stronger, lighter, and more energy efficient', *Advanced Materials*, vol. 23, pp. 821-842.

International Energy Agency (IEA), 2013, 'Global EV outlook: Understanding the electric vehicle landscape to 2020', *IEA Publications*. Available from: https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook_2013.pdf [09 August 2019]

Lacal-Arántegui, R 2015, 'Materials use in electricity generators in wind turbines– state-of-the-art and future specification', *Journal of Cleaner Production*, vol. 87, pp. 275-283.

Lacal-Arántegui, R & Serrano-González, J, 2015, '2014 JRC wind status report' *Joint Research Centre (JRC) of the European Commission*, EUR 27254 EN, doi:10.2790/676580.

Lucas, J, Lucas, P, Le Mercier, T, Rollat, A & Davenportet, WG 2015, *Rare Earths: Science, Technology, Production and Use*, Elsevier, Amsterdam.

Månberger, A, & Stenqvist, B, 2018, 'Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development', *Energy Policy*, vol. 119, pp. 226-241.

McLellan, BC, Corder, GD, Golev, A. & Ali, SH, 2014, 'Sustainability of the Rare Earths Industry', *Procedia Environmental Sciences*, vol. 20, pp. 280-287.

Pavel, CC, Lacal-Arántegui, R, Marmier, A, Schüler, D, Tzimas, E, Buchert, M, Jenseit, W & Blagoeva D 2017a, 'Substitution strategies for reducing the use of rare earths in wind turbines', *Resources Policy*, vol. 52, pp. 349-357.

Pavel, CC, Thiel, C, Degreif, S, Blagoeva, D, Buchert, M, Schüler, D & Tzimas, E 2017b, 'Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications', *Sustainable Materials and Technologies*, vol. 12, pp. 62-72.

Pavel, CC, Marmier, A, Alves Dias, P, Blagoeva, D, Tzimas, E, Schüler, D, Schleicher, T, Jenseit, W, Degreif, S & Buchert, M 2016, 'Substitution of critical raw materials in low-carbon technologies: lighting, wind turbines and electric vehicles', *Joint Research Centre (JRC) of the European Commission*, EUR 28152 EN, doi:10.2790/793319.

Roskill 2016, 'Rare earths: Global industry, markets & outlook (16th ed.)', London, UK: Roskill.

Roskill 2019, 'Rare Earths Outlook to 2029, 19th Edition', London, UK:Roskill.

Smith Stegen, K 2015, 'Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis', *Energy Policy*, vol. 79, pp. 1-8.

Speirs, J, Houari, Y, Contestabile, M, Gross, R & Gross, B 2013, 'Materials availability: potential constraints to future low-carbon economy. Working paper II: batteries, magnets and materials', *UKERC Publications,* UKERC/WP/TPA/2013/003, Available from: http://www.ukerc.ac.uk/publications/materials-availability-potential-constraints-to-the-future-lowcarbon-economy-working-paper-ii-batteries-magnets-and-materials.html [09 August 2019]

Takaya Y, Yasukawa, K, Kawasaki, T, Fujinaga, K, Ohta, J, Usui, Y Nakamura, K, Kimura, J-I, Chang, Q, Hamada, M, Dodbiba, G, Nozaki, T, Iijima, K, Morisawa, T, Kuwahara, T, Ishida, Y, Ichimura, T, Kitazume, M, Fujita, T & Kato Y 2018, 'The tremendous potential of deep-sea mud as a source of rare-earth elements', *Scientific Reports*, vol. 8, art. nb. 5763, doi:10.1038/s41598-018-23948-5.

U.S. Geological Survey (USGS) 2011, *2011 Mineral Commodity Summaries*. Available from https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/rare-earth/mcs-2011-raree.pdf. [09 August 2019].

U.S. Geological Survey (USGS) 2020, *Mineral Commodity Summaries 2020*. Available from https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf. [28 April 2020].

U.S. Geological Survey (USGS) 2019, *2016 Minerals Year Book: Rare Earths [Advance Release]*. Available from: https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-raree.pdf [29 April 2020].

Vázquez Hernández, C, Telsnig, T, Villalba Pradas, A, 2017, 'JRC Wind Energy Status Report 2016 Edition: Market, technology and regulatory aspects of wind energy', *JRC Wind Energy Status Report 201 Joint Research Centre (JRC) of the European Commission*, EUR 28530 EN, doi:10.2760/332535.

Yang, Y, Walton, A, Sheridan, R, Güth, K, Gauß, R, Gutfleisch, O, Buchert, M, Steenari, B-M, et al., 2017, 'REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review', *Journal of Sustainable Metallurgy,* vol. 3(1), pp. 122-149.

Zhou, B, Li, Z & Chen, C 2017 'Global potential of rare earth resources and rare earth demand from clean technologies', *Minerals*, vol. 7(11), pp. 203.

Zhou, B, Li, Z, Zhao, Y, Zhang, C & Wei, Y 2016 'Rare Earth Elements supply vs. clean energy technologies: new problems to be solved', *Mineral Resources Management*, vol. 32(4), pp. 29–44.