IMT002-019 Wind Turbine Magnets Study

Wind turbine market and opportunities for recovery of neodymium magnets in Scotland

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Contents

1 Introduction

This report presents the findings from research conducted between December 2013 and March 2014 into the UK and Scottish wind market and the use of Neodymium (Nd) in certain types of turbines. This introduction section of the report sets out the project background and aims along with relevant information on magnets and wind turbines and the study aims and objectives.

1.1 Project Background

In recent years Scotland has set out its national ambition to drive greater resource circularity through a combination of policy, market intervention, guidance and support. In the recent communication on the Scottish Government's programme to create a more productive and circular economy[1], the objectives include stimulating innovation and business opportunities in re-use and remanufacture. This study considers the potential for Scottish intervention to create a circular economy for Neodymium-iron-boron (NdFeB) permanent magnets found in wind turbines.

Scotland has a strong renewables programme and plentiful wind resources on and offshore. This has led to the development of significant numbers of wind farms with the numbers set to grow substantially over the next decade. The wind turbines being deployed are highly advanced machines that use state of the art design and components to maximise their efficiency. Certain direct drive designs (i.e. those without a separate generator gearbox) use a series of powerful Neodymium-iron-boron (NdFeB) permanent magnets to generate electricity from the rotation of the rotors. These NdFeB magnets are amongst the most powerful in the world and can create lighter and more efficient generator assemblies that require lower levels of maintenance, ideal for offshore applications where up to £100m funding is now being directed to[2].

This in turn is leading to an increase in the size of turbines, furthering the efficiencies that can be gained. The Neodymium and Dysprosium used in the permanent magnets are both rare earth elements (REEs), which are costly to mine, process and purchase but are essential in some of the direct drive technologies now being employed. Housed within the nacelle of the wind turbine, these rare earth elements (up to 200 kilo per nacelle) may have a significant market value at end of life. With investment in wind energy in Scotland as well as targets and policies to significantly increase capacity, operational turbines may at some point in the future present a rich source of potentially recoverable, re-usable and recyclable rare earth elements, particularly Neodymium.

Neodymium (as with many REEs) is a commodity traded on the global materials market. Along with important catalyst elements such as rhodium, platinum and palladium, it has seen significant swings in its value over the past decade. In particular, the price spikes in 2010/11, which stemmed from the Chinese (which is estimated to control over 95% of the supply of Neodymium) confirming it was considering setting export quotas on some rare earth materials[3], led to significant supply chain resilience concerns amongst major manufacturers and users of NdFeB magnets (and Neodymium more widely).

In response to these concerns, major manufacturers in the wind market reacted by trying to secure supply chains through joint ventures (e.g. Siemens-Lynas processing plant in Malaysia), researching substitutes, stockpiling (leading to price deflation) and improving magnet design. US Geological Survey data estimates just over 19,000 tonnes of Neodymium was produced in 2009 but this supply level may not keep pace with rising demand. However there remains a high degree of uncertainty around the future forecast for rare earth production with some commentators now suggesting that the

[1] Scottish Government, 2013, Safeguarding Scotland's Resources: Blueprint for a more resource efficient and circular economy

[2] http://eandt.theiet.org/news/2014/mar/offshore-innovation.cfm

[3] http://www.techmetalsresearch.com/2013/12/the-first-round-of-chinese-rare-earth-export-quota-allocations-for-2014/

northern arctic zone (including Canada) may actually have the richest ores on the planet for rare earths (though not necessarily Neodymium). Due to the remote location, rare and sensitive arctic and tundra habitats there would be logistical and environmental challenges associated with the exploration and exploitation of these resources. As well as the obvious environmental impacts from mining, environmental campaigners have cited significant risk of environmental damage from contamination of water resources and habitat destruction. Shell announced in 2014 it was shelving its arctic oil exploration programme due to stakeholder pressures and lack of agreement around permitting of exploratory activities. It is likely we would see similar obstacles to widescale exploration of the arctic tundra in northern Canada, much of which remains in the ownership of the indigenous Inuit people.

Therefore, the supply chains built around China are likely to remain dominant for the foreseeable future and therefore issues of export quotas, restrictions, internal demand and ever increasing competition certainly feature in the analytical thinking being done by major corporate entities that are reliant on rare earths for their products.

Given the likely increases in offshore turbines for power generation of the Scottish coast there is a potential supply chain resilience concern with Neodymium that may limit growth of this sector in Scotland. Should the trends observed through this research prove accurate, Neodymium demand in both the wind and other sectors may become a critical supply issue. In respect of the wind market, this could hamper progress meeting the 2020 and 2030 renewables capacity targets set for Scotland. Combined with the research work demonstrating that Neodymium can be effectively recovered from magnet assemblies[4], this evidence guides Scotland towards consideration of potential interventions to enhance and encourage greater circularity of Neodymium at end of life. Figure 1 gives projected demand for rare-earth based magnets and clearly shows that use in turbines is likely to increase more relative to other use categories by 2020.

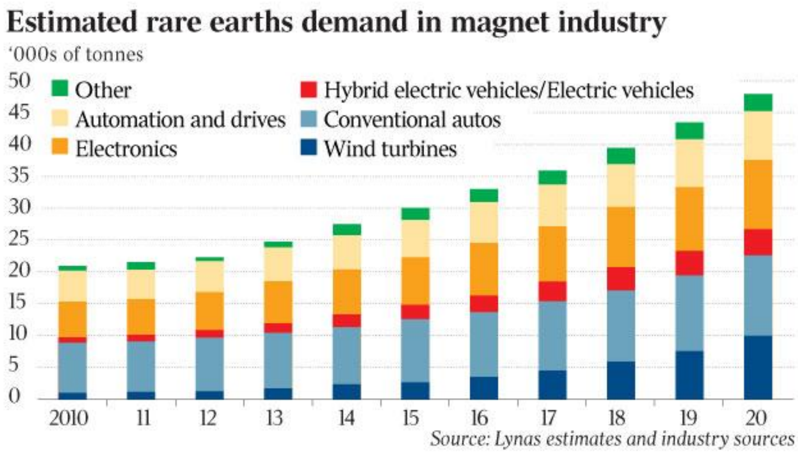


Figure 1: Projected demand for rare-earth materials in the worldwide magnet industry

1.2 Project aims

This report aims to provide a wind market analysis and to identify what potential interventions the evidence suggests could be made to create a circular economy for NdFeB turbine magnets in Scotland (if indeed such interventions are required). This has been divided into three tasks:

- Assess the wind turbine market and trends;
- Analysis of End-of-Life (EoL) recovery solutions for NdFeB magnets (found in wind turbines); and

[4] This research has been conducted by University of Birmingham and its partners to demonstrate effective techniques and technologies to recover Neodymium from the magnets of HDDs (hard disc drives), which offers a demonstration in principle but is likely to need assessment for scale-up to much larger magnet assemblies in turbine drives.

- Analyse the potential market interventions for NdFeB magnets in Scotland.

This purpose of this report is to inform Zero Waste Scotland on the volume of Neodymium used in the NdFeB magnets employed in direct drive technology wind turbines and to provide information on the possible future trends in wind turbine use and the associated increases in NdFeB (where these are used). The report also presents information on the opportunities and challenges for the re-use or recycling of Neodymium arising from EoL wind turbines based on the current evidence. The focus is on Scotland but by necessity includes commentary on the global situation as well as consideration of the wind market for the UK as a whole. Finally this report provides some commentary on where ZWS (or the Scottish Government) could intervene to create a circular economy for NdFeB magnets from wind farms (if any are required).

1.3 Report structure

Subsequent to this section this report is structured as listed below:

a Section 2, Assessment of the wind turbine market and forecast growth/trends in growth;
b Section 3, Analysis of End of Life (EoL) recovery solutions for NdFeB turbine magnets; and
c Section 4, Market analysis and possible interventions for NdFeB turbine magnets in Scotland.

2 Assessment of the wind turbine market and forecast growth/trends in growth

This section establishes the number of wind turbines currently installed in the UK, both on and offshore, and seeks to establish the current and future demand for direct drive wind turbines, along with the volume of Neodymium used and the potential for its recovery.

2.1 Turbine types and Neodymium (Nd) use

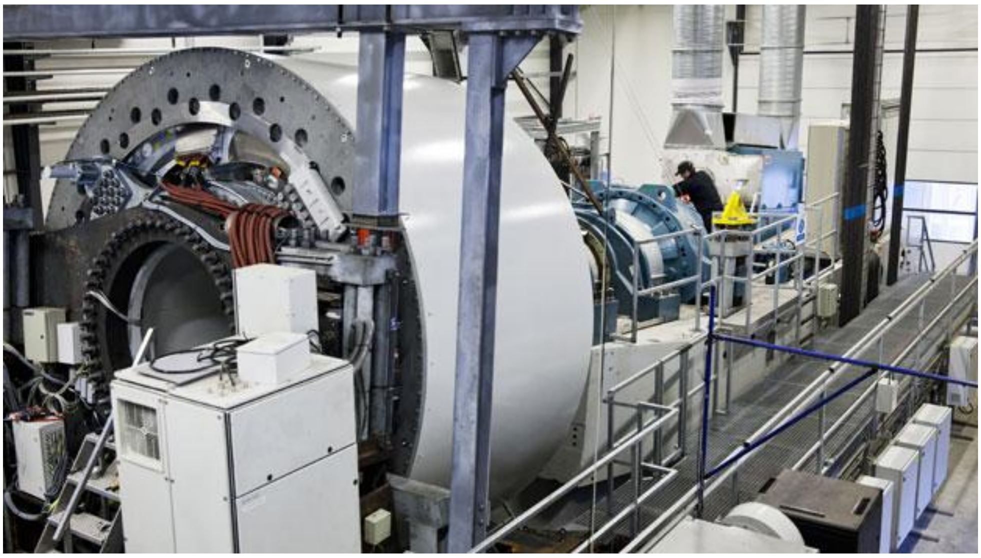
2.1.1 *Wind turbines*

A wind turbine is a device that converts kinetic energy from the wind into electrical power. Wind power has been used for millennia in a variety of forms from grinding corn to pumping water. Modern wind turbines are manufactured in a wide range of vertical and horizontal axis types and turbines are found in a huge variety of sizes, ranging from small battery charging types found on boats and caravans, to commercial scale devices capable of generating in excess of 6MW of power.

Today, only horizontal axis wind turbine (HAWT) designs are used in commercial scale wind farms, although some vertical axis designs are found for smaller domestic scale turbines. A HAWT consists of the main rotor shaft and electrical generator at the top of a tower, which points into the direction of the wind. Large turbines use wind sensors coupled with a servo motor to move the nacelle into the wind. Typically 3 blades are found on the nacelle, although some systems use a 2 bladed design.

Until relatively recently the predominant wind turbine design consisted of a gearbox that converted the relatively slow rotation of the blades into a quicker rotation suitable to drive an electrical generator. Recent developments in drive train technology have seen the development of direct drive permanent magnet generator [PMG] wind turbines, which replace the gearbox with permanent magnets. In a direct drive wind turbine the rotor hub and annular generator are connected directly to each other as a fixed unit without gears, whilst the rotor unit is mounted on a fixed axle. The PMG assembly is shown in the photograph below:

Image of a PMG wind turbine assembly



Source: BBC, courtesy of Siemens A.G.

The key drivers behind the development of direct drive wind turbines are that without the gearbox the turbine nacelle is significantly lighter (in terms of tens of tonnes) than with a traditionally driven turbine of the same size, and has less moving parts which therefore require less maintenance. It is however the case that whilst the nacelles are significantly lighter in a direct drive system, the nacelle itself if typically much larger when a PMG direct drive system is used. The increasing number of offshore wind turbines means that a lower maintenance, lighter drive train solution is an attractive proposition, given the scale of effort and cost associated with unscheduled maintenance at an offshore wind farm.

Permanent Magnet Generators

A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. Rare-earth magnets are strong permanent magnets made from alloys of rare earth elements. Developed in the 1970s and '80s, rare-earth magnets are the strongest type of permanent magnets made, producing significantly stronger magnetic fields than other types such as ferrite or alnico magnets. More detailed information on the materials used in PMGs is presented in Appendix A.

Use of Neodymium and Rare Earth Elements

Neodymium magnets, invented in the 1980s, are the strongest and most affordable type of rare-earth magnet. They are made of an alloy of Neodymium, iron and boron ($Nd_2Fe_{14}B$), sometimes abbreviated as NIB. Neodymium magnets are used in numerous applications requiring strong, compact permanent magnets, such as electric motors for cordless tools, hard drives, and magnetic hold-downs and more recently, PMG's for direct drive wind turbines.

Neodymium is mined as a rare earth material, although it not particularly rare itself. It is never found in nature as a free element, but rather it occurs in ores such as monazite and bastnäsite that contain small amounts of all the rare earth metals. The main mining areas for Nd are China, Brazil, USA and Australia, which at present represent the most economic areas to mine the ores due to the scale and accessibility of the deposits. Other ore-rich sources are known to exist (e.g. crustal rocks in the deep ocean seabed) but the difficulty in reaching and extracting the ore would mean prices would be have to be higher to cover extraction costs. Such materials would then struggle to compete with material mined from active on-shore sites.

2.2 Wind farm database evaluation

2.2.1 *Database development approach*

In order to establish the current and future usage of direct drive turbines in the UK market, the first stage was to develop a comprehensive and up to date database of all operational and consented wind farms in the UK. Research was undertaken that drew on external and internal sources of information, including AMEC's already established (live) wind farm database and knowledge of the UK and Scottish wind markets. The database was updated to incorporate information relating to the wind turbine manufacturer and turbine model at every operational site in the UK.

This was done by joining together AMEC's existing database with other databases at DECC, Renewable UK and www.thewindpower.net, as well as drawing on additional web research, trade magazines and existing manufacturer contacts.

Once the database was complete further research was undertaken into wind turbine drive train technology to understand:

1) Which manufacturers use direct drive technology and which use traditional gear box solutions.
    a. Of those that do, is it prevalent across all their product range or just a selection?
2) Do the manufacturers that use direct drive technology use PMG's which incorporate Neodymium?
3) What quantities of Neodymium are used in each turbine model's PMG?

Following this research, contact was made with the resulting manufacturers with a questionnaire to obtain additional information relating more specifically to points 2 and 3 above.

2.2.2 *Database evaluation*

Summary of Findings

Direct Drive Wind Turbines

Our research suggests that of all the manufacturers present within the UK market, the following use direct drive wind turbine models at least in some part across their model range:

- Enercon;
- EWT;
- GE;
- Siemens; and
- Vestas.

Of these, Enercon have confirmed that they do not use Neodymium in their direct drive wind turbines[5], rather they use a separately excited annular generator. The remaining manufacturers with any significant presence within the UK market all use gearbox based drive trains.

A detailed list of manufacturers / models is found within Appendix A. Of the onshore manufacturers only EWT, Siemens and Vestas have any significant number of direct drive turbines which use Neodymium within the UK market.

GE Wind Turbines.

In the past, GE wind turbines used direct drive technology (for its 2.5XL model). However the 1.5 and 2.5/2.75 series do not and have reverted to a doubly fed induction generator (DFIG)[6].

The GE 4.1 – 113 offshore wind turbine does use a direct drive PMG system; however none of these units have been installed in the UK to date.

Siemens Wind Turbines

Siemens is one of the UK market leaders and has a range of turbines within the country. Siemens produces direct drive wind turbines for both the onshore and offshore market, along with gearbox driven models. However the technology has only been used for the current generation of 3MW onshore, and 6MW offshore wind turbines, through the D3 and D6 platforms. The most prevalent onshore model, the Siemens SWT-2.3 series uses a gearbox[7]. Siemens continues to offer both gearbox and direct drive offshore wind turbines.

In 2011 Siemens and mining company Lynas launched a joint venture for the production of rare earth elements[8], in response to a sudden surge in rare earth element prices.

Vestas Wind Turbines

Vestas is an established company within the UK wind market, and has offered its mainstay V80 and V90 models for over ten years. Until recently these were only available in DFIG design but in 2011 a new product line, *Gridstreamer,* was offered alongside the traditional gearbox models for the 2MW

[5] http://www.enercon.de/en-en/1337.htm

[6] http://www.windpowermonthly.com/article/1153928/10-years-ge-goes-back-dfigs

[7] http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/platforms/

[8] http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2011/industry/i20110742.htm

and V112 3.0MW models. On launch, the new models used direct drive permanent magnets along with one planetary stage and two helical stages within the gearbox.[9] This means less rare earth material is required than in a traditional PMG direct drive machine.

EWT Wind Turbines

EWT produce mainly 500kW and 900kW wind turbines, which are popular with farmers and small (one or two turbine) projects. All their turbines are direct drive design which use permanent magnets, and there are over 70 installed in the UK. However these are sub 1.3MW and so are not included in the study figures. EWT have also recently released a 2MW direct drive model, however none have been installed in the UK to date.

Other Turbine Manufacturers

Of the remaining main players in the UK wind energy market, Acciona, Alstom, Enercon, Gamesa, Nordex and REpower all produce onshore wind turbines with a traditional gear-box driven system, and so do not use Nd permanent magnets in their current machines.

Offshore wind turbines

As of January 2014, there are only 3 manufacturers with operational wind turbines in offshore wind farms in UK waters. These are Siemens, Vestas and REpower. Of these, the Vestas and Siemens machines are known to use Nd in the magnet assemblies of some of the turbines (although Vestas use a mix of PMG and a gearbox) and the REpower is an induction machine using gearbox technology (i.e. no Nd).

A detailed summary of wind turbine models can be found in Appendix B.

Operational UK Wind Energy Market

As of 17th January 2014, there is around 10.2GW of operational wind capacity in the UK (excluding NI). Of this, 6.5GW is onshore wind, whilst 3.65GW is offshore. In addition, there is another 5.5GW of onshore consented capacity either under construction or waiting to be built, along with 3.2GW of consented offshore projects.

Currently there are 4.2GW of operational wind farms within Scotland, 3.9GW of consented projects and around 3.9GW of onshore wind within the planning process. Of this only 190MW is operational offshore wind, although there is around 5GW currently submitted to the planning system.

The 2013 Renewable UK State of the Industry Report shows how UK wind capacity has grown since 2000.

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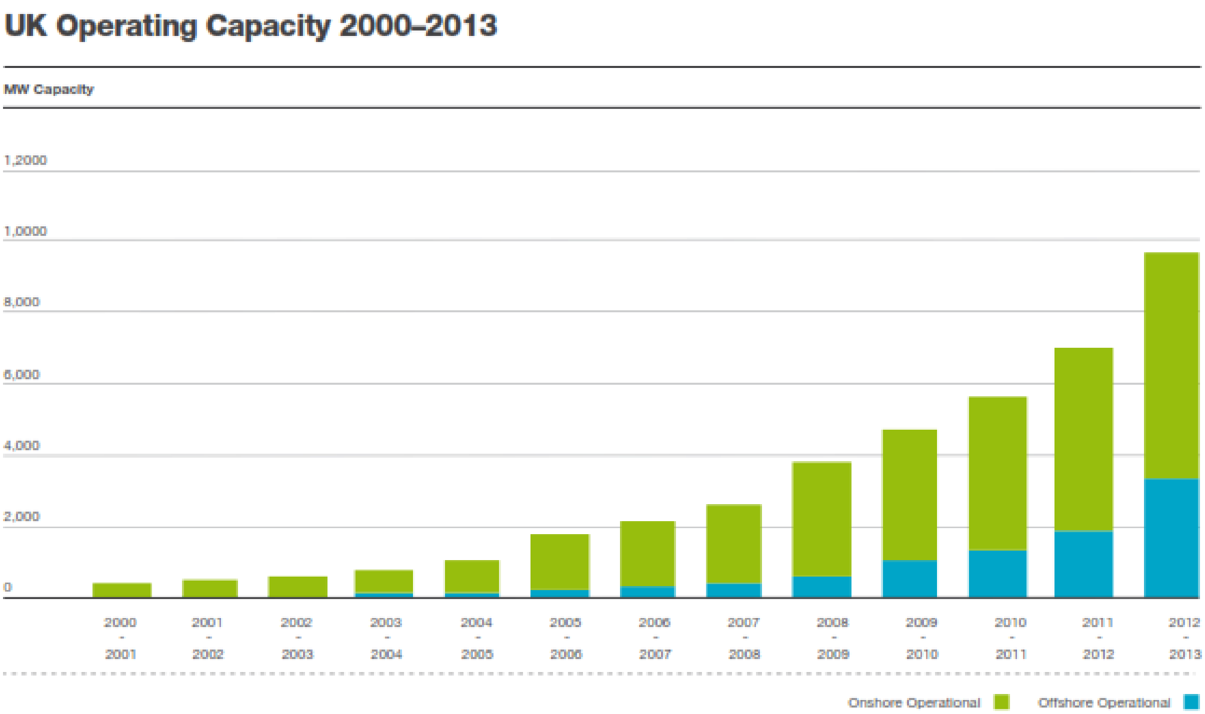
[9] http://vestas.com/en/about/sustainability#!material-use

Figure 2.1 UK Operating Capacity



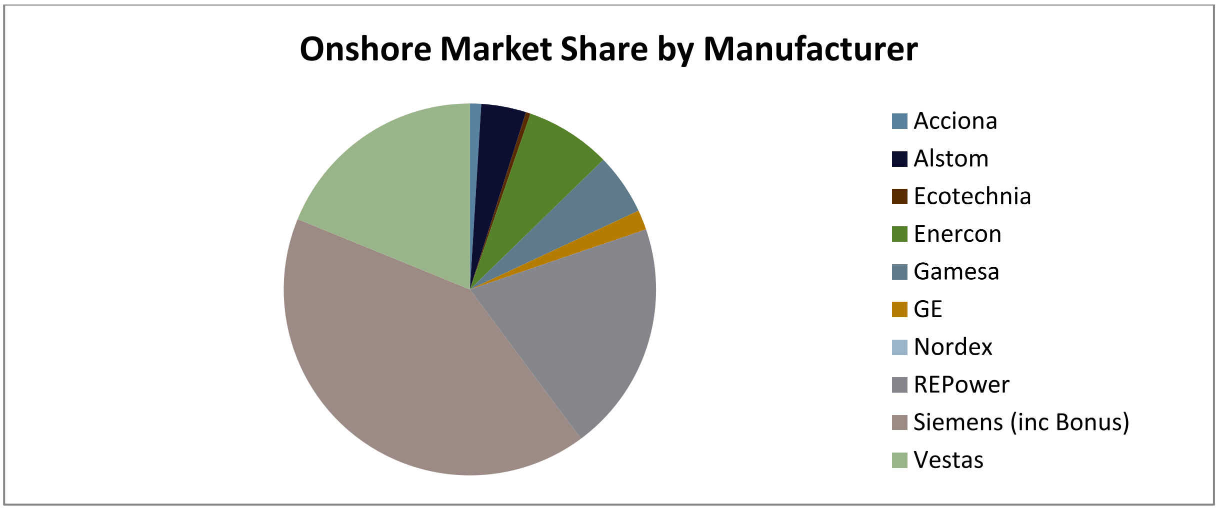
Source: Renewable UK State of the Industry Report 2013

For the purpose of giving necessary focus to this scoping project, from this point on only wind turbines with a capacity of 1.3MW or more are considered. This decision was taken as an assumption that for economies of scale only turbines above this size would be suitable for recycling of Neodymium.

UK Onshore Wind Market

Within the onshore UK wind market, for turbines above 1.3MW, the three market leaders are Siemens (including Bonus) (41% of the market), REpower (20%) and Vestas (19%). Figure 2.2 illustrates the current composition of the market.

Figure 2.2 UK Onshore Market Share (for turbines above 1.3MW)



Within this, the most dominant wind turbine is the Siemens SWT-2.3 model (including some Bonus B82 models – Siemens took over Bonus in 2004), accounting for 29% of the total market share.

There are currently around 2,650 onshore wind turbines rated 1.3MW or above installed in the UK onshore market. Of these, only 25 turbines (0.9%) are confirmed as using Neodymium PMG direct drive technology (17 x Siemens SWT-3.0 and 8 x Vestas V80 Gridstreamer). Of these, only 12 (from 1,740) are in Scotland. There may be more Vestas Gridstreamer turbines than this but it has not been possible to confirm.

Scotland Onshore Wind Market

The Scottish onshore wind market broadly reflects that of the wider UK market, which is to be expected as Scotland currently accounts for 65% of the installed wind capacity. Figure 2.3 shows the breakdown of the Scottish market by manufacturer, whilst Figure 2.4 shows the breakdown by turbine model.

The evidence shows that Siemens are the dominant manufacturer in this market, with 58% of total installed capacity over 1.3MW. Again, the Siemens SWT-2.3 machine is the most common turbine, accounting for 42% of the total market share. This is largely driven by Siemens success in supplying some large sites, such as Clyde and Whitelee (292 turbines between the 2 sites). It is also clear that there is a large range of wind turbines available to the onshore market.

As previously discussed, there are only 12 wind turbines (out of 1,740 installed) in Scotland which use Nd-based PMG direct drive systems. There are 3 Vestas V80 Gridstreamer turbines, and 9 Siemens SWT-3.0 machines.

Figure 2.3 Scotland Onshore Market Share by Manufacturer

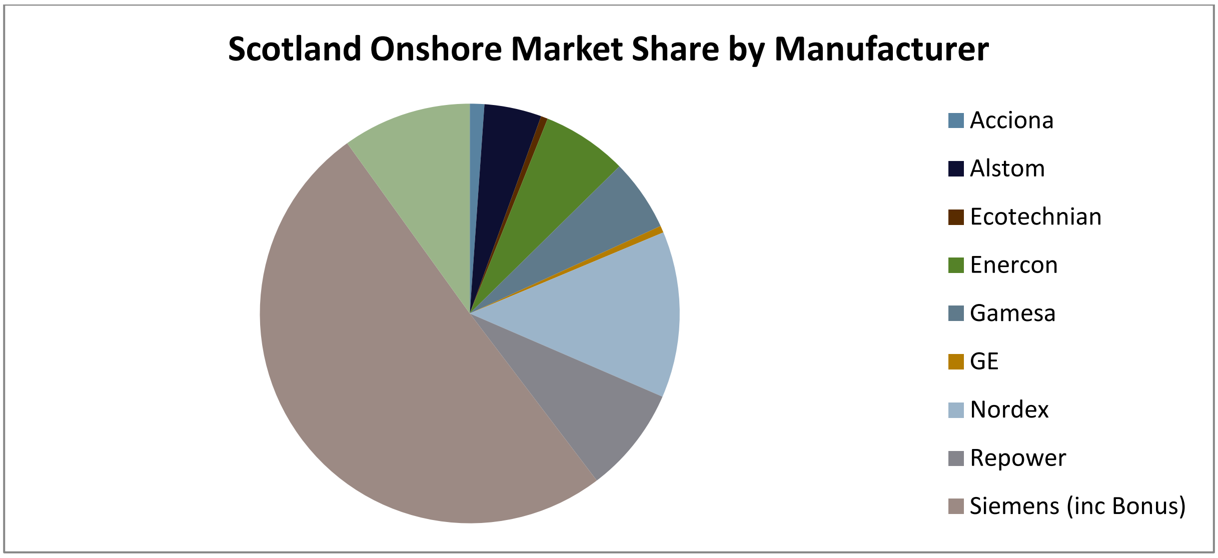
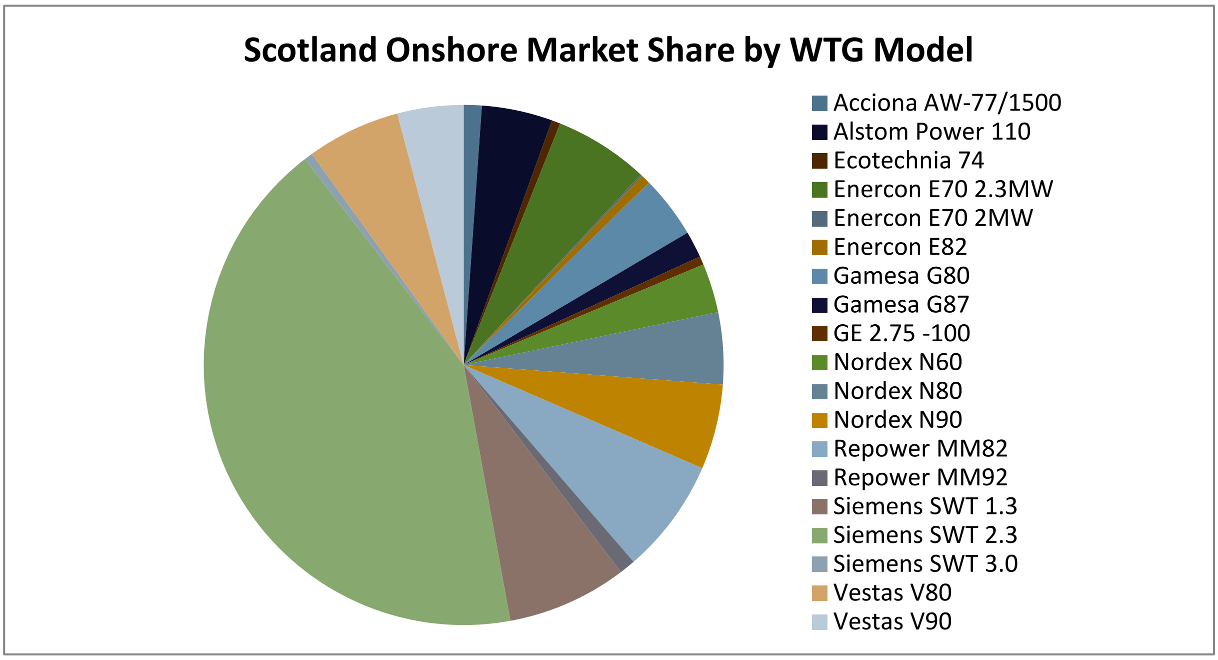


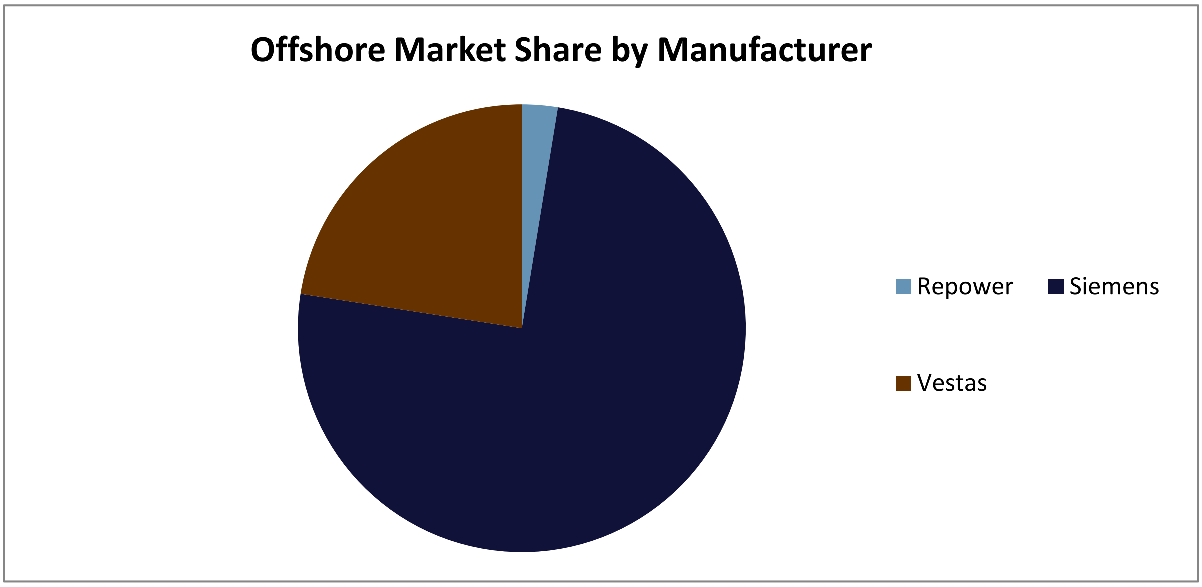
Figure 2.4 Scotland Onshore Market Share by Turbine Model



UK Offshore Wind Market

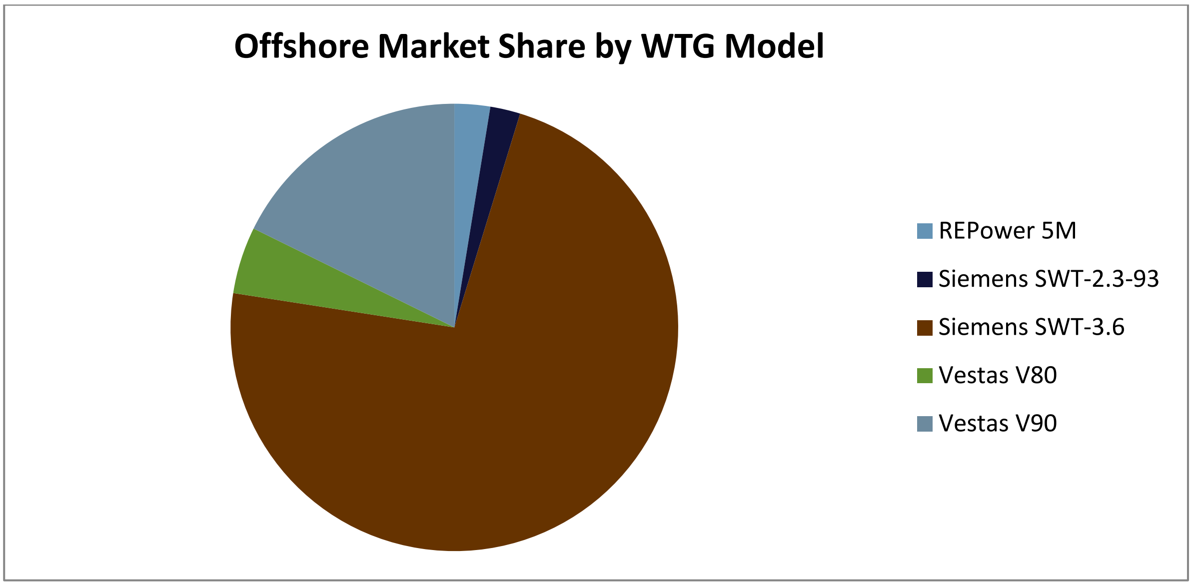
Figure 2.5 illustrates the composition of the UK offshore wind market as of January 2014. There are currently 22 operational offshore wind farms in UK waters, comprising of 1074 wind turbines with a capacity of 3.65GW.

Figure 2.5 UK Offshore Market Share



Offshore wind in the UK is again dominated by Siemens. Figure 2.6 shows the breakdown of the offshore market by turbine model.

Figure 2.6 UK Offshore Market Share – Operational Schemes not including prototypes



There are far fewer turbine models in the offshore market, and the dominance of the Siemens SWT-3.6 machine is clear (903 turbines out of 1,074). However this machine uses gearbox technology (although 2 direct drive prototypes were developed, but not produced), and the first of these started operating at Burbo Bank wind farm in 2007.

The research suggests that there is currently only 1 operational direct drive wind turbine in the UK offshore market at present; the Samsung prototype machine at Methil, in Scotland.

Consented and Under Construction UK Wind Market

As of January 2014 there are around 2,675 consented but not yet built wind turbines in the UK. Of these, 1,420 are in Scotland and around 650 offshore. Please note that offshore turbine numbers are harder to definitively confirm as consented projects often reduce turbine numbers as individual turbine capacity increases between consent and construction.

Choice of Wind Turbine

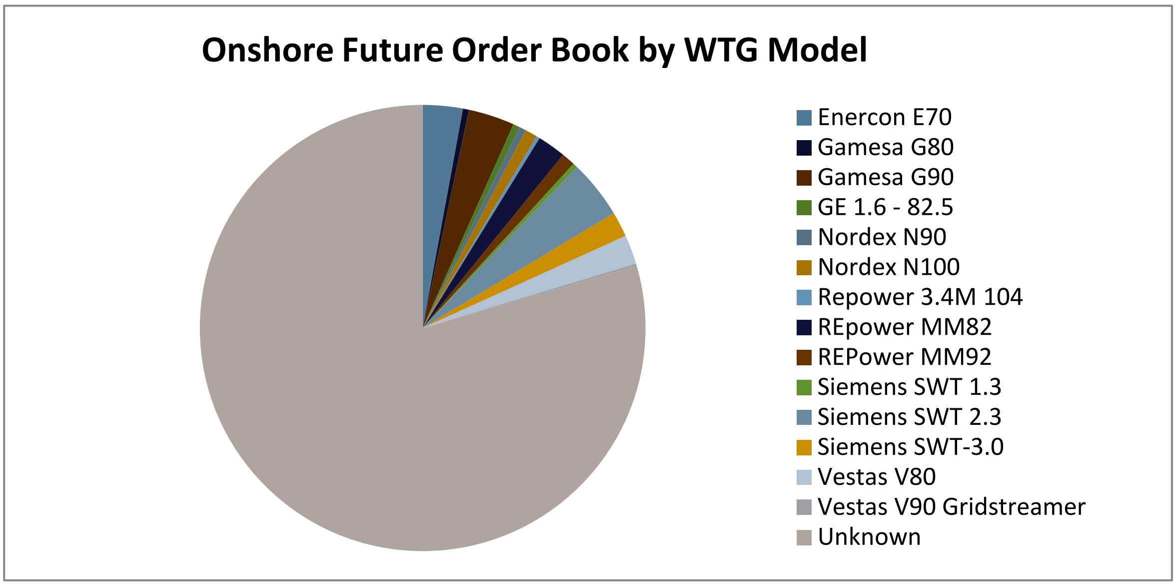
The final choice of wind turbine following consent for a wind farm depends on a number of factors. Developers' criteria for onshore turbine selection are roughly as follows:

1) Size limits on turbines arising from consent (application will be guided by what LVIA consultant will suggest and feel comfortable defending);
2) What turbines fall within these dimensions, plus meet noise constraints;
3) Of these turbines, which meet IEC wind class and turbulence intensity requirements?
4) Which turbine returns the best energy yield;
5) Grid code compliance;
6) Availability and supply timetable; and
7) Competitive tendering also applies.

Our research for future orders is limited mostly to industry news reports and knowledge of the wind farm market. Nevertheless we have attempted to identify confirmed turbine orders as far as possible.

Figure 2.7 illustrates the break down of known future onshore wind turbines. As can be seen, the majority of consented sites do not yet have a confirmed turbine model. This is a key area of uncertainty when interpreting future trends around growth of specific models (e.g. PMGs).

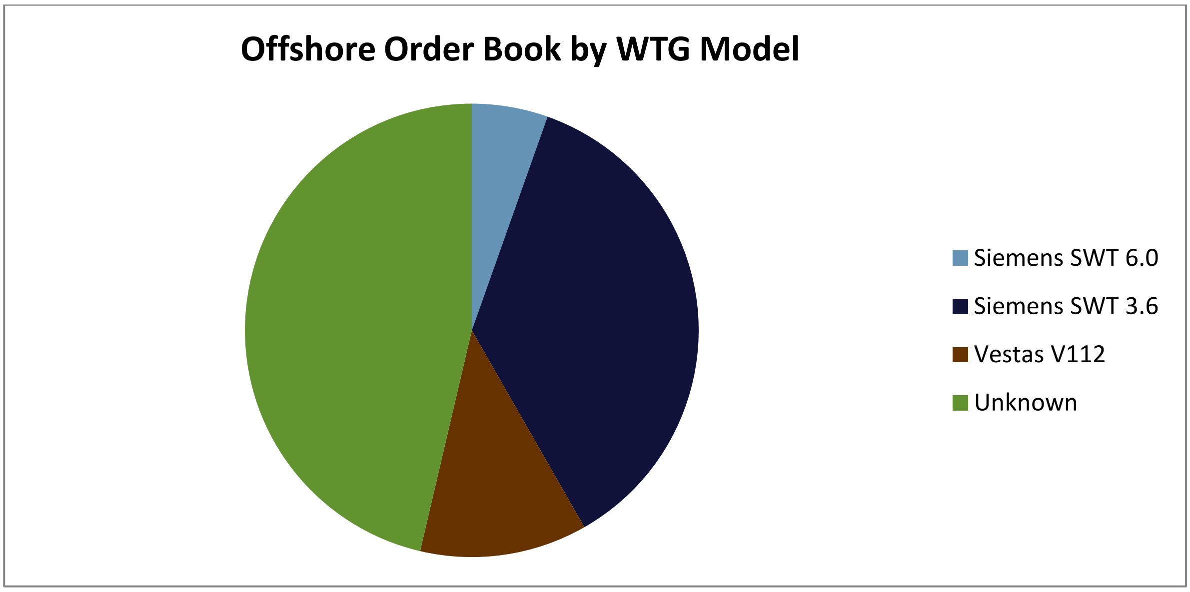
Figure 2.7 Onshore Wind Turbines Order Book



Examining the order book for onshore wind shows that 37 out of 2,037 (1.8%) consented wind turbines will be Siemens SWT-3.0 turbines, which use direct drive technology. The trend for a mixed market also continues.

Offshore, there are around 738 consented or under construction turbines, equating to around 3.2GW of capacity. Of these sites, 40 turbines (5.4%) will be Siemens SWT-6.0 machines which use direct drive technology. The known order book for offshore wind is shown in Figure 2.8.

Figure 2.8 Offshore Wind Turbines Order Book



Neodymium use in wind turbines

A recent study by the Crown Estate[10] - Use of rare earth metals in offshore windfarms (2011) examined the quantities of rare earth metals used in offshore wind turbines. It consulted turbine manufacturers about the quantities of rare earths used in the permanent magnets in the wind turbines and concluded that the range of use is quite broad; the weights of rare earths (the majority of which, though not all would be Nd) used per MW installed range from just less than 20kg/MW for the smaller faster rotation machines up to 217 kg/MW for the largest, slowest rotating machines.

Our research was focused on the manufacturers outlined in Section 2.2.2, and the results are summarised in the table below.

Table 2.1 Neodymium Use in Wind Turbines in the UK

Manufacturer	Turbine Model	Capacity	Total Neodymium[11]
Samsung	Samsung S7.0-171 (prototype)	7.0 MW	1306 kg
Siemens	SWT-3.0	3.0MW	560 kg
	SWT 6.0	6.0MW	1120 kg
Vestas	V112	3 – 3.3MW	616 kg
	V164	8MW	1493 kg

Summary

There are currently around 3,900 wind turbines of 1.3MW and above installed in onshore and offshore UK wind farms. Siemens is the dominant manufacturer both onshore and offshore. Of the installed wind turbines above 1.3MW, around 194 (4.9%) are direct drive wind models. Of these only 26 (0.67%) use Nd-based PMG systems (most direct drive machines at present are Enercon machines which do not use Nd in their assembly).

Based on anecdotal information and industry press, the known future order book for PMG machines suggests numbers will increase, particularly offshore as the next generation of Siemens SWT-6.0 become more established in the market. At present there is limited information on which to make accurate projections, as the turbine types are not agreed until wind farm construction. Table 2.3 presents a current 'best guess' based on limited industry intelligence, market data and conversations had as part of this study.

Table 2.2 Neodymium Use in Operational Wind Turbines in the UK

Location	Total Turbines (> 1.3MW)	Direct Drive using PMG	% of Total	Estimated Total Neodymium (kg)
Whole of UK	3,900	26	0.67	4,850
Scotland, Offshore	1,245	1	0.08	186
Scotland, Onshore	1,740	12	0.7	2,240

[10] Griffiths, J.G. and Easton, S. 2011. 'Use of rare earth metals in offshore wind farms'. The Crown Estate

[11] Calculations are based on Nd content of 186.6kg per MW and 6.6 kg/MW dysprosium, with assumed linearity in Nd use as capacity rises

Table 2.3 Predicted Neodymium Use from Known Future Order Book

Location	Total Turbines (> 1.3MW)	WTG Unknown / not yet announced	Direct Drive using PMG	% of Total	Total Neodymium (kg)
Whole of UK	2,744	1,750	165	6.0	30,789
UK Offshore (incl. Scotland)	707	342	128	18	23,885
Scotland, Onshore	1,425	1,065	37	2.8	6,904

Note: Limited information is known about consented projects as final turbine choice is only just prior to, or during construction of a wind farm.

2.3 Wind farm and Nd use future trends and growth

UK Energy Policy

UK Targets

The UK is legally committed to meeting 15% of its energy needs from renewable sources by 2020. Although there are no specific generation targets relating to individual technologies the most recent DECC Renewable Energy Roadmap (2013)[12] reinforces the view that on-and-offshore wind is likely to play a leading role within meeting these targets.

Scottish Government Targets

The Scottish Government has a target of generating 50% of Scotland's electricity from renewable energy by 2015, and 100% by 2020[13]. It is estimated that 13GW of installed wind capacity will be required in Scotland to meet these targets[14].

Future Policy trends

Onshore Wind:

The 2013 DECC Renewable Energy Roadmap suggests that a plateauing of onshore wind farm developments may be starting to occur. This assumption is based on a projection from the 2011 Energy Roadmap which suggested that onshore wind would plateau in 2015 as the number of technically feasible sites starts to fall, along with cumulative planning impacts and the emergence of other technologies. This conclusion is based on the reduction in projects within the planning process from 7GW in 2011 to 6GW in 2013.

Offshore Wind:

The 2013 DECC Renewable Energy Roadmap states that:

"Offshore wind is an ideal technology for the UK where our shallow seas and strong winds make it an important national asset which will play a key role in enabling the UK to meet its legally binding 2020

[12] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255182/UK_Renewable_Energy_Roadmap_-_5_November_-_FINAL_DOCUMENT_FOR_PUBLICATION.pdf

[13] http://www.scotland.gov.uk/Publications/2013/06/5757/2

[14] http://www.scotland.gov.uk/Publications/2013/06/5757/5

renewable energy target. In the following decades, the UK has ambitious plans to decarbonise the economy as part of the drive to tackle climate change. As offshore wind becomes a more mature technology and costs fall, it has the potential to play a very significant role in the 2020s and out to 2050 alongside other low carbon technologies. The draft EMR Delivery Plan showed potential deployment of up to 16 GW of offshore wind by 2020, and up to 39 GW by 2030".

There is currently 3.5GW of operational offshore wind capacity with another 3.2GW consented. A further 11.5GW currently lies within the planning process.

The UK currently has the largest offshore wind market with more capacity currently deployed than anywhere else. This is anticipated to remain the case until 2020 and beyond. The Electricity Market Reform currently undergoing consultation will replace the current Renewable Obligation Certificates with Contracts for Difference (CfD). The support levels for offshore wind will increase slightly, and that onshore wind subsidy will fall by the same amount. This is likely to drive the offshore wind market to 2020 and beyond.

Wind Turbine Technologies and future developments.

Manufacturers are constantly seeking to further develop performance improvements in their turbines. As such, new prototypes are coming onto the market each year. Current models on the market include the Vestas V164 8MW, which has reverted to a medium speed gearbox, rather then direct drive technology[15], whilst Samsung[16] and Mitsubishi[17] have both launched 7MW direct drive turbines. Other manufacturers with direct drive offshore prototype machines are Alstom and GE.

Current technology reports and market trends appear to suggest that direct drive turbine technology will peak at around 7-8MW, due to mechanical/technological challenges at this size, combined with the cost of the large PMG magnets and quantities of rare earths required at this scale.

Currently, manufacturers seeking to develop 8MW and above machines are leaning towards medium speed geared drivetrain technology, which removes the unreliable higher speed gearbox and the cost of the rare earth PMGs. Should this trend continue then it is likely that PMG use could fall significantly in offshore wind turbines. It is also the case that even manufacturers who have invested in PMG technology, particularly for off-shore, are still conducting research to lower the level of REMs within magnet assemblies and seek alternative materials.

Figure 2.9 shows the increase in offshore wind turbine size over the last 20 years. Since 2000, the average offshore wind turbine has nearly doubled in rated power from 2MW to nearly 4MW. Currently a number of turbines between 5 and 8MW[18] are available, although these are relatively new to the market and machines around 3.6MW continue to dominate the market. Should this trend continue then the average turbine size should approach 6MW by 2017, and 8MW by 2024.

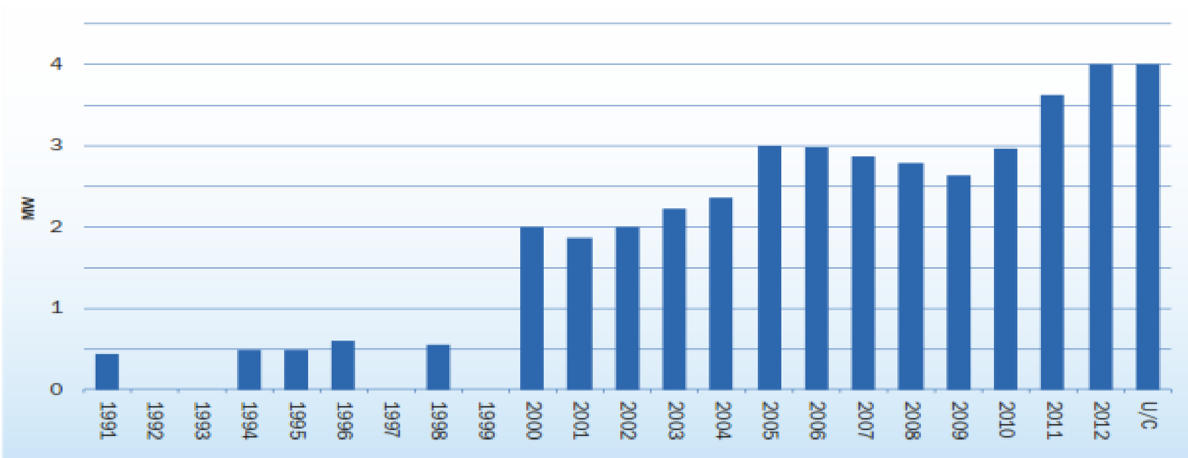
[15] http://www.windpowermonthly.com/article/1169347/vestas-v164-drivetrain-choice

[16] http://www.4coffshore.com/windfarms/turbine-samsung-heavy-industries-s7.0-171-tid37.html

[17] http://www.sse.com/Hunterston/ProjectInformation/

[18] http://www.vestas.com/en/products_and_services/turbines/v164-8_0-mw

Figure 2.9 Average Offshore Wind Turbine Size to 2013



Source – The European Offshore Wind Industry – Key trends and statistics 2012

2.3.1 *Modelling future Nd use in Scottish wind farms*

Model Assumptions and Trends

When a wind farm obtains planning permission, it receives consent for a wind turbine of up to a certain height to blade tip, for example 125m. This is because at the time of planning a supply contract for a specific model of wind turbine will not have been agreed. Once consent is obtained a competitive tendering process is undertaken which leads to the agreement of a turbine supplier. Often the exact turbine model is not known until general site construction has begun. Thus it is often difficult to ascertain which turbine will be used on a consented site.

Given the very limited number of 1.3MW and above direct drive wind turbines identified onshore, combined with the predicted slow down in onshore growth, it appears sensible that the future focus for recovery of Nd is likely to lie in offshore wind turbines.

Industry expects between 10 – 15 GW of offshore capacity by 2020[19], and Government estimates of up to 39GW by 2030, suggesting that there is still plenty of capacity still to be developed.

The 2011-12 and 2012-13 offshore market was dominated almost entirely by Siemens, and this trend appears to be continuing in the short term given their recent securing of an order from the Gwynt-y-Mor 160 turbine site.

To forecast potential arising of Neodymium from wind turbines, three growth scenarios were developed based around the 2020 and 2030 capacity targets set in Scotland. This is shown in Figure 2.10.

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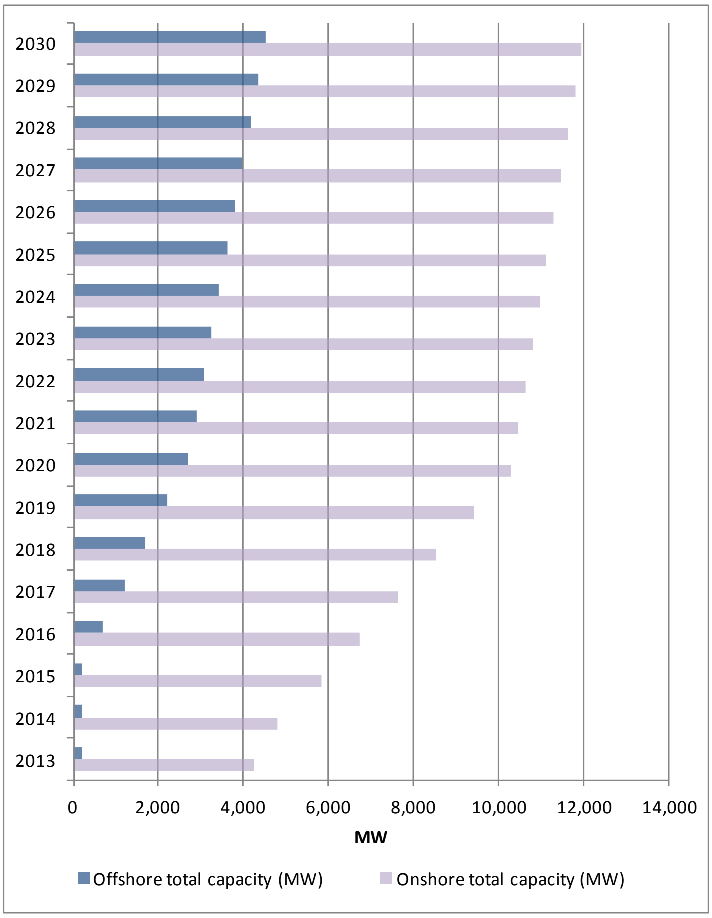
[19] http://www.renewableuk.com/en/publications/reports.cfm/state-of-the-industry-report-2012-13

Figure 2.10 Capacity assumptions used in modelling (2015-2030)

Target Capacity for Scotland (wind)				
Year	**2015**	**2020**	**2030**	
Total Capacity All Turbines (MW)	6,000	13,000	16,500	
Baseline:	**Scotland Onshore (MW)**	**Scotland Offshore (MW)**	**Scotland total**	**Share, % offshore in total**
Current Installed Capacity	4,256	190	4,446	4.3
Consented Capacity under construction	1,140	0	1,140	0.0
Consented Capacity not yet in construction	2,742	114	2,856	4.0
Sub-total: current& consented	8,138	304	8,442	
Capacity within the planning system	4,565	5,050	9,615	52.5
Total	12,703	5,354	18,057	
Required outstanding capacity to meet the targets (from within the planning system)	3826	4232	8,058	84

Using these assumptions, the forecast structural composition of the on-shore and off-shore wind markets have been calculated, as shown in Figure 2.11.

Figure 2.11 Forecast Scottish on-shore and off-shore wind capacity (≥1.3MW turbines) (2013-2030)



These figures are then used as a baseline from which to calculate the volumes of embedded Neodymium based on a series of assumptions around expected take up of PMG machines, volume of Neodymium used per MW capacity etc…

The assumptions and scenarios that have been developed to support the model have been built around the intelligence on short, medium and long term trends in the wind market:

Short Term Trends – 2014/15

3.2GW of offshore wind is currently awaiting construction, or being built. This equates to approximately 580 turbines, although this may change as developers are sometimes reducing turbine numbers, but increasing capacity as new turbines enter the market. The majority of these turbines will likely be Siemens machines, given current trends.

Medium Term Trends – 2016-20

This period is likely to see the continued consenting and construction of the 11.5 GW of offshore wind that is currently within the planning system. Based on current estimates this is likely to consist of anywhere from 1,500 to 3,200 turbines, depending on final turbine capacity. Additional schemes are likely to enter the planning process.

Turbine rated power is likely to continue its upwards trend to be around 6MW. 10MW direct drive High Temperature Superconductor technology may be introduced[20]. Commercial availability of competitors to Siemens should see the market share change slightly.

Long Term Trend – 2020 onwards

Based on current projections further offshore wind farms will continue to be constructed, potentially up to 39GW. This period could also start to see the first offshore repowering projects, replacing original direct drive machines from 2007-2010, depending on turbine longevity.

Trend towards larger, 7MW+ turbines should see Neodymium use falling as larger turbines use medium speed gearboxes. Mainstream introduction of 10MW offshore wind turbines will start to occur.

JRC has developed a series of assumptions around future mix of turbines, which appear to be sensible and provide the relevant range to allow for some unquantified uncertainties in the estimates. The assumptions have already been applied to a forecast model, which the EWEA has responded to.

- *Technology mix 1 gives a market share to low speed wind turbines installed in Europe using Neodymium and dysprosium 15% in 2020 and 20% 2030.*
- *Technology mix 2 gives a market share to turbines installed in Europe using Neodymium and dysprosium 20% in 2020 and 10% in 2030;*
- *Technology mix 3 gives a market share to turbines installed in Europe using Neodymium and dysprosium 35% in 2020 and 30% in 2030.*
- *EWEA technology mix assumption gives a market share to turbines installed in Europe using Neodymium and dysprosium 12.5% in 2020 and 20% in 2030*

The three scenarios presented below represent a low, high and best estimate for the growth of PMG turbines in Scotland that use Nd. All three scenarios use the same base-case data on overall growth in the wind turbine market based on figures presented in Figure 2.10.

- **Scenario 1 (low)**: this foresees that:
    - For on-shore, the total capacity provided by turbines using Neodymium stays constant at 2015 year level as a share of total potential (1.3MW or above);
    - For off-shore, the total capacity provided by turbines using Neodymium stays constant at 2016 onwards as a share of total potential (1.3MW or above) (based on UK data on consented capacity under/awaiting construction); and

[20] http://www.4coffshore.com/windfarms/turbine-AMSC-SeaTitan-tid67.html

  - Neodymium arisings commence 25 years in the future (based on the anticipated lifespan of PMG)

- **Scenario 2 (high)**: this foresees that:
  - For both on-shore and off-shore, the total capacity provided by turbines using Neodymium is at a maximum level, based on turbines where PMG machines could feasibly be used. This level represents 86% of the total capacity growth being from PMG machines using Neodymium and therefore represents a theoretically maximum uptake of PMGs but at a level believed to be unrealistic based on current evidence; and
  - Neodymium arisings commence 25 years in the future (based on the anticipated lifespan of PMG)

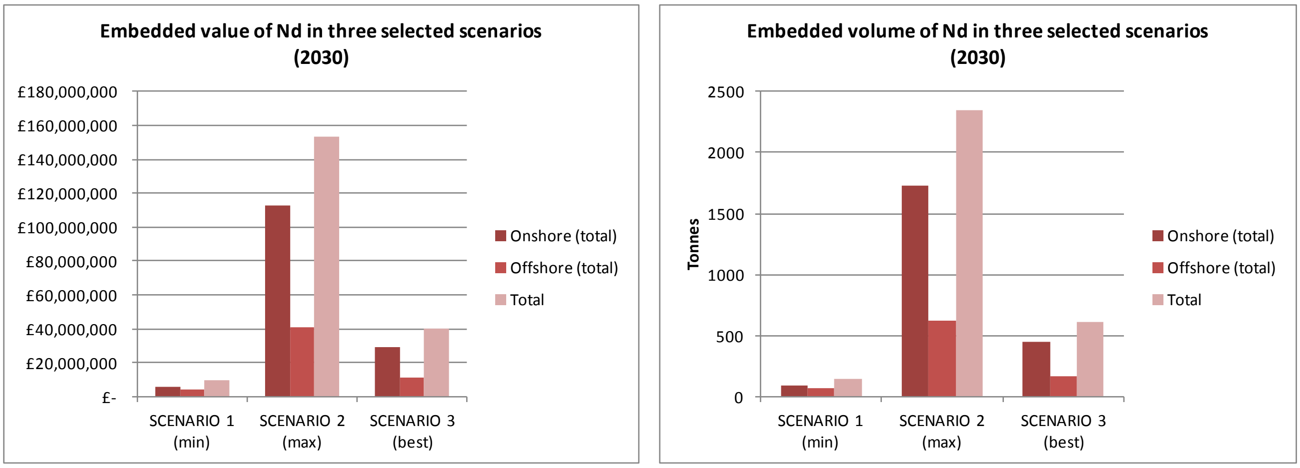
- **Scenario 3 (best)**: this foresees that:
  - For on-shore and off-shore, the total capacity provided by turbines using Neodymium grows over the short to medium term strongly reaching a market share of 12.5% in 2020 and a market share of 20% by 2030 (1.3MW or above) – based on the EWEA forecasts (above); and
  - Neodymium arisings commence 25 years in the future (based on the anticipated lifespan of PMG)

2.3.2 *Model results*

The results of modelling the three scenarios provide very different views on the value of embedded Neodymium that is likely to be 'locked-up' in operational turbines by 2030. Using an average price (2008-2013) for Neodymium on the spot market and not taking into account the investment, recovery and recycling costs (or process losses at end of life), the value of Neodymium in Scottish wind turbines is likely to be between £10 million and £150 million with a best estimate of £40 million.

Figures 2.12 and 2.13 show the values and embedded volumes graphically.

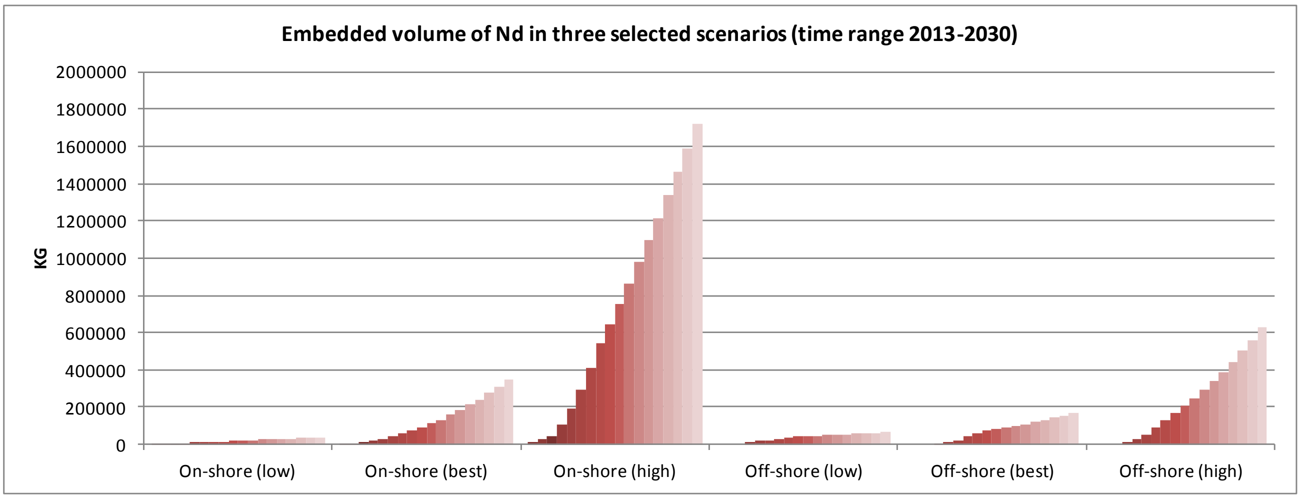
Figure 2.12 and 2.13 Embedded value and volume of Neodymium in Scottish wind turbines ≥1.3MW (2030)



The rate at which the Neodymium accumulates as capacity targets are met with new turbines varies dramatically by scenario and between on-shore and off-shore. Figure 2.14 (overpage) graphically represents the accumulation of Neodymium in operational turbines over time in the three modelled scenarios.

The graphic presents year-on-year demand and does not represent cumulative totals (the additional of individual years would lead to the totals outlined in Figure 2.13). For comparison, US Geological Survey estimates put (annual) world production of Neodymium in 2009 at approximately 19,000 tonnes.

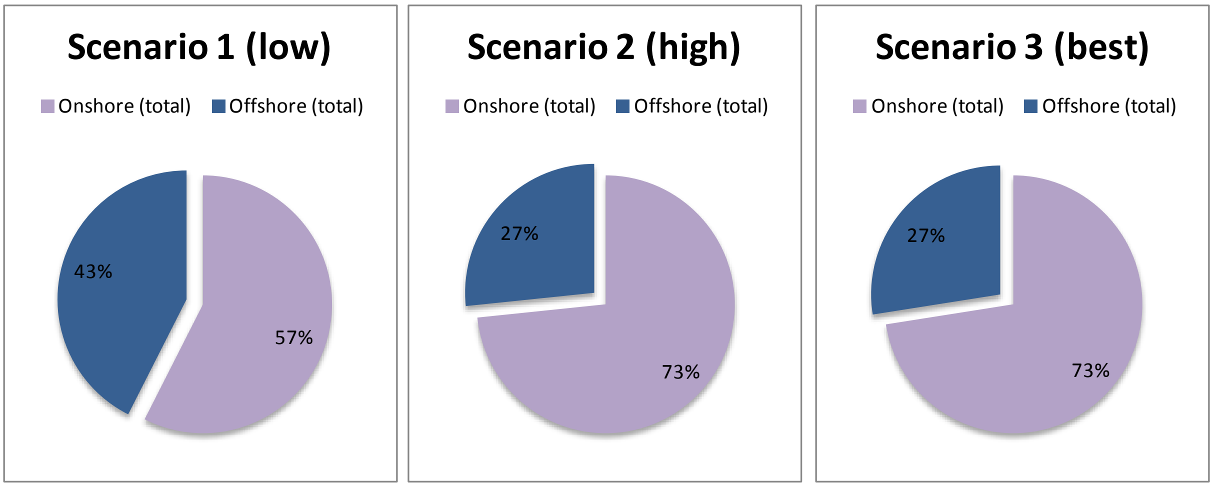
Figure 2.14 Accumulation of Neodymium in Scottish wind turbines ≥1.3MW (2013 - 2030)



Discounting the high scenario (which is modelled as a theoretical maximum), the results in Figure 2.14 show that based on the assumptions taken for the best estimate, the accumulation of Neodymium over time rises steadily in both the on-shore and off-shore turbines ≥1.3MW. On-shore is the more voluminous source by 2030. In the low estimate, growth in off-shore wind means that this becomes a larger repository for Neodymium but at a much lower overall volume than the best estimate.

If we examine the relative splits of Neodymium that will arise from on-shore and off-shore in the three scenarios, we see that in all cases on-shore is likely to be a more important source by 2030.

Figure 2.15 Shares of Neodymium in low, high and best scenarios for Scottish wind turbines ≥1.3MW



3 Analysis of End of Life (EoL) recovery solutions for NdFeB turbine magnets

This section presents findings from the research on the opportunities, challenges and markets for re-use, and recycling and recovery of Neodymium arising from end of life wind turbines. The focus of the assessment has been made with Scotland in mind (i.e. consideration of the geo-spatial and market situation with regard to, for example, logistics) but by necessity, consideration of the global context was necessary to understand the issues associated with end of life recovery and recycling of Neodymium.

3.1 NdFeB magnets

From the research into the wider recycling infrastructure, Neodymium is almost entirely supplied by China and raises the importance of giving consideration to trends around supply and demand in a global marketplace. It also acts as a driver for measures to be taken to increase the resilience of manufacturing supply chains and end of life processes. A summary of the research is included in this section with further detail consigned to Appendix A.

3.1.1 *Geography*

The available evidence suggests that China's current domination of Neodymium production is the result of a carefully crafted long term strategy. However, it is Hitachi metals of Japan who continue to pursue patents and licensing related to sintered NdFeB magnets used in wind turbines. There are currently 9 manufacturers in China licensed to manufacture and sell sintered rare earth magnets under certain Hitachi Metals patents. There are also a further 2 companies in Japan eligible to manufacture and sell sintered rare earth magnets under patent, but with limited rights to manufacture, sell or ship to China.

One of the few semi-commercial recycling processes is run by Hitachi, recovering Neodymium (and other rare earth metals) from computer disk drives and air-conditioning compressors. This process necessitates specialist machinery to disassemble the products, and then uses a special extraction material that has a high affinity for the rare earths. This process is currently in the pilot scale, but it is anticipated that it will be full scale in the near future.

Overall, mining of materials and the manufacture of magnets has been concentrated in China. This also coincides with spurred economic growth and increased consumer demand from within the country to produce wind turbines, consumer electronics and other sectors requiring more of its domestic Neodymium supplies.

These non competitive and restrictive characteristics of the Neodymium market in China will have worldwide impacts for supply and the growth of the Neodymium magnet sector. This however does increase the importance of Scotland and indeed the EU, on developing infrastructure not only to ensure supply chain resilience for the future development of wind turbines and other high tech applications for Neodymium, but also to mitigate inevitable market price rises if supply becomes increasingly constrained.

3.1.2 *Infrastructure*

Besides wind turbines, Neodymium is also used in post-consumer scrap WEEE (such as hi-fi speakers and hard-disk drives) as well as batteries (mainly from electric vehicles). It is believed as much as 300,000 tonnes of REEs are contained in this waste stream in Japan alone, and as indicated above, methods for recycling and recovery are actively being sought and implemented[21].

[21] European Pathway to Zero Waste, Environment Agency, Study into the feasibility of protecting and recovering critical raw materials through infrastructure development in the South East of England. See: http://www.environment-agency.gov.uk/static/documents/Business/EPOW-recovering-critical-raw-materials-T5v2.pdf

By contrast, activity related to Neodymium recycling in Scotland (as well as the rest of the UK) has been limited experimental and research phases, with very small quantities of Neodymium material being recovered.

The Magnetic Materials Group at the University of Birmingham has investigated the use of hydrogen to extract magnets from electrical goods and then reprocess that material into new magnetic materials. The group has also examined methods to recycle magnets and assemblies from medium to large scale devices such as generators and motors found in electric vehicles using hydrogen gas. Further information regarding recycling approaches/infrastructure is reviewed in detail later in this report.

It is worthy of note however that much of the technology is being developed to capture the small amounts of Neodymium from batteries, hybrid vehicle motors, HDD and so on and not the hundreds of kilos found in the magnet arrays within wind turbine nacelles. The technology developed and the plant commissioned may simply be unable to cope with the sheer volume of the nacelles and magnets.

On this latter logistical point, there is market evidence to support potential recovery and re-use/recycling challenges. G&P batteries are already finding issues with the non uniform battery sizes from BMW's award winning hybrid vehicles. To ensure optimum reprocessing and recycling, infrastructure may require modification, tweaks and adaptation. If not expressly designed with sufficient flexibility to cope with evolutionary design in batteries and magnets infrastructure sites will be limited in the volumes of magnets that can be processed.

3.1.3 *Specifications*

Each manufacturer utilising NdFeB magnets in their turbines stipulates the chemistry and composition to suit the application. This is supported by demandingly tight specifications, which recyclers would need to match if closed loop recycling is to be achieved. In addition to this, intellectual property rights exist for commercially viable NdFeB magnet alloys.

Neodymium magnets contains a few percent dysprosium, which is also a heavy rare earth element of 'high value', therefore the establishment of a recycling technology from end of life magnets is a priority not just for Neodymium but also other elements. Neodymium magnets contain 60-70% iron, therefore it is considered uneconomic to totally dissolve the magnet by acid. Instead, selective leaching is required, which dissolves only the REEs and leaves the iron in the residue. There are examples from industry which use a REE separation process in which oxidative roasting is applied to the demagnetised magnet to transform iron to hematite, Fe_2O_3. It is not clear at present if the scale of such processes would suit the physical characteristics (size, density and volume) or chemistry of Nd-rich magnetic material arising from wind turbines at end of life.

Magnet manufacturing produces a large amount of process-related scrap, mainly as a consequence of the cutting and polishing processes. This scrap material is currently recycled by the manufacturers, demonstrating the principle that scrap magnetic materials are recyclable, but recovery rates for post-consumer (end-of-life) magnetic materials are very low when evaluated against global supply.

End of life magnets that contain rare earth materials also contain a significant number of impurities and the magnet specifications (including the exact composition) are often not well matched for direct recycling into new magnets (unless via a manufacturer driven take back system). Therefore, commercially viable recycling relies on a process that assesses the magnet specifications, removes the impurities and separates the rare earth elements into constituent parts.

There is little in the way of evidence to suggest this level of sophistication is prevalent within the current industry although obviously pockets of technical knowhow and capability clearly exist (e.g. Umicore, Hitatchi). If and how this expertise could be drawn to Scotland remains an area that warrants further investigation.

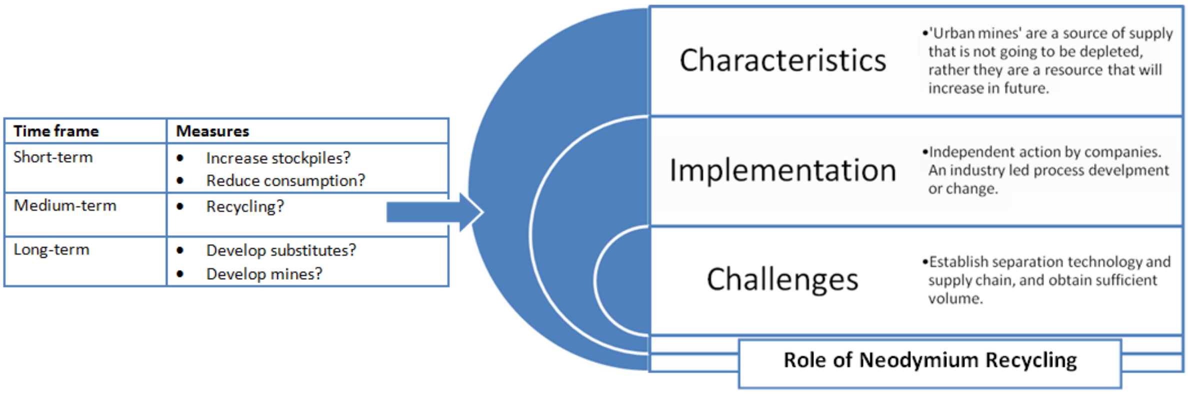
3.1.4 *Supply*

Review of the literature and sectoral activities indicates that funded research is already ongoing regarding end-of-life processes. However, this raises further questions as many of the foreseeable issues surrounding disposal of magnets from large-scale wind turbines are yet to occur (given the 25 year life cycle of the turbines that contain Nd). Best estimates[22] put the period where the materials locked-up within turbines in Scotland might begin to become available for recovery, re-use or recycling to be around 2038.

China's policy initiatives restrict the exports of rare earth materials and it is unclear how much the export restrictions affect exports of downstream metal and magnets. China's goal is to build-out and serve its domestic manufacturing industry and attract foreign investors to participate by locating foreign-owned facilities in China in exchange for access to Neodymium and other raw materials, metals and alloys, as well as access to the emerging Chinese market[23].

The figure below illustrates short, medium and long-term measures for ensuring a secure supply of Neodymium. The short-term measures consist of increasing stockpiles and decreasing consumption, the medium-term measures involve recycling, and the long-term measures involve the development of new mines and alternative materials. Recycling means separating Neodymium magnets from used wind turbines (and other products) so they can reused as raw materials. Further than simply recycling resources, this can also be seen as something that companies ought to be doing to prevent Neodymium being lost to landfill. To this extent there are similarities with the lighting recycling industries model to divert Mercury away from landfill (described further in the Infrastructure section of this chapter).

Figure 3.1 Measures for ensuring a secure supply of Neodymium



3.1.5 *European Resource Strategy*

The EU have set up the task force Critical Raw Materials Network (funded by the EU member states) with the sole aim to drive innovation in the field of critical raw materials: "The coordinators of the project believe that the scarcity of critical raw materials, together with their economic importance, makes it necessary to explore new avenues towards substitutions, which can reduce the EU's consumption and decrease the relative dependence on imports."[24]

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[22] According to the model developed by the study team as part of this work and based on industry intelligence.

[23] China's Rare Earth Elements Industry: What can the West Learn? by Cindy Hurst, Institute for the Analysis of Global Security, March 2010.

[24] Critical Raw Materials for the EU. (2012, December 18). Retrieved from Community Research and Development Information Service: http://cordis.europa.eu/fetch?CALLER=EN_NEWS&ACTION=D&SESSION=&RCN=35357

An article published on 15th January 2013 adds optimism to the potential, continued supply of elements on the EU "critical raw materials" list, with Greenland being the latest source of testing for future prospective mining. It does go on to say that Greenland possessed no bias towards the EU (given its close links to Denmark) as to who shall be receiving the mining contracts and stated that they would not be opposed to Chinese companies taking on the project.[25]. There are other signs that new sites are being opened up around the globe that possess potential mining for REE's. For example, Jamaica has worked alongside Japan's privately owned Nippon Light Metal to undertake tests that could prove beneficial to all with the success of extracting REE's for commercial sale. Nippon Light Metal approached Jamaica saying it had the capacity to extract rare-earth elements and wanted to evaluate the local red mud. Since then, it has done chemical research and successfully extracted some rare-earth elements[26].

3.2 Supply Chain

This section provides a summary of key elements of the supply chain process for Neodymium magnets. Figure 3.2 shows the supply chain flow summary chart based on what the literature suggests is a more common linear 'take-make-consume-dispose' model.

Figure 3.2 Supply-chain map for Neodymium permanent magnets

The supply chain for ND and Nd-based magnets is discussed in greater detail within Appendix A. Key observations noted during the analysis of the literature and evidence include:

- **The global nature of the supplier networks and the level of interconnectivity**; the evidence indicates that in regard to both the initial processing and end of life recovery of rare earths, the manufacturers rely on often long distance movements of the materials around the globe (even to the extent that some process steps may occur in different geographies);

- **There are obvious opportunities from advanced reverse logistics**; but there is evidence that in some cases, particularly where the circular material flows are internalised within one organisation, this is already happening as part of operational efficiency;

- **Supply chain resilience is a big issue for organisations whose models rely on a steady supply of rare earth materials** and the evidence points to supply chain strategies that include strategic alliances, joint ventures, longer-term supply contracts and investment in the exploration and production in new mineral and ore-rich areas outside of China.

- **There is evidence of rare earth closed loop re-use and recycling supply chains**, but this applies to industries including the aerospace and motor vehicles (use of batteries and direct drive motors) rather than the wind turbine industry. Anecdotally, turbine and turbine motor manufacturers do acknowledge the opportunities from closing material loops at end of life but there is little in the way of concrete evidence to suggest a lot of action being taken at this point in time. Internalisation of the loops appears to be a key driver.

[25] Greenland rare earths: No special favours for EU, 2013

[26] McFadden, D. (2013, January 15). Official: Rare Earth Elements in Jamaica's Red Mud. Retrieved from Associated Press: http://hosted.ap.org/dynamic/stories/C/CB_JAMAICA_RARE_EARTH?SITE=AP&SECTION=HOME&TEMPLATE=DEFAULT&CTIME=2013-01-15-19-12-16

3.3 Infrastructure distribution and availability

This section of the report describes the known infrastructure for the UK (including Scotland), Europe and then the rest of the world.

The infrastructure research has found no formal wind turbine recycling and certainly no commercial scale recycling of Neodymium from any source in Scotland (or the rest of the UK). The following sections therefore should be considered in a theoretical context due to the lack of infrastructure. It is however worth considering what infrastructure the UK might have in the future based upon current EU and Worldwide infrastructure. It is also worthy of note that the size, shape, logistics, magnet type and access to the magnet in the nacelle will all contribute to the commercial viability of recycling Neodymium magnets from wind turbines. There are obvious lessons to be learnt from other sectors here, most notably the motor manufacturing industry.

3.3.1 *The UK*

End–of-life recycling rates are low as a result of historical low demand for recycled Neodymium, the relatively low financial value for Neodymium (compared to some other materials e.g. Dysprosium) and the high dispersion of small volumes of Neodymium in multiple applications. Most of the UK facilities are focused upon magnets and there is some processing of Neodymium at a research stage in the UK.

The desk based research identified a company called 'Retrench' in Birmingham where small volumes of magnets are reprocessed and returned to a confidential supplier[27]. The specific process or supplier details could not be disclosed due to commercial sensitivities. Birmingham University's Magnetic Materials Group have a pilot plant capable of extracting 10-40kg of NdFeB per run from pre-processed HDDs as feedstock. A mechanical stage is also being introduced to shake the powder out of the HDDs once hydrided. The rare earths can subsequently be removed from the NdFeB alloy by using solvent extraction techniques.[28] Both of these facilities are small scale and at a pilot stage.

In general within the UK the recycling of Rare Earth Elements (REE's) is being lead by Great Western Minerals Group subsidiary company Less Common Metals (LCM) limited.

The desk based research for this study did not highlight any specific plants for the recycling of Neodymium in Scotland.

3.3.2 *Europe*

During the research into the wider recycling infrastructure into Europe several organisations have been found to be developing processes to recycle the REE's from batteries and in specific Neodymium from hybrid vehicle batteries. Additionally several organisations have been found to be researching the processes to recycle REE's from magnets.

Umicore, a major Belgium based metal refiner, has also developed a process for recycling rare earth elements from nickel metal hydride rechargeable batteries [57] . After the separation of the nickel and iron from the rare earths, Umicore will process the rare earths into a high grade concentrate that will be refined and formulated into rare earth materials at Rhodia's plant in La Rochelle (France). Toyota is working jointly on the issue with Panasonic to recycle lanthanum and Neodymium from hybrid vehicle batteries (this also involves joint working with SNAM in France)[29].

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[27] Commercial sensitivities have restricted the disclosure of the process used and the supplier.

[28] Materials World, Rare Earth Recovery, August 2011.

[29] http://www.scotland.gov.uk/Publications/2013/12/9124/5

A German led partnership project (MORE - MOtor REcycling) has been funded by the German Federal Research Ministry. The project is led by Siemens and also involves Daimler, Umicore and several universities and research institutions. The objective is to investigate different approaches to the recycling of electric motors from vehicles, such as: the dismantling of the magnets; the repair, refurbishment and reuse of the electric motor or its components; and the recycling of magnetic materials and rare earth recovery from pre-sorted and shredded material [58].

In Norway, the state research organisation has funded a project to develop techniques for extracting rare earth elements from permanent magnets. The project is investigating the potential of technology transfer from the aluminium smelting industry [60]. Other organisations researching REE and Neodymium recovery include Batrec Industries AG in Switzerland, Akkuser OY in Norway and Falconbridge International in Norway (and Canada).

Through the desk research it is clear that dedicated funding and research is already occurring within the EU to focus on the recycling of some critical materials including REE's (for example the Centre for Resource Recovery and Recycling[30] (CR3)). The Centre aims to "develop technologies to identify and separate scrap materials from waste streams and build strategies and technologies to enable greater scrap utilization within materials processes". Current research activities include efforts focused on REE recycling such as its recovery from Magnets, Catalysts, and other Secondary Resources[31]. The research from this study has identified that research and recovery of some of the critical materials is occurring outside of the EU including in United States, China and Japan.

Siemens is currently working with the ministry of research, academic institutions and companies in Germany to extract REE's including Neodymium from smelting slag. This process is expected to be available for industrial use in the next few years[32].

3.3.3 *Rest of the World*

A brief rest of the world search of technologies capable of extracting rare earth elements has identified a number of pre commercial developments in Japan. Japan appears to be market leader , in part due to the Japanese government setting aside some $1.2bn(US) for research into rare-earth recycling, as well as opening new supply routes and stockpiling rare earth elements. The Japanese government is also drafting legislation to promote the re-use of rare earth elements from used products [53]. The promotion of new or existing legislation appears to be a key factor in the development technology and facilities for the recycling of REE's such as the impact of the End of life Vehicle regulations upon vehicle manufacturers and retailers in the EU. Toyota is working jointly on the issue with Panasonic to recycle lanthanum and Neodymium from hybrid vehicle batteries (this also involves joint working with SNAM in France). Honda is working jointly with Japan Metals & Chemicals to establish a large scale facility to recapture rare earth elements from Honda parts (with claims that up to 80% of rare earth elements can be recovered from nickel metal hydride batteries) [56].

In Japan, the Ministry of Economy, Trade and Industry has selected Tokyo based Hitachi for a project to find technology solutions for the recycling of rare earth metals from 'urban mines'. Hitachi has developed a method to recycle high-performance rare earth magnets from the motors of hard disk drives (HDD), air conditioners and other compressors. Experiments with Neodymium and Dysprosium extraction technologies have been undertaken which result in the systems containing rare earth magnets emerging from the machinery separately meaning workers can pick out the desired systems

[30] Includes the Colorado School of Mines, Worchester Polythechnic Institute and Katholieke Universiteit Leuven in Belgium.

[31] Center for Resource Recovery and Recycling (CR3) http://www.wpi.edu/academics/Research/MPI/News/cr3201930.html (viewed December 2012)

[32] http://www.siemens.com/innovation/apps/pof_microsite/_pof-fall-2011/_html_en/raw-materials.html

easily by visual screening. The machine has a capacity to process around 100 magnets per hour - around eight times faster than using manual labour. Hitachi aims to commence full recycling operations by 2013[33]. The Ashahi Pretec Group in Kobe, Japan also recovers indium from FPDs found in WEEE waste streams by dissolution techniques. In Japan Kosaka Smelting and Refining (a subsidiary of Dowa Holdings) is attempting to recover rare earth elements, such as Neodymium, using a smelting a refining process [54]. The Dowa Group also recycles indium in Japan. Hitachi's facility should now be in full operation and Mitsui Metal Mining Company in Japan is recycling REE's from NiMH now.

GreenRock Rare Earth Recovery Corporation, in the US, plans to establish four rare earth recovery facilities processing 277,000 tonnes of consumer electronics, magnets, phosphors and industrial batteries per annum [59] . There are other organisations in North America that are seeking to recycling REE's including SIMS Recycling in the US and Toxco Inc in Canada. Molycorp has also purchased Neo Materials Technology (now Moly Canada) in China to recycle REE's and has a separation plant at Mountain Pass in the US. GE is recycling REE's within lighting phosphor powders and magnets as well as researching substitutes.

3.3.4 *Skills and capability commentary*

Within Scotland there are no facilities for the recycling of Neodymium. There is however some similarity in the skill base for the recycling processes identified for Neodymium and high tech industries such as Aerospace. Aerospace in Scotland employs a highly skilled workforce of around 30,000 people across 150 companies in civil aerospace and defence equipment industries[34]. In the aerospace sector around 32% of the aerospace workforce (16,000) is of graduate or equivalent level in the areas of design, avionics (electronics) and maintenance/remanufacturing. There may be potential for suitably skilled individuals with transferable skills to provide sufficient technological 'knowhow' to seed an embryonic Scottish rare earth recycling market.

The research into the recycling of Neodymium is widespread, particularly when considered within the wider remit of REE's. There does however appear to be a focus in Japan and China with some research occurring in Europe (including the UK). Japanese based Hitachi also appears to dominate the recycling technologies and is some way in advance of other companies in developing the technology. This is in part due to substantial funding into REE's by the Japanese Government ($1.2Billion US). This technology should be transferable to other countries subject to patent and commercial considerations.

3.3.5 *Infrastructure summary*

It is not entirely clear what the future value for Neodymium will be and therefore difficult to predict whether the case for investment in re-use or recycling infrastructure would be made on a volume or value basis. There is an obvious challenge around the nature of Neodymium being locked-up in operational wind turbines for what is likely to be the next 25 years. Even taking a very long-term view of investment, this time horizon is too great to support infrastructure investment now; although it is recognised that at some point in the future there will be an 'optimum investment point', where market forces and investment strategies should be reconsidered.

On the presumption that the use of Neodymium in wind turbines within Scotland, and to some extent the UK - as recycling infrastructure in Scotland could capture EoL materials – increases toward the higher end of the growth projections made in Section 2, the case for investment grows increasingly strong. However, many things can change; a good illustration being that of HDDs, which contain very small quantities but do offer a volume driven model, i.e. there a lots of HDDs in use. However, even

[33] Waste management world (2022), Recycling: the easy option? http://www.waste-management-world.com/index/display/article-display/4336604733/articles/waste-management-world/volume-12/issue-5/features/recycling-rarely-so-critical.html

[34] http://www.realscience.org.uk/makeitb/scottish-manufacturing-industry.html

here technological innovation and product trends are moving rapidly. HDDs are starting to be replaced with SSDs (solid state drives), which do not contain the same materials.

Where further consideration could be given is to the extent to which the arisings of Neodymium from wind turbines when coupled with other sources (e.g. the motor industry) may create a 'tipping point' for additional recycling infrastructure in the UK and particularly Scotland. The recycling infrastructure for vehicles and components of vehicles is far better developed, having been driven as it has by the Batteries Directive[35] and the End of Life Vehicle (ELV) Regulations[36].

These regulations specify targets that have driven the automotive sector to include Design for Disposal considerations at the design stage to ensure that the vehicle can be recycled at the end of its life. Vehicle manufacturers such as Honda, Toyota and Jaguar Land Rover are aware of supply side issues with REE's and are designing vehicles with this in mind. These point to the fact that legislation and enforcement are important drivers for organisations to become more circular; and with this the development of re-use, recycling and material recovery capabilities within the wider resource management chain.

3.4 Barriers and opportunities for magnet re-use/recycling

In 2009 Japan published a document entitled 'Strategy for Ensuring Stable Supplies of Rare Metals'. As one of its four pillars for securing supplies of rare metals, including REEs, the strategy calls for the recycling of such materials from scrap. Furthermore, it urges the government to facilitate the recovery of used rare metals by establishing a new recycling system and better utilising the existing system, as well as promoting research and development of recycling technology. In addition, Japan's environmental ministry has recently set out plans to develop a system for recycling the rare and precious metals used in 45 gadgets, such as mobile phones.

Strategies covering critical material supply, including many REEs have also been recently produced by both the EU[37] and the U.S.[38] Both of these documents call for the development of recycling technologies to help meet the rising demand for REEs.

3.4.1 *Design for disposal considerations*

The very nature of some of these materials means that often there is no component within wind turbines that is made from Neodymium and easily separated.

The process of separating and collecting rare earth magnets safely from products not only requires a great deal of time and effort but also uses acids and other chemicals for the process of extracting rare earths. This results in toxic liquid wastes, the disposal of which creates environmental and cost issues.

Furthermore, a recent study by European environmental research consultancy, Öko-Institut e.V., - Study on Rare Earths and Their Recycling - found that while electronic scrap is often recycled in classic pyro-metallurgical plants and metals recovered, rare earths are lost as they become a part of the slag which is not currently recovered and Neodymium and other rare earth metals are lost to slag of smelter plants. Nevertheless the sharp increase of rare earth prices since 2010 and the high media coverage of possible supply shortages and export restrictions by China have put the issue of recycling rare earths on the agenda worldwide.

[35] http://www.sepa.org.uk/waste/waste_regulation/producer_responsibility/batteries/uk_regulations.aspx

[36] http://www.sepa.org.uk/waste/waste_regulation/producer_responsibility/end_of_life_vehicles.aspx

[37] Library of the European Parliament – China's export restrictions on rare earth elements. See: http://www.europarl.europa.eu/RegData/bibliotheque/briefing/2013/130357/LDM_BRI(2013)130357_REV1_EN.pdf

[38] Congressional Research Service, Rare Earth Elements: The Global Supply Chain. See: http://www.fas.org/sgp/crs/natsec/R41347.pdf

There are several existing processes for recycling other products containing Neodymium such as batteries; however all are focussed on recycling small portable batteries with the primary objective of recovering cobalt. Conversely, companies are actively gearing recycling processes towards recovering lithium, zinc and nickel from larger hybrid and fully electric vehicle batteries. As the logistics for recovering these materials is already in place, it is considered that certain processes could be adapted to capture rare earth material from wind turbines if market conditions were fitting.

Likewise, the issues surrounding adaptation to changing technologies for batteries is similar to that of wind turbines. Like NdFeB magnets, the chemistry in all electric vehicle batteries is likely to be different from the ones in current processes. Further to this, there is great difference in size and shape of portable cells and vehicle batteries much like the varying size and shapes of wind turbine magnets.

Most operators claim to be aware of the capabilities needed for treating larger magnet types although they may need some sort of pre-treatment in terms of casing removal or to be cut into smaller parts. The cost for handling larger magnets should be lower per weight and hence more cost-effective than smaller magnets such as those found in HDDs. However, large high-strength magnets could be difficult to handle in a general process suggesting large turbine magnets are to be recycled in a dedicated process.

Siemens are undertaking design for disassembly project for Neodymium magnets in Germany[39].

3.4.2 *Possible re-use approaches*

There are obvious parallels in re-use of the magnets in wind turbines with those in other direct drive motors but some considerable logistical, practical and compositional issues. The research suggests the following points are highly relevant when examining potential opportunities in re-use:

- Technological advances in the wind turbine manufacturing industry are moving very rapidly. This creates a situation where the magnets that are currently locked-up in the operational turbines are likely to be very different to the magnets used in new turbines, commissioned and built from 2038 onwards. The evidence already suggests turbine and motor manufacturers are employing material optimisation, composition and substitution strategies to ensure magnets can be manufactured even in a climate where demand outstrips supply.

- The magnet assemblies (arrays) are physically large components that would require knowledge, skill and suitable equipment to disassemble – to some extent the issues of design for disassembly is being evaluated within the wind industries R&D teams but turbines being commissioned now do not yet have designs that would facilitate simple and easy magnet recovery.

- The issue of whether industry favours internalised or externalised approaches to circular material flows has not been adequately answered. From the perspective of the recycling of magnets, the chemistry and specifications are of particular importance and critical to the efficiency of the design. The internalisation of EoL magnets maintains the integrity of materials and potentially reduces the need for the complex standardisation necessary if recovery, re-use and recycling were to be primarily delivered by third parties. Of particular interest in this respect are the new service driven models, where the turbine (asset) is leased by the energy supplier from the manufacturer. At EoL, the manufacturer retains full control and ownership of the asset (including the PMG magnets) and therefore has much greater levels of control over the final recovery – expansion of this model certainly presents a compelling case for creating the correct conditions for greater internal material circularity.

[39] http://www.siemens.com/innovation/apps/pof_microsite/_pof-fall-2011/_html_en/raw-materials.html

- The research has been able to establish that the magnets and the assemblies in the nacelle do vary in terms of specifications, design and arrangements between the main manufacturers – this creates an issue where one manufacturer's magnets may not practically be able to be reused in another. Common standards within the magnet and motor assembly manufacturing would substantially reduce this barrier to potential re-use (notwithstanding the above).

We can really only conclude, based on the evidence that has been reviewed in this study, that barriers to re-use are quite substantial and a far more detailed level of understanding (ideally though collaborative working with the industry) is required to reach reliable judgements. The evidence for re-use is relatively limited and subject to commercial restrictions in many cases to protect designs and specifications. The study has found anecdotal evidence that some major manufacturers are examining the end of life options for NdFeB magnets but that this research is at a very early stage and from which little conclusive facts can be drawn.

3.4.3 *Possible recycling approaches*

The recycling approaches and two main philosophies surrounding large NdFeB magnets are summarised in the following table:

Volume Driven	**Value Driven**
Early stage is standardised and volume driven unit processes: recovery of rare earth metals	*Dedicated processes for each magnet type: value driven processes: recovery of compounds*
• Minimum sorting and mechanical preconditioning; • Hydrometallurgical separation of metals; • Resulting REE mixed salt.	• Intensive sorting and mechanical preconditioning • Physical separation of fractions (plastic parts, steel, foils etc.); • Propriety technology to extract fractions of material.
Ideally, REEs are further refined to the level that they can be transformed into new materials	*Ideally, valuable materials can be recovered*
• Main effort at the end of the recycling loop • Typically large-scale volume driven installation	• Main efforts at the start of the recycling loop • Typically dedicated small-scale installations, driven to recover valuable components

3.4.4 *Strategies compared*

REE Recovery – Large Scale	**REE Recovery – Small Scale**
Energy Efficiency	*Energy Efficiency*
• Energy needed to transport waste magnets to a central recycling plant is compensated by energy efficiency of larger plant; • Excess energy could be recovered.	• Proximity principle can save on transport, however this is balanced by energy losses inherent to small scale operations; • Hydrometallurgical processes require large volumes of chemicals with high global warming potential (GWP).
Process Robustness	*Process Robustness*
• Accepts all known battery chemistries with flexibility to adapt to new chemistries; • Also suited for other materials	• Dedicated processes for well-defined magnet types; requires B2B relationship; • Unclear how the process will cope with contamination (badly sorted supply);

	• Possibly that process is totally unsuited for future magnet types.

In many respects the magnet industry for recycling NdFeB magnets is still under development and therefore strategies are limited by market status. The Öko-Institut suggests taking action in the short term in order to establish a European recycling scheme for REEs and proposes the development of a recycling scheme based on the following steps prior to a large scale implementation:

- Forming a European competence network with recyclers, manufacturers and politicians;
- Basic research is necessary as few companies in Europe are involved in rare earth refining;
- Material flow analysis to identify the main waste streams;
- Major R&D projects into the complex chemical process; and adapt the legal EU framework in order to optimise rare-earth recycling

3.4.5 *Substitution*

Although the evolution of wind turbine technology over time has allowed for lighter, more compact mechanical systems, manufacturers have only recently developed designs requiring simpler gearboxes or eliminating them completely. As each application has unique requirements set by the manufacturer, substituting materials is challenging and impacts on the following:

- Flux density;
- Energy product;
- Resistance to demagnetisation;
- Usable temperature range;
- Magnetisation change with temperature – Reversible Temperature Coefficient;
- Demagnetisation;
- Recoil permeability;
- Corrosion resistance;
- Physical strength – tensile strength, bending strength, chip resistance;
- Electrical resistivity;
- Magnetising field requirements;
- Available sizes, shapes and manufacturability; and
- Raw material cost and availability

Substituting critical raw materials with those that are more abundant is one way of addressing the resource security problem associated with Neodymium; however these materials have properties and characteristics that make them uniquely suitable for specific applications meaning that a whole system substitution might be necessary to reduce the use of critical materials.

For example, Neodymium is not the only rare earth in these magnets. Dysprosium and terbium are also used while praseodymium may also be added, depending on application. Many NdFeB magnets employ a Neodymium, dysprosium and terbium mixture in a weight percentage ratio of 29:3:1 (1% boron and 66% iron). Dysprosium and terbium help improve a magnets coercivity and resistance to high-temperature demagnetisation. One downside is that NdFeB magnets suffer a loss of magnetic output when dysprosium is added. The substitutability between Dy and Nd and how this affects the magnet properties is not well understood[40] and research in this area continues.

As NdFeB magnets are very susceptible to corrosion a variety of coating and plating options are used to protect them from the environment. They require surface preparation before coating or plating and many magnet surface treatment facilities are not familiar with this type of magnet alloy and are not capable of successfully coating or plating it. Therefore it is likely the composition and design for

[40] Evaluating United States and World Consumption of Neodymium, Dysprosium, Terbium and Praseodymium in Final products. See: http://digitool.library.colostate.edu///exlibris/dtl/d3_1/apache_media/L2V4bGlicmlzL2R0bC9kM18xL2FwYWNoZV9tZWRpYS8yMDM4ODE=.pdf

NdFeB magnets used offshore can be assumed to utilise the same end-of-life process once brought into commercial operation.

Neodymium itself is a substitute material for permanent magnets. From ferrous permanent magnets (PM) with low magnetic strength to Cobalt based PM, the magnet material has evolved over the last century. Neodymium was developed as a PM material in early 1980's, after Zaire, which produces 65% of the world's cobalt, suffered political unrest. Japan (Hitachi) with its high technology leadership was instrumental in developing the Neodymium substitute to Cobalt. Neodymium alone is not very strong, and needs another REE Dysprosium (added 5% by weight) to increase demagnetization at high temperature. Currently the Jiangxi Province of China is the sole producer of Dysprosium in the world[41]. With so much dependency on single source China, for the basic raw material for REE, poses serious supply chain risk. But this risk to the rest-of-world poses the greatest opportunity for China to develop Hybrid Electric vehicle technology as well as remanufacturing and recycling technologies. Given the concerns over supply the potential for new sources of Neodymium to be developed is high as is the potential for substitution.

Siemens approach appears to be around minimising the use of Neodymium and dysprosium along with seeking substitutes[42] including research into the design of Iron-Cobalt magnets.

[41] www.infosysblogs.com/supply-chain/2010/08/Neodymium_toyotas_pain_and_chi.html

[42] http://www.siemens.com/innovation/apps/pof_microsite/_pof-fall-2011/_html_en/raw-materials.html

4 Analysis of possible intervention points for NdFeB magnets

This section highlights the findings from the research and presents the conclusions that can be drawn around what possible interventions could be made to foster the conditions for enhanced circularity around NdFeB magnets from end of life wind turbines.

4.1 Main observations and conclusions

4.1.1 *Wind turbine market and growth of PMG turbines using Nd*

The evidence suggests that the use of wind turbines employing Neodymium in their designs (PMG) is relatively limited at present. 26 operational wind turbines (above 1.3 MW) are known to be using NdFeB magnets in their design in the UK with 12 currently being located onshore in Scotland and only 1 (a test unit in Robin Rigg) being sited offshore at present.

The growth in use of turbine designs using Neodymium is anticipated to increase however, particularly for off-shore, where the low maintenance and low weight advantages of direct drive makes a strong case. Using the best available evidence, which suggests around 186 kg of Neodymium is contained in the magnets per MW of capacity, by 2030 the amount of Neodymium 'locked-up' within the nacelles of operational wind turbines in Scotland alone is likely to be between 149 and 2,349 tonnes. The best estimate is around 616 tonnes, which when calculated on the basis of the 2008-2013 average spot price for Nd, equates to a value of just over £40 million (excluding any recovery or reprocessing costs).

The future use of Neodymium is however far from certain. Wind turbine manufacturers and those supplying the generator and magnet assemblies for PMG machines are known to be investing in research and development around material optimisation, substitution and elimination in order to mitigate some of the supply chain risks. It is very unclear what, if any, interventions could be made at this stage with regard to magnet use, research on magnet design and specification is already being driven by market forces.

The time issue also poses an issue for accurate forecasting. The evidence reviewed by the study team clearly indicates a fast pace of change in the wind industry, with technological and design advancement that rarely stands still. It would be a bold assumption to conclude that the PMG technologies (and magnets therein) are likely to be exactly the same for turbines being commissioned in 2020 or 2025 and this leads to considerable uncertainty in whether there will be a market demand for greater volumes of Neodymium in the wind market. In a recent article for the BBC[43], a key figure at Siemens was asked about the reliance on rare earths and in response to a question about continued access to Dysprosium, responded in a way that clearly demonstrates the technological pace of change around substitution and supply risk management:

"It turns out you can tweak the way you deal with your alloy so you need less. In today's magnets we have 0.7% dysprosium, and in a few years it will be all gone." Henrik Stiesdal, Chief Technology Officer, Siemens.

Such insight brings into question any assumption that could be made now about what magnet technology will be in commonplace use even within the next decade, let alone the next three. Whilst this may not diminish the soundness of the argument for greater circularity for key rare earth materials at end of life, it does make intervening now based on simple assumptions somewhat challenging and not without risk.

Having reviewed the evidence, the conclusions of the study team were that forecast annual growth (market share) in PMG turbines was likely to be:

[43] http://www.bbc.co.uk/news/magazine-26687605

- On-shore: an annual increase of 1.7% between 2015-2020, dropping back to an annual increase of 0.75% between 2020-2030; and
- Off-shore: an annual increase of 2.5% between 2015-2020, also dropping back to an annual increase of 0.75% between 2020-2030.

With respect to the forecast around the share of the market that will potentially be PMG-based turbines using Neodymium, there are no interventions that should or could be foreseen as being necessary for the Scottish Government to take at this time. The designs of these turbines have both disadvantages and advantages, which should be considered at planning stage according to the relative costs, location and specification of the array.

4.1.2 *Recovery of Neodymium at end of life*

There are two inescapable truths that dominate the findings from this research; that the Neodymium locked up in operational turbines is likely to remain in this state for a significant amount of time (at least 25 years) and that the methods for recovery of it have received little, if any, study. Both these factors would dominate a case for investment in recycling technologies at a commercial scale, even if it was to be assumed that the potential values locked up made an economically sound case for recovery, re-use and recycling. There is no practical reason why the Neodymium could not be recovered but the logistical and technological challenges require further study.

The case for recovery

Examination of information on the recycling of motors and batteries in the motor manufacturing sector indicates a significant amount of activity around recovery, re-use and recycling of rare earth elements within the components (particularly hybrid vehicles). The circular models being employed in this sector demonstrate (albeit driven by stronger regulatory as well as other factors) that there is potential value to be gained for greater assessment of the opportunities presented by end of life wind turbines.

The opportunity for the wind sector may therefore lie in greater cross-sector collaboration; on the basis that the motor industry is likely to be vastly more advanced in terms of technologies, techniques and infrastructure for Neodymium (and other materials) recovery from key components by the time the first PMG wind turbines are being decommissioned.

The evidence suggests that circularity and internalisation of material loops within the wind turbine industry is at an early stage, particularly with respect to Neodymium. Companies have sought to secure front-end supply chains but a more sustainable long-term solution would be greater internalisation of flows at the end of life. This would ensure industry is able to gain maximum value from recovery of magnets. The need for such changes may therefore represent a key opportunity to push new service driven models, which give greater control over material flows at end of life. Such models can provide a strong commercial case, but also mean fewer risks to the manufacturer when re-using or recycling the magnets. Magnet design and specifications are critical to the design and operation of PMG turbines, and therefore having tighter controls over your own materials at the end of life ensures the integrity of the magnet quality, composition and specification. Such a level of control, as well as better data sharing, may be essential if magnet re-use was to become a reality in the industry.

Design for disassembly is a major consideration in the cost-effective recovery of key materials. Well considered design can make the difference between commercial success and failure for end of life re-use, remanufacture and recovery. Wind turbines are pieces of high technology engineering, with the design centred on wind energy capture and electrical power generation efficiencies, operational resilience and maintenance reduction, rather than a design approach that puts modularisation at the forefront of the designers' minds. With trends for larger off-shore turbines to meet renewables capacity targets in Scotland, the logistics associated with turbine decommissioning, dismantling and component recovery will pose a significant challenge. Whilst there are other sectors where logistics are a challenge (e.g. steel recovery from off-shore oil and gas production), the state of development of a rare earth recycling industry can only be described as at vision stage.

However, the level of investment in specialist recycling and recovery technologies is expected to need to be considerable and the commercial case far from well proven at this point. With much uncertainty around the forecast demand and unknown ability for direct re-use of the NdFeB magnets and the Neodymium itself, it is anticipated that much of the advancement will be drive from within the industry itself as it seeks to manage risk and gain operational efficiencies.

Possible interventions

In terms of potential interventions around recovery of Neodymium, these are difficult to judge based on the evidence available at this point. Certainly, financial, technological and logistical support (possibly using partnership approaches) for development of a Scottish-based Centre of Excellence in recovery of rare earth materials would send a clear message of intent. The research team has not found evidence of one currently existing although it has found pockets or technical expertise in this area residing within the turbine and generator manufacturing companies themselves. Whether such an intervention would make sense only from a Scottish perspective remains an unanswered question; it is clear that the commercial viability of such a Centre and initiative would hinge on being able to access critical thresholds of magnets for re-use, remanufacturing etc…and with a reasonably consistent supply over time.

The magnetic properties of the NdFeB magnets are understood to be the same at end of life, meaning that re-use as a magnet in another turbine or another application is possible. However, the evidence suggests that magnet composition, quality and specifications are critically important. A possible intervention here could be an initiative to develop common standards in wind turbine generator magnet design, composition and specification. Such standards would allow the possibility for a more open material recovery loop, where end of life re-use, remanufacturing and recycling may not need to be controlled by the turbine and generator manufacturers to ensure maintenance of critical quality standards. In principle, such an intervention may be seen attractive; facilitating conditions at end of life that make it easier for partnerships between manufacturers and recyclers to exist.

However, as noted in this report, turbine magnet design, specification and composition is likely to change, potentially quite dramatically in response to some perceived future supply risks. In such a scenario, re-use and remanufacturing demand may well fall to zero, leaving only the residual market for recycled Neodymium itself. It is doubtful that the Scottish or even UK wind market would contain sufficient quantities to make such recycling models a commercial reality, although again the viability will be highly influenced by the global supply market – restrict supply enough and/or increase the demand and price high enough and recovery of even small quantities can become commercially viable (e.g. recovery of minute quantities of gold from electronic circuits). A much more detailed understanding of the NdFeB magnet specifications would be needed before the case for such an intervention could be reasonably assessed and recommended.

4.2 Recommendations

Based on meeting the renewables capacity targets set for 2020 and 2030 in Scotland, annual demand for Neodymium in wind turbines (primarily off-shore) is likely to rise; strongly in the next three to five years and more slowly after 2020. In a peak scenario, annual demand in Scotland alone may reach almost 200,000 kg in 2030, driven by a rise in large off-shore PMG turbines to meet capacity targets. In a minimum scenario, demand is predicted to peak at 16,000 kg per annum in 2015/16, falling off after this as PMG machines are perceived to be too costly/risky and high capacity geared variants favoured for new off-shore sites. In all scenarios, embedded volumes of Neodymium will rise between now and 2030, representing a potentially valuable asset to be recovered at end of the turbine's operational life. It is therefore a recommendation that further consideration is given to options around recycling this material. Conclusions on magnet re-use can not be made at this time because so little is known about the magnets and the timings are so long that both markets and technologies are likely to have substantially advanced by the time the PMG turbines in Scotland exist service. This may, for example include:

- Establishment of a rare earth materials working group, the aim of which would be to encourage, advise and collaborate with industries that might hold a valid interest in this area on the development, possibly using a partnership approach, of circular material models that are technologically and commercially viable. There is already some evidence that the wind industry is examining service-driven models, the development of which would provide an excellent vehicle for greater internalisation of the loops at end of life.

- Working in partnership with the material recycling industry and the turbine manufacturers, undertake a practical study aimed at understanding the logistical and technological challenges in recovery of the magnets from PMG turbines. This work should go beyond the simple physical considerations and also examine the commercial implications and magnet chemistry to better understand if the magnets could be recycled, who might wish to buy the recovered material and how the existing market structures might need to be adapted.

- Engagement with other sectors where use of rare earth materials (including Neodymium) is prevalent and which are already operating in Scotland. This includes the motor, defence and aerospace sectors, which already have technologically advanced infrastructure for remanufacture and recycling and are a key part of the Scottish economy. A solution that is not simply focused on the wind market may be the route to ensuring higher levels of investment, stronger contributions technically and financially and to access markets that may eventually have an interest in any recovered Neodymium.

- Development of new regulations that require the wind turbine manufacturers to consider design for recovery in new turbine models. As a big driver within the motor industry, regulatory mechanisms may be a powerful tool to ensure manufacturing companies take the necessary steps to recover the Neodymium material, although market forces and technological advancement are still anticipated to be strong drivers in this area.

The development of other interventions at this stage is not an area upon which any meaningful recommendations can be drawn. For a range of factors, many described in the preceding pages, incentives such as tax breaks for manufacturer take-back schemes, development of end of life standards and grants for investment in recycling technologies are all focused on a point in time so far ahead that any intervention at this stage may be meaningless, simply because so many variables will act to influence what happens in the intervening period.

Action taken on the basis of evidence generated through examination of a single industry sector to solve a challenge that cuts horizontally across many other sectors is not seen as being an effective solution. Collaborative action between sectors to develop new methods for recovery, new markets for recovered material and new businesses willing to invest in this is seen as being the aspiration. Here they may be a place for the Scottish government to intervene; to support investment in new research and development on the basis that the Neodymium locked up in Scottish wind turbines is only one part of the picture rather than a focal point.

5 Appendix A

5.1 Further Background information

Neodymium magnets, developed in 1982 by General Motors and Sumitomo Special Metals, are the strongest and most affordable type of rare-earth magnet consisting of an alloy of Neodymium, iron and boron ($Nd_2Fe_{14}B$). Neodymium magnets are used in numerous applications requiring strong, compact permanent magnets, such as those used in some wind turbines. On a smaller scale these magnets form the motors for cordless tools and hard drives.

They have the highest magnetic field strength and have a higher coercively (which makes them magnetically stable), but they have a lower Curie temperature and are more vulnerable to oxidation than samarium-cobalt magnets. Corrosion can cause unprotected magnets to spall off the surface layer, or to crumble into a powder. Use of protective surface treatments such as gold, zinc and tin plating and epoxy resin coatings can provide corrosion protection. Originally, the high cost of these magnets limited their use to applications requiring compactness together with high field strength as both the raw materials and the patent licences were comparatively expensive.

The cost of rare earth elements and materials made from them has increased dramatically since 2010, when the global commodities market reacted to the news that China (which is the dominant producer) was suggesting the imposition of export quotas on rare earth materials. Prices have since slipped back from 2010 highs. Demand for technologies that rely on rare earths continues to rise although investments are being made in research and development for substitutes and in technological advancement that reduces the use of rare earths for the same functionality; this applies equally to industries reliant on rare earths including, *inter alia*, the renewable energy, electronics and motor industries.

A good example of this comes from the US, where the Advanced Research Projects Agency and US Department of Energy (USDoE) have initiated the Rare Earth Alternatives in Critical Technology (REACT) programme, which aims to develop cost-effective alternatives to rare earths such as Neodymium. The programme is designed to realise alternatives to the naturally occurring minerals with unique magnetic properties that are used in electric vehicles and wind turbine generators. The REACT projects are seeking to identify lower-cost and abundant replacement materials while encouraging existing technologies to use (or recycle existing Neodymium) materials more efficiently. Some of the awarded projects are currently investigating carbon-based magnets, cerium-based magnets, iron-nickel based super magnets and iron-nitride alloy magnets as alternatives.

Principal uses of Neodymium[44]

Metal	Major applications	Use (%)
Neodymium (Nd)	Magnets	33
	Catalysts	26
	Optical	18

The following manufacturers are licenced or authorised to manufacture and sell sintered Neodymium magnets under certain Hitachi Metals' patents worldwide, except Japan.

- Advanced Technology & Materials Co., Ltd.
  Anhui Earth-Panda Advance Magnetic Material Co., Ltd.

[44] European Parliament, Science and Technology Options Assessment – Future Metal Demand from Photovoltaic Cells and Wind Turbines (as citied in Graedel, 2011).

Beijing Jingci Magnet Co.
Beijing Zhong Ke San Huan High-Tech Co., Ltd.
Ningbo Jinji Strong Magnetic Material Co., Ltd.
Ningbo Yunsheng Co., Ltd.
The Morgan Crucible Company plc
Thinova Magnet Co., Ltd.
Yantai Zhenghai Magnetic Material Co., Ltd

5.1.1 *Supply concerns*

US-based Molycorp has begun production at its Mountain Pass mine and anticipates production at full capacity (19,050 metric tonnes) by end of 2014. Molycorp also operates a separation plant at Mountain Pass, California, and sells rare earth concentrates and refined products from newly mined and previously mined above-ground stocks. Molycorp announced its purchase of Neo Materials Technology (renamed Moly Canada), a rare earth processor and producer of permanent magnet powders which has facilities in China. In March 2012, the Obama Administration announced the filing of a World Trade Organization case against China, citing unfair trade practices in rare earths. A final decision is expected to be announced in early 2014[45].

According to the Ministry of Economy and Industry (METI) of Japan, prices for dysprosium and Neodymium rose dramatically between 2008-2103. Most noticeably, the price for Neodymium metal rose from $42/kg in April 2010 to $334/kg in July 2011. Spurred by economic growth and increased consumer demand, China is ramping up for increased production of wind turbines, consumer electronics, and other sectors, which would require more of its domestic rare earth elements. Safety and environmental issues may eventually increase the costs of operations in China's rare earth industry as domestic consumption is becoming a priority for China. REE manufacturing is set to power China's surging demand for consumer electronics—cell phones, laptops and green energy technologies. According to the report by Hurst, China is anticipating going from 12 gigawatts (GW) of wind energy in 2009 to 100 GW in 2020. Neodymium magnets are needed for this growth.

China's policy initiatives restrict the exports of Neodymium materials and it is unclear how much the export restrictions affect exports of downstream metal and magnets. According to a report produced by Congressional Research Service, US; China wants an expanded and fully integrated REE industry where exports of value-added materials are preferred (including consumer products). It is common for a country to want to develop more value-added production and exports if it is possible. China's goal is to build-out and serve its domestic manufacturing industry and attract foreign investors to participate by locating foreign-owned facilities in China in exchange for access to rare earths and other raw materials, metals and alloys, as well as access to the emerging Chinese market.

However, some foreign investors are hesitant to invest in China because of the concerns related to technology sharing. Also, the September 2010 maritime conflict between China and Japan in which Japanese officials claimed that China held up rare earth shipments to Japan (denied by Chinese officials) which has heightened the urgency among many buyers to seek diversity in its sources of rare earth materials.

5.2 Supply Chain

This section provides a summary of key elements of the supply chain process for Neodymium magnets. Figure 3.2 shows the supply chain flow summary chart based on what the literature suggests is a more common linear 'take-make-consume-dispose' model.

Figure 3.2 Supply-chain map for Neodymium permanent magnets

[45] Congressional Research Service, Rare Elements: The Global Supply Chain. See: http://www.fas.org/sgp/crs/natsec/R41347.pdf

The supply chain for ND and Nd-based magnets is discussed in greater detail within Appendix A. Key observations noted during the analysis of the literature and evidence includes:

- **The global nature of the supplier networks and the level of interconnectivity**; the evidence indicates that in regard to both the initial processing and end of life recovery of rare earths, the manufacturers rely on often long distance movements of the materials around the globe (even to the extent that some process steps may occur in different geographies;

- **There are obvious opportunities from advanced reverse logistics**; but there is evidence that in some cases, particularly where the circular material flows are internalised within one organisation, this is already happening as part of operational efficiency;

- **Supply chain resilience is a big issue for organisations whose models rely on a steady supply of rare earth materials**, and the evidence points to supply chain strategies that include strategic alliances, joint ventures, longer-term supply contracts and investment in the exploration and production in new mineral and ore-rich areas outside of China.

- **There is evidence of rare earth closed loop re-use and recycling supply chains**, but this applies to industries including the aerospace and motor vehicles (use of batteries and direct drive motors) rather than the wind turbine industry. Anecdotally, turbine and turbine motor manufacturers do acknowledge the opportunities from closing material loops at end of life but there is little in the way of concrete evidence to suggest a lot of action being taken at this point in time. Internalisation of the loops appears to be a key driver.

5.2.1 *Mining and Production*

Currently, the majority of the production, mining and concentration of the Neodymium ores take place in China. Processing is complex as the individual elements like Neodymium are chemically similar to other elements such as dysprosium meaning each ore body requires specific technology unique for that particular deposit to be developed in order to extract and separate the rare earth elements[46].

The Chinese government announced in 2010 that it intended to restructure the rare earth mining industry under the umbrella of a few world-class mining and metal conglomerates for greater efficiencies and to reduce environmental degradation. In addition to the consolidation of the industry and environmental cleanup efforts, investor analyst Jack Lifton reports that China is building strategic stockpiles of rare earths and other critical materials that could meet domestic demand for several years with South Korea and Japan also building strategic stockpiles[47]. The level of stockpiling could have a dramatic impact on the market.

5.2.2 *Purifying the Metals*

The next stage is to refine and purify the rare earth oxides into their metals using ion-exchange purification to achieve the highest purities. For 2015, over 95% of dysprosium and over 90% of

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[46] OECD, October 2009. Export Restrictions on Strategic Raw Materials and their Impact on Trade and Global supply.

[47] "Implications for Investors of the Dramatically Increasing Chinese Demand for Rare Earths," Jack Lifton, Technology Metals Research, June 15, 2011, http://www.techmetalsresearch.com.

Neodymium production is forecast to be consumed within permanent magnets[48]. For the forming of the metals into magnet alloy powders and the manufacturing of the actual magnet, intellectual property plays a significant role in the supply chain.

5.2.3 *Manufacturing process*

Fully dense NdFeB magnets are usually manufactured by a powdered metallurgical process. Micron size Neodymium and iron-boron powder is produced in an inert gas atmosphere and then compacted in a rigid steel or rubber mould. The rubber mould is compacted on all sides by fluid; referred to as isostatic pressing. The steel moulds will produce shapes similar to the final product, while the rubber mould will only create large blocks (loaves) of NdFeB magnet alloy. The magnetic alloy's performance in both compacting methods is optimised by applying a magnetic field before or during the pressing operation. This applied field imparts a preferred direction of magnetisation or orientation[49] to the NdFeB alloy. The alignment of particles results in an anisotropic[50] alloy and vastly improves the residual induction (Br)[51] and other magnetic characteristics of the finished magnet.

Two main types of permanent magnets are produced: higher performance sintered magnets for electric drive and wind turbines applications and bonded magnets for other applications such as electronics[52]. The respective master patents are controlled by two firms: Hitachi Metals (as previously cited) and Magnequench, a Chinese–backed consortium. For locations of NdFeB manufacture, it has been estimated that currently 75-80% occurs in China, 17-25% in Japan and 3-5% in Europe[53].

The magnets are then used as components for a range of applications of which hard disc drives (31%), generator motors (26%) and automobile (24%) are the major uses. Other applications include optical devices, acoustic applications and MRI. With the exception of hard disc drives, most of these applications have long lifetimes, meaning that only limited volumes of permanent magnets are presently occurring in the waste stream.

5.2.4 *Nd use in wind turbines*

Wind power technology has evolved over the last 40 years – from being able to produce 20 kW per turbine in the 1980's to being able to produce up to 7.5 MW per turbine today[54]. The trend towards ever larger turbines has stabilised during recent years. Currently land-based turbines (98% of all installed capacity) are mostly rated at the 750 – 850 kW, the 1.5 – 2 MW or the 3 MW range. For offshore machines however, both industry and academia see larger turbines (10-20 MW) as the future.

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[48] Critical Metals in Strategic Energy Technologies – *Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Technologies*. JRC Scientific and Technical Reports.

[49] An oriented (anisotropic) material is one that has better magnetic properties in a given direction; also known as "Axis".

[50] Anisotropy, literally means having different properties depending on the inspected direction. Magnets which are anisotropic, or have an easy axis of magnetisation, have their anisotropy developed by two methods: Shape and Magnetocrystalline.

[51] Br, Residual Induction (or flux density), is the magnetic induction of corresponding to zero magnetising force in a magnetic material after saturation in a closed circuit; measured in gauss.

[52] US Department of Energy (2010), Critical Materials Strategy

[53] Oko-Institut (2011), *Study on Rare Earths and Their Recycling*

[54] European Commission (Institute for Energy and Transport, Joint Research Centre (JRC)). (2011b). Critical Metals in Strategic Energy Technologies

The main lines of research for larger turbines has been in drive-train innovations and efficiency gains, light-weighting the nacelle, blade design and the logistics of operating in deepwater offshore environments. Drive train research has led to simpler nacelle systems, increased reliability and enhanced efficiency and in the case of direct drive, an absence of gearbox maintenance issues. Drive-direct solutions may use permanent magnets that contain rare earth metals such as Neodymium, which are of interest to this study, although other technologies include copper electromagnets and (not yet commercially proven) High Temperature Superconductor (HTS) systems.

The European Wind Initiative (EWI) is the technology roadmap to reduce the cost of wind energy. Its implementation will help improve the competitiveness of the industry by ensuring large-scale deployment of wind energy worldwide and securing long-term European technological and market leadership. In addition, the EWI aims at ensuring that aspects other than technology are met in order to facilitate the deployment of wind energy. The strategic objectives of the EWI are:

- To maintain Europe's technology leadership in both onshore and offshore wind power;
- To make onshore wind the most competitive energy source by 2020 with offshore following by 2030; and
- To enable wind energy to supply 20% of Europe's electricity in 2030, 33% in 2030 and 50% in 2050.

Depending on the combination of technologies used, the volume and type of metals required for the manufacturing of a wind turbine will vary. When looking at metal use in wind turbines, those that have permanent magnet generators are of special interest since they incorporate a wider range of metals. The reason for this is that permanent magnets have to be very strong in order to work as a substitute for electromagnets (which is most commonly used), with the strongest magnets available being NdFeB magnets that incorporate several metals.

5.2.5 *Re-use, recycling and recovery processes for Nd magnets*

In general the recycling and recovery of rare earth elements occurs at low levels and it is reported that less than 1% of rare earth elements are recycled from old scrap, mainly from old magnets[55]. Pre-consumer waste is an issue for NdFeB magnets; they are brittle and fracture easily, creating scrap materials within the manufacturing process. An estimated 20-30% of the magnet material is scrapped during manufacturing due to breakages and waste cuttings[56]. At present it is cheaper to buy newly manufactured magnets than to reprocess the scrap material, and typically the scrap materials can end up in generic scrap metal waste streams.

As for post-consumer magnets, many of the products (such as electric vehicles) within which the magnets are contained have long lifetimes and are not expected to reach their end-of-life in the near future. For example, the low numbers of end-of-life hybrid electric vehicles mean that this is not yet viable or cost-effective to implement systems for the recovery and recycling of rare earth magnets, although it may become attractive in the second half of this decade[57]. Similar dynamics apply to the magnets used in wind turbines, though on a longer time scale, as permanent magnet wind installations have only begun and have a typical lifespan of 25 years.

A general flow diagram of the processes involved in the manufacture and reprocessing of Nd-magnets is outlined below. In the manufacturing procedure, up to 30% of unused starting alloy can be generated as a consequence of the cutting, grinding and polishing steps. Encouragingly, these

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[55] European Commission (2010). *Critical raw materials for the EU*.

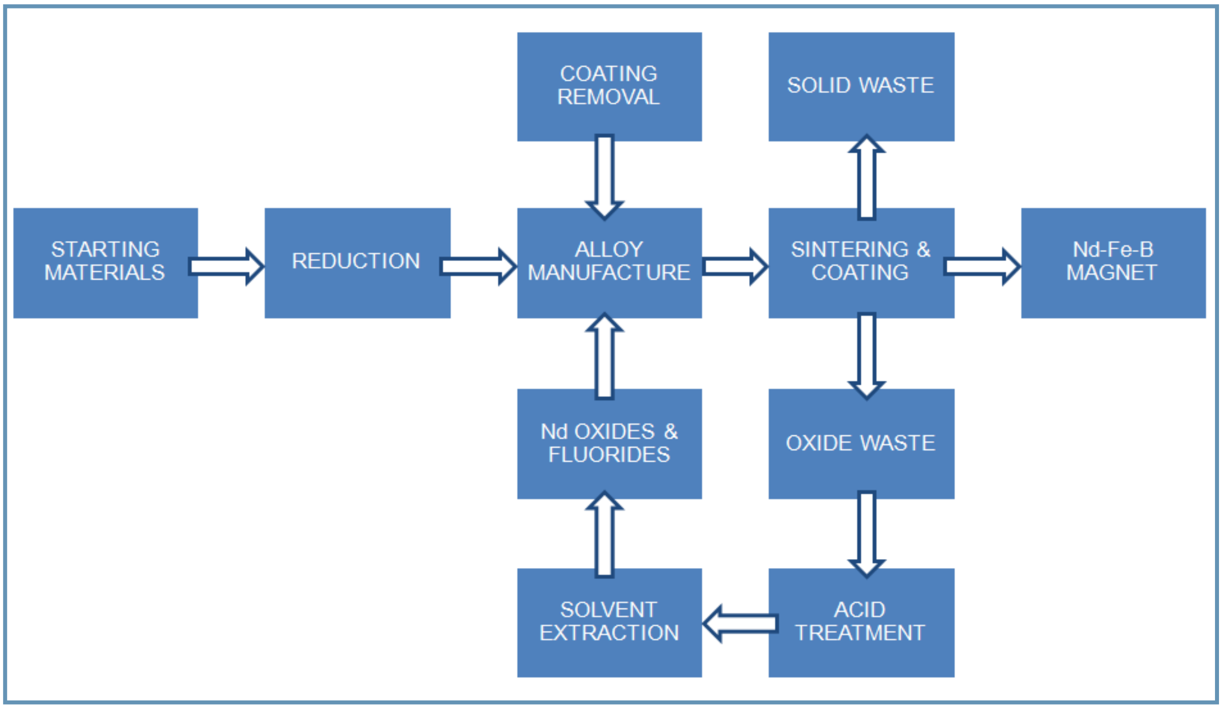
[56] Critical Metals in Strategic Energy Technologies – *Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Technologies*. JRC Scientific and Technical Reports (as cited in Akai 2008).

[57] Oakdene Hollins for EPOW (2011), *Study into the Feasibility of Protecting and Recovering Critical Raw Materials through Infrastructure Development in the South East of England*.

residues are often currently recycled by the relevant manufacturing companies where up to 95% of solid material is recovered. This process involves roasting steps to oxidise the alloy residues fully, followed by several hydrometallurgical methods (acid treatment and solvent extraction) before conversion before conversion to the rare earth oxides and reduction to the metallic forms by either thermal reduction or salt electrolysis.

Direct recovery of Neodymium from NdFeB magnet scraps and other Nd containing scraps by continuous extraction with molten magnesium and with silver, was investigated by the group of Takeda, resulting in the formation of MdNd and AgNd alloys. The Neodymium metal was subsequently obtained at 98% purity by removal of the magnesium through sublimation and, in the case of silver, Neodymium was recovered in greater than 90% yield as the oxide (Nd_2O_3) following oxidation in air.

Fractional crystallisation of Neodymium and iron has been demonstrated by Sato and co-workers by selective crystallisation of $Nd_2(SO_4)_3\ 8H_2O$ and Nd2(SO4)3 5H2O from sulphuric acid-water mixtures in the temperature range 0-80°C and at 80°C respectively. Addition of ethanol sufficiently reduced the solubility of the sulphate salts, permitting the recovery of hydrates of Neodymium sulphate in 96.8% purity and in 97.1% yields with respect to the original Neodymium-iron-born magnet scrap sample. Sulphuric acid has additionally been employed in whole leaching of Nd-magnet waste by precipitation of Neodymium ammonium or sodium sulphate. In this process the iron is removed by precipitation as the sulphate mineral jarosite, K[Fe3(OH)6(SO4)2]. It has been suggested that the boron may be precipitated as zinc borate.



5.2.6 *The metals in a wind turbine*

The metals that can be found in different parts of different wind turbines are summarised in the following table.

Table 5.1 Elements found and used in different types of wind turbines[58]

[58] European Commission (Institute for Energy and Transport, Joint Research Centre (JRC)). (2011b). Critical Metals in Strategic Energy Technologies

Metal	Class	Use	Other uses
Aluminium (Al)	N	NdFeB-magnets, turbine body	Construction, transportation, packaging, electrical transmission lines, heat sinks, coins, magnets
Boron (B)	S	NdFeB-magnets	Glass, ceramics. NdFeB magnets, detergents, insecticides, semiconductors, shielding
Cobalt Co)	S	SmCo-magnets	Super alloys, catalysts, Li-ion batteries, synthetic fuels
Copper (Cu)	N	Electromagnets, wires	Construction, electrical transportation, industrial machinery, efficient electric motors, RFID, photovoltaic's
Chromium (Cr)	F	Turbine body steel alloy	Seawater desalinisation, marine technologies, photovoltaic's
Dysprosium (Dy)	R, S	NdFeB-magnets	NdFeB magnets (for computers, audio systems, automobiles, household app, MRI)
Iron (Fe)	F	NdFeB-magnets, turbine body	Construction, transport, tools, alloys
Molybdenum (Mo)	F	Turbine body steel alloy	High temperature alloys, special fertilisers, solid lubricants, photovoltaics
Manganese (Mn)	F	Turbine body steel alloy	Steel alloys, aluminium alloys, fuel additive, batteries, pigments
Nickel (ni)	F	Turbine body steel alloy	NiMH batteries, alloys, alnico magnets, photovoltaics
Neodymium (Nd)	R, S	NdFeB-magnets	NdFeB magents (for computers, audio systems, automobiles, household app, MRI), catalysts, optical glass, lasers
Niobium (Nb)	F	NdFeB-magnets	Steel production, super alloys, super magnets, electro ceramics, hypoallergenic applications, numismatics
Praseodymium (Pr)	R, S	NdFeB-magnets	NdFeB magnets
Samarium (Sm)	R, S	SmCo-magnets	Military equipment, catalysts, nuclear reactors
Terbium (Tb)	R, S	NdFeB-magnets	NdFeB magnets (for computers, audio systems, automobiles, household app)

Metal classification by UNEP (2011)[59]. F – ferrous metal; N – non ferrous metal; P – precious metal; S specialty metal.

5.3 Magnet (Nd) market trends and applications

As discussed within this report one of the key applications for Neodymium is that it is a constituent of the strongest permanent magnets available These are used in a range of modern technologies including[60];

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59 UNEP (2011). Recycling Rates of Metals – A Stauts Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel [online]. http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf

- Wind Turbine generators;
- Microphones;
- Loudspeakers;
- Computer hard drives;
- Industrial motors;
- Hybrid cars (electric motor);
- Mobile phones; and
- Medical equipment.

There has been sufficient research conducted to date to being to draw conclusions around the projected increase in demand for Neodymium-based magnets in some of the above applications, in particular hybrid cars[61] and wind turbine generators[62]. A range of figures is suggested and each study shows variations on the theme of a rising demand curve. A 2012 study by the Massachusetts Institute of Technology's Materials Systems Laboratory concluded that demand for Neodymium will rise by as much as 700% over the next 25 years[63].

Neodymium it is a critical component for electric vehicle development across the world and companies such as Toyota have estimated that the "average annual demand for Neodymium in 2010 was 29,000 metric tonnes with an estimated annual growth in demand of 13%"[64].

This rise in demand has resulted in some instability in the supply of the market. A 2011 PricewaterhouseCoopers (PwC) survey of the largest clean energy manufacturers showed that 78% of them where experiencing instability in the supply of rare earth metals and most said they did not expect shortages to ease for at least 5 years[65]. Such conclusions should be set within the context of a significant spike in the market prices for REEs around 2010-11 as a reaction to the introduction of export quotas postured by the Chinese[66]. Some commentators cite the growth in internal demand for REEs within China as being one of the reasons it has considered reserving a large amount of rare earth minerals for its own industries. Such supply-side constraints are linked to rapid rises in the material and manufacturing costs for key technologies, particularly for those countries, such as the UK, which are 100% reliant on imports to meet consumer demand. Such conditions also create the necessary conditions and drivers for the economics, logistics and commercial case for extraction of Neodymium from end of life products to be revisited.

5.3.1 *Growth / trend projections for Nd*

Section 2.3 of this report identified the Scottish and UK policies which may act as drivers in regards to the future use of on-and-offshore wind. The UK currently has the largest offshore wind market with more capacity currently deployed than anywhere else; this is anticipated to remain the case until 2020 and beyond[67]. The Scottish Government has a target of generating 50% of Scotland's electricity from

[60] http://www.oeko.de/oekodoc/1112/2011-003-en.pdf

[61] http://www.thegreencarwebsite.co.uk/blog/index.php/2013/10/02/hybrid-and-electric-vehicles-to-make-6-of-new-car-market-by-2020/

[62] http://www.scotland.gov.uk/Publications/2013/06/5757/2

[63] http://au.ibtimes.com/articles/327503/20120413/rare-earths-china.htm

[64] http://www.infosysblogs.com/supply-chain/2010/08/Neodymium_toyotas_pain_and_chi.html

[65] http://www.globalresearch.ca/shortages-of-rare-minerals-china-s-strategic-control-over-terbium-yttrium-dysprosium-europium-and-Neodymium/29033

[66] http://www.infosysblogs.com/supply-chain/2010/08/Neodymium_toyotas_pain_and_chi.html

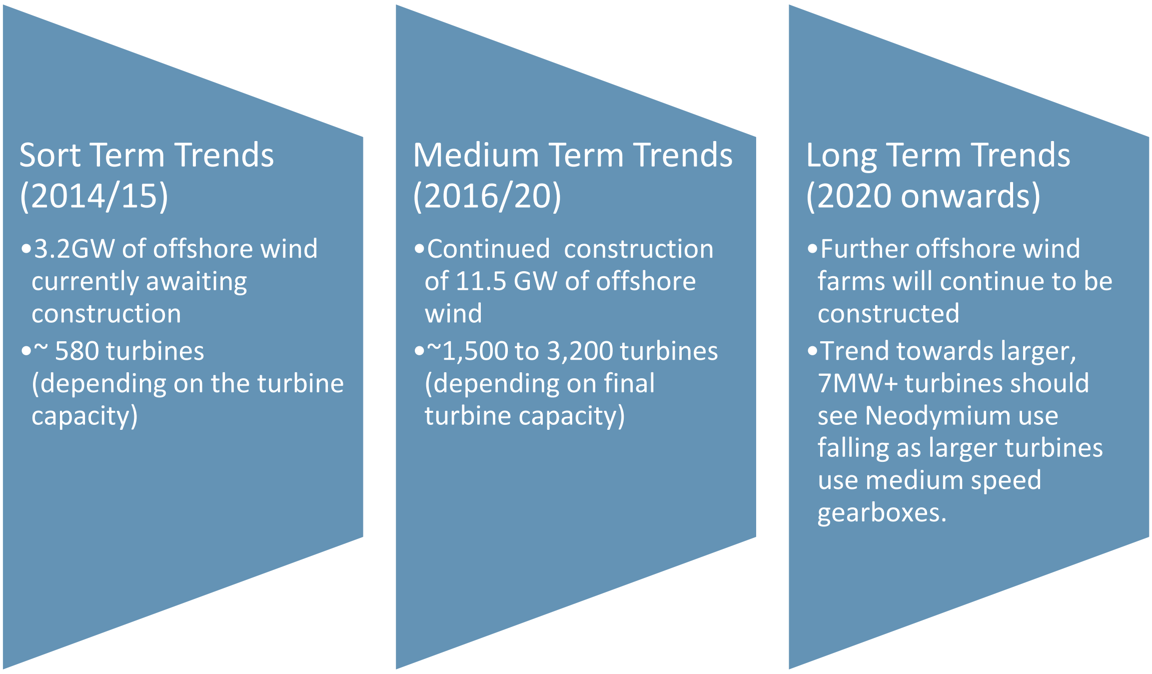
[67] 2013 DECC Renewable Energy Roadmap

renewable energy by 2015, and 100% by 2020[68] and it is estimated that 13GW of installed wind capacity will be required in Scotland to meet these targets[69]. Therefore as suggested previously in this report there is still plenty of wind capacity still to be developed.

Based on the future trends identified in Section 2.3 of this report (summarised in the figure below) it looks that the number on-and-offshore wind is set to increase and therefore increasing the demand for Neodymium for manufacturing in the short/ medium term. Depending on the life span (suggested 20-30 years) and maintenance of the on-and-offshore wind turbines the number of used magnets could potentially increase from 2034 and continue to increase. Figure 3.3 illustrates some of the short, medium and longer term trends in the wind turbine/renewables industry.

The large offshore assemblies have an estimated lifetime of 25 years, it is unlikely Neodymium will be recycled from end of life turbines for the next two decades. This leaves the market for recycling Neodymium from wind turbines underdeveloped and reduces pressure on companies to close the loop for Neodymium recycling and recovery. Reuse of these materials will rely on an improved understanding of magnet shape, characterisation and disassembly. The latest trends also indicate larger offshore assemblies will be developed in the coming years signifying larger material concentrations.

Figure 3.3 Trends in the wind turbine market (UK and Scotland)



There are other applications for Neodymium such as hybrid vehicles where the batteries and motors (containing Neodymium) are likely to reach end of life in the next 5 to 10 years. There will therefore be a need to recycle these items long before the wind turbines are decommissioned and the UK's infrastructure will be more likely to develop around the automotive sector than the Neodymium magnets from wind turbines in the medium term. The volume of Neodymium (65 - 200 kilo) per magnet in wind turbine nacelles will however be attractive to the recycling infrastructure due to the high volume of the valuable resource in a single source. This will however be offset somewhat if the

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[68] http://www.scotland.gov.uk/Publications/2013/06/5757/2

[69] http://www.scotland.gov.uk/Publications/2013/06/5757/5

magnet is not accessible i.e. there has been a poor design for disassembly process applied by the nacelle manufacturer.

The use of hybrid and electric vehicles in the UK is also predicted to increase over the coming years. In 2012 hybrids and electric vehicles accounted for just 1.4% of the UK market. However sales of hybrid and plug-in electric vehicles are projected to reach 6.6 million sales annually by 2020 to represent almost 7% of the global market for light duty vehicles.

As part of this project it was not possible to identify the lifetime of the electric motor and batteries used in cars. However Toyota offers an 8 year warranty on the Prius electric motor which suggests they should last at least 8 years. Based on this assessment the market is set to increase however it is not clear when the used components will arise. Every Prius is estimated to have approximately 1 Kg of Neodymium present in its batteries and as highlighted above, Toyota are already extracting the Neodymium from the batteries which suggests it is viable operation however, the replacement period for batteries is 3-5 years providing a more immediate opportunity (and a regular medium term flow of material) for recycling than the 25 year lifespan of the Wind turbine nacelle. This is consistent with Toyota's sustainable development commitments to contribute to a recycling based society[70] and has to date collected 30,000 hybrid vehicle batteries for recycling. Toyota's model is different from the wind turbines as the Toyota model currently offers a constant stream of feedstock with corporate support and vision. The wind turbine model offers no materials out until the 2030's and then bulk amount of Neodymium over a 3 - 5 year (or so period) in line with current known developments. Toyota's model therefore is far more investable and sustainable than the wind turbines. Needless to say Toyota's model (and other similar models) will take advantage of the bonanza of Neodymium produced the decommissioning period but this will be dependent on the market value of Neodymium and the abundance of substitutes (materials and technologies) in 25 years time as well as factors such as the accessibility of the magnets in the nacelle.

The REEs are the essential "protozoa" of 21st Century products and China is in the driver's seat to fuel worldwide growth and China has a 97% monopoly in production of these elements. The supply chain risk is higher for permanent magnet electric vehicle components that are not manufactured by the OEMs like Toyota, but by their Tier-1 and Tier-2 suppliers. The manufacturer of Neodymium magnets are further down in the supply chain tiers. These manufacturers do not yield so much clout and influence to ensure regular supply of REE raw material. This risk has been further heightened with China's restriction of REE raw material exports by around 72%[71]. Though this measure has been taken to establish a unified price mechanism and prevent the indiscriminate mining and safeguard the environment, the raw material supply of REE to these low-tier suppliers looms large. To ensure supply security, Toyota through one of its subsidiary Toyota Tsusho Corp is setting up a JV with Sojitz Corp of Vietnam, to develop the Dong Po deposits of REE. But this will again serve only about a quarter of Japan's demand for Lanthanum (10-15 kilo per hybrid vehicle), Cerium and Neodymium so EoL sources will continue to be of significant interest to Japan (and Toyota) to continue growth in high tech applications for the 21st Century. To develop the green technology in automotive industry, the quest for further diversified sources of material and substitute material will continue.

5.3.2 *Worldwide trends and applications*

There are no exact figures for the world reserves of Neodymium, however with an estimated 50% of world reserves of all rare earth metals china dominates the world supply[72]. The table below illustrates the estimated world supply of Neodymium in 2010. As highlighted previously China are a key player when it comes to the supply of Neodymium, it has been suggested 95% of world Neodymium being

70 http://www.toyota-global.com/sustainability/report/sr/pdf/sustainability_report13_me.pdf

71 www.infosysblogs.com/supply-chain/2010/08/Neodymium_toyotas_pain_and_chi.html

72 http://www.fas.org/sgp/crs/natsec/R41347.pdf

supplied by China[73]. With so much dependency on single source this potentially poses a risk to the supply of this material[74] and the stability of the market.

Material	World Supply, 2010 (tonnes)	Primary Producing Countries (%)	Major Applications (%)	US	Price – ($/kg)
Neodymium	21,000 [75]	China (98%) India (2%)	Magnets (76%) Metallurgy (8%) Battery alloys (5%)	Y	Metal (06.12.12) $100-$110 Metal oxide (06.12.12) $70-$80

As identified previously in this section of this report China is now reserving a large amount of rare earth minerals for its own industries which has resulted in cost increases as shown in the figure below. "The price spike of 2011 is reflective of the export restrictions put in place by China and resulted in a twenty-fold increase in price over a few months"[76]. With China currently supplying so much of the Neodymium to the rest of the world this could potential help driver an increase in recycling of this material.

Figure 1: Changes in World rare earth metal prices (2008-2013) [77]

[73] http://www.infosysblogs.com/supply-chain/2010/08/Neodymium_toyotas_pain_and_chi.html

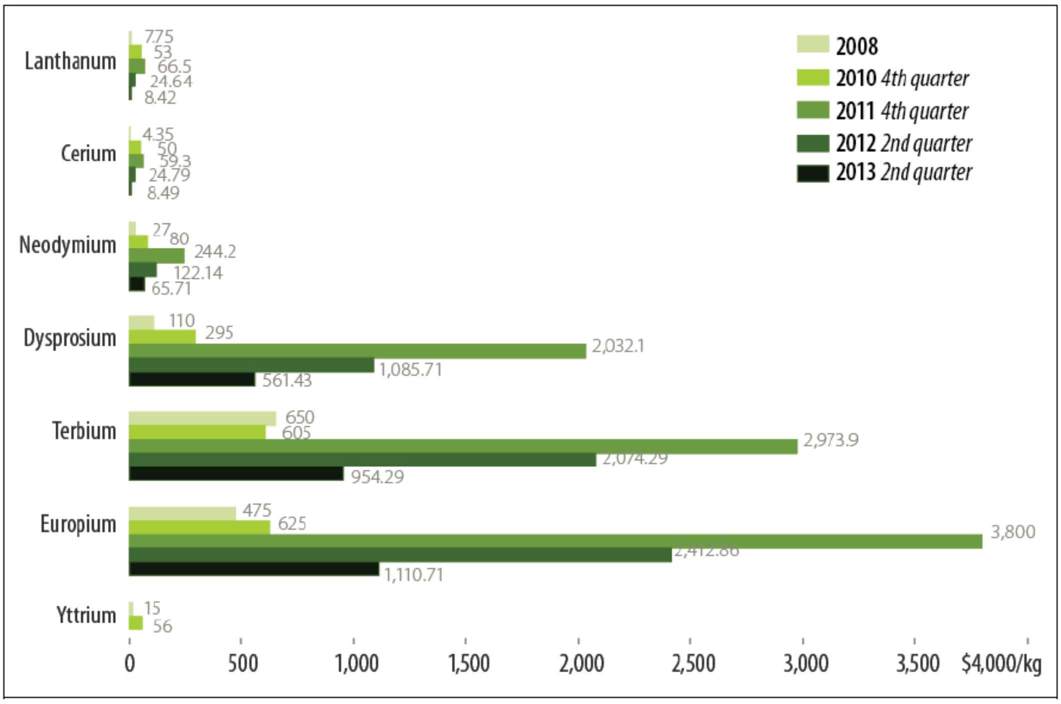
[74] http://www.infosysblogs.com/supply-chain/2010/08/Neodymium_toyotas_pain_and_chi.html

[75] British Geological Survey, Rare Earth Elements, 2011.

[76] Changes in World rare earth metal prices (2008-2013), http://www.fas.org/sgp/crs/natsec/R41347.pdf[3].

[77] Changes in World rare earth metal prices (2008-2013), http://www.fas.org/sgp/crs/natsec/R41347.pdf[3].

Figure 3. Selected Rare Earth Oxide Prices, 2008-2013
(US $/kg)



Source: IMCOA, 2011, 2013 and METI, 2011.

The European Wind Energy Association (EWEA) suggest that the demand for Neodymium and dysprosium by the European wind power sector will be less than 1% of world supply in both the 2020 and 2030 timeframe. A European Commission Joint Research Council (JRC) report has predicted the use of Neodymium in the wind industry will be between 1.1% and 4.0% as shown below. There are some discrepancies in the figures quoted however it does suggest in regards to the wind power sector that that the EU will not be a major producer compared to other continuants[78].

2020

- The European wind industry will use between 326 and 635 tonnes, between 1.8% and 3.5% of world (2010) supply

2030

- The European wind industry will use between 192 and 730 tonnes, between 1.1% and 4.0% of world (2010) supply

5.4 Current EoL Practices and technology

According to K.A. Gschneidner, Jr. of the Ames Laboratory, U.S. Department of Energy and Department of Materials Science and Engineering Iowa State University, there is little recycling of rare earth containing products, except in Japan. For example, the Shin Etsu Chemical Co Ltd uses ion-exchange, dehydration and calcination to recover rare earth elements from manufacturing product waste streams. However, wastage still occurs in industries such as magnet production, where cutting scraps are not reclaimed as no mechanism exists for recovery at present.

The estimated recycling rate for Neodymium (as well as many other lanthanides), is less than 1% globally. Furthermore, the more recent use of Neodymium for use in large-scale wind turbines means

[78] The European Wind Energy Association (EWEA), EWEA response to the Joint Research Centre and Institute for Energy report

that most countries lack the necessary infrastructure to collect, separate and recycle it. Finally, as a lot of these materials are used in products that have long lifetimes (such as wind turbines or electric vehicles), they will only reach the waste stream several years after their production.Recycling of Neodymium in the UK is problematic. In a UK-focused report on the possible routes for recycling REEs (including Neodymium), it was concluded that it is both difficult and expensive due to the nature of the products and the dispersion of the materials[79]. Factors such as geographical limitations (i.e. end of life materials arising far from the point of manufacturing); logistics (collection, transportation and transfrontier movement) and the total volumes available have so far presented substantial market barriers to increased REE recycling. Such difficulties have resulted in Neodymium magnet recycling rates being less than 1% globally. The major advances in the technologies are being led by Japan. In the UK, REE recycling is led by Great Western Minerals Group and their subsidiary company Less Common Metals Limited.

In other areas Mitsui Metal Mining Co in Japan is to recycle rare earth elements from NiMH batteries and General Electric (GE) is looking at recycling REEs from light phosphors and magnets as well as investigating alternative magnet technologies[80].

A host of potential recycling technologies exist in research stages, which may or may not reach commercialisation. The following are examples of such technologies regarding Neodymium with the most likely commercial operation to be produced by Hitachi Metals Limited:

5.4.1 *Hitachi Metals Ltd*

Hitachi Metals

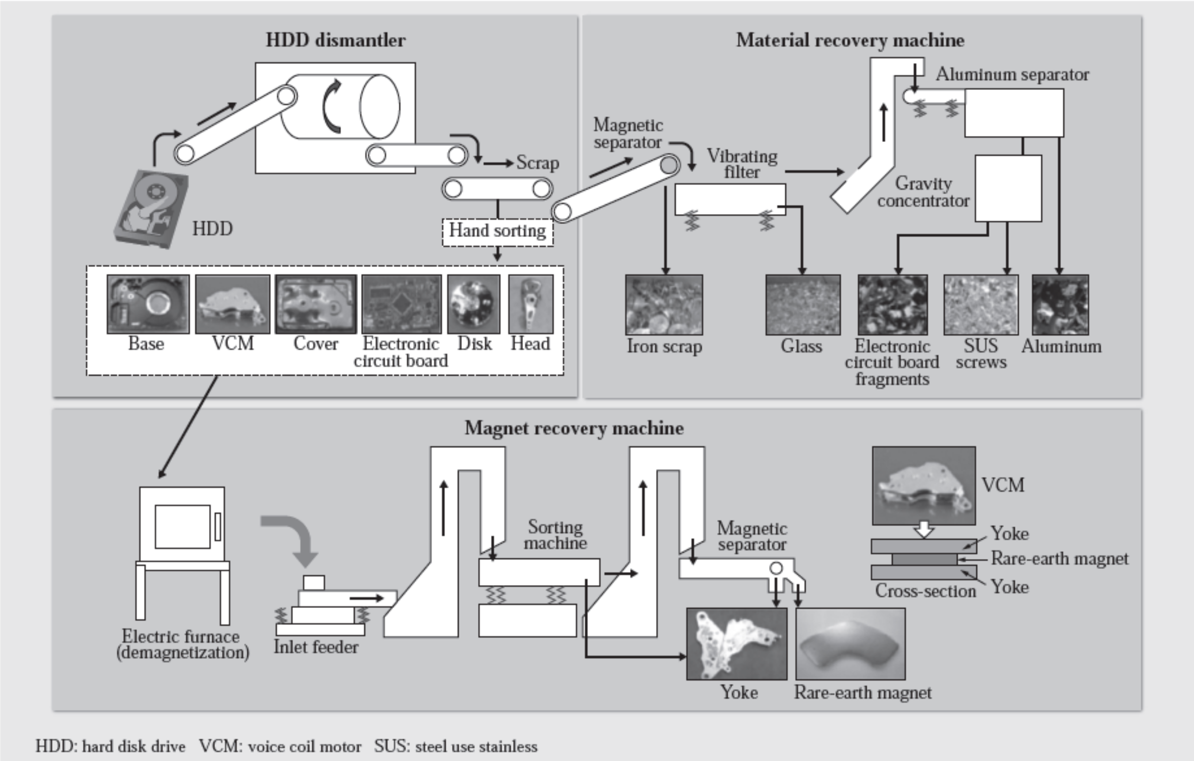
Hitachi has developed magnet recovery machines designed for use with specific products that contain rare earths, specifically hard disk drives (HDDs) and air conditioning compressors. For example, the electric motors in HDDs contain Neodymium stemming from the voice coil motors. The figure below shows the process used to separate and recover the magnets.

Rare earth magnet recovery from HDDs

Figure 1 – Process used to separate and recover rare-earth magnets from HDDs

[79] Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, AEA Technology. See: http://www.ricardo-aea.com/cms/assets/Bullet-boxes/ReportReview-of-the-Future-Resource-Risks-Faced-by-UK-Business-and-an-Assessment-of-Future-ViabilityJan2011.pdf

[80] http://inhabitat.com/ge-developing-new-magnets-that-could-reduce-demand-for-rare-earth-metals/



Source: Hitachi

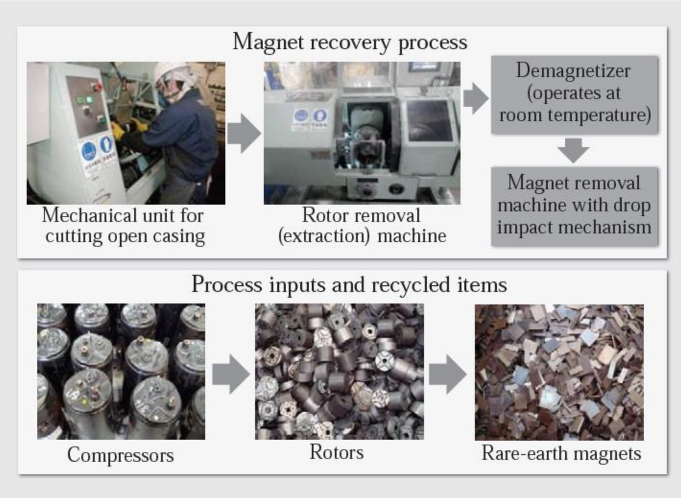
The process used to separate and recover the rare-earth magnets. While the development of a HDD dismantler that removes voice coil motors from HDDs and demagnetises them has already been completed, Hitachi has also developed new recovery machines for the magnets and other material respectively. The magnet recovery machine automatically removes and separates the magnets from the demagnetised voice control motors and the material recovery machine effectively recovers the different materials from the scrap left over by the HDD dismantler. The voice control motors disassembled by the HDD dismantler are then demagnetised in an electric furnace, but the external yoke and rare-earths that make up the voice control motors remain joined by a carbonised adhesive. The magnet recovery machine then separates the rare-earths from the yoke, using a machine for performing the process.

The scrap from the HDD dismantler contains iron, glass, electronic circuit fragments, steel and aluminium. The material recovery machine uses a combination of techniques, including a magnetic separator, vibrating filter, and gravity concentration to separate and recover the different materials from the mixture. As electronic circuit board fragments in particular contain precious metals, this process acts as a form of precious metal recovery.

Rare earth magnet recovery machine for air-conditioners

Magnets are also used in compressors of energy-efficient air conditioners. The process used to recover these includes a mechanical unit for cutting open the casing, a rotor removal machine that extracts the rotor from the motor, a demagnetiser that operates at room temperature using resonance damping demagnetisation, and magnet removal machine with a drop impact mechanism. The basic technologies for these already exist, however while all compressors may have the same basic design, there are minor differences in the shapes and structures used by different manufacturers that the system must be able to cope with. Hitachi has addressed this by enhancing the practicality of the machine through improvements to increase operational performance and processing speed. This included modifying the process to work with compressors which have elliptical section shapes for example.

Figure 2 – Process used to separate and recover rare-earth magnets from air conditioners.



Preparations for Commercial Operation

Tokyo Eco Recycle Co Ltd is a Hitachi Group company based in Koto ward, Tokyo that was founded as a recycling business for recovering resources from home appliances and personal computers (PCs). It has been using the aforementioned magnet recovery machines on HDDs and air conditioning compressors since 2012 with a trial proceeding smoothly which is producing magnets in the order of tons. The plan is to increase plant utilisation by increasing the quantity of material collected from the market in-line with the available processing capacity.

While the recovery of Neodymium and other rare earth magnets is the primary purpose of the newly developed machines, they are also designed to separate other materials in order to gain 'best value'. The overall aim is to guard against fluctuations in the price of rare earth magnet material by augmenting the business through the sale of other materials.

5.4.2 *REMANENCE European FP7 Project*

REMANENCE brings together industry and academia across the supply chain to develop the innovative technologies, business models and market information required to reduce dependence on primary resources, namely Neodymium. The project aims to develop a new process for the recovery and recycling of NdFeB magnets from a range of waste electronic and electrical equipment (mainly HDDs). Advanced sensing and mechanical separation techniques are being developed in combination with innovative processes to recover the rare earth magnets in the WEEE.

The project involves multi-disciplinary organisations from across Europe:

- C-Tech Innovation Limited (project lead and R&D company)
- University of Birmingham (academic partner)
- Stena Technoworld AB (electronics and white goods recycler)
- Acreo Swedish ICT AB (R&D company in the field of sensors and actuators)
- Leitat Technological Centre (R&D organisation)
- OptiSort AB (battery sorting machinery)
- Chalmers Industriteknik (academic partner)
- Magneti Ljubljana (manufacturer of NdFeB magnets)
- Kolektor Magnet Technology (magnet and plastic-bonded materials producer)

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- If fully implemented, REMANENCE will provide a secondary source of Neodymium material for the EU, large enough to supply a significant proportion of the EU's high value magnet production (1,500 – 2000Tpa). The project is due to develop this technology over the next 4 years.

5.4.3 *University of Birmingham*

Recent work by the university has shown that hydrogen can be used as a processing gas to reduce NdFeB magnets to a soft magnetic hydride powder, which can be removed from electronic components (using the hydrogen decrepitation process). The extracted material can be used to remanufacture new NdFeB magnets directly from alloy powders.

The most recent work focuses on the use of hydrogen to remove individual or all sintered NdFeB magnets from large commercial rotor assemblies, with the aim of reusing the underlying structure once the magnets are removed.

Sintered NdFeB magnets have a similar microstructure to cast NdFeB alloys, however the grain size is approximately an order of magnitude smaller (cast approximately 100-200µm; sintered approximately 5-10µm). Sintered magnets react with hydrogen in a similar way to cast material, breaking into a hydride from of the powder. Experiments have involved preparing a variety of magnets (e.g. stripping of Nickel coatings), hydrogen processing and commercial assembly experiments based on rotor assemblies from electric vehicles (namely the Electric Smart Car). Work by the university is ongoing namely through REMENANCE project outlined above.