REE4EU: Integrated High Temperature Electrolysis (HTE) and Ion Liquid Extraction

(ILE) for a strong and independent European Rare Earth Elements supply chain

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Responsible Author(s)	Nader Akil, Savvina Loutatidou, Doga Arslan, Emanuele Festa (PNO Innovation N.V.) Patrizia Circelli, Silvia Colella (Ciaotech)
Contributor(s)	Bert Witkamp (European Association for Electromobility), Sverker Sjölin (Stena Technoworld AB), Richard Laucournet (Commissariat à l'Energie Atomique et aux Energies alternatives), Rolf Blank (Vacuumschmelze GmbH & Co. KG)
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Abbreviations

Abbreviation	Definition
EC	European Commission
EoL	End of Life
EPAC	Electric power assisted cycle
EPS	Electric power steering
EU	European Union
EV	Electric vehicle(s)
GG	Gearbox generator(s)
HDD	Hard Disk Drive(s)
PM	Permanent magnet(s)
REE	Rare Earth Elements
REPM	rare-earth permanent magnet
WT	Wind turbine(s)

Notice

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[1] This report was jointly authored by representatives of PNO Innovation N.V. (Brussels office-Belgium) and Ciaotech (Italy). Both PNO Innovation and Ciaotech belong to the same mother company, PNO Group B.V. (PNO). PNO is a European leader in Grants and Innovation bringing about 1 Billion euro annually to its clients. PNO Innovation (beneficiary of the REE4EU project) is located in Brussels and leads the intelligence services for the purpose of PNO Group's activities. Among other services, PNO carries out value chains and stakeholders analyses, market and business analysis, IPR management and exploitation plans, road-mapping, development of innovation ecosystems and new communities around a specific topic. PNO also generates open innovation opportunities by managing an open innovation portal (www.innovationplace.eu) wherein information about innovative ideas, projects and funding opportunities in several European countries is constantly provided. For more information about this deliverable, the REE4EU project, or PNO in general, the authors can be reached at nader.akil@pnoconsultants.com and Savvina.Loutatidou@pnoconsultants.com

…This transition towards a more circular economy is about reshaping the market economy and improving our competitiveness. If we can be more resource efficient and reduce our dependency on scarce raw materials, we can develop a competitive edge. The job creation potential of the circular economy is huge, and the demand for better, more efficient products and services is booming..."

Brussels, 2 December 2015

European Commission Vice-President for Jobs, Growth,
Investment and Competitiveness

Jyrki Katainen

Executive Summary

This report analysed the prospective European market of secondary rare earth elements (REE) contained in selected End of Life products that have the potential to become viable feedstocks for REE recovery at industrial scale. The findings of the European Rare Earths Competency Network (ERECON) report directed the focus of this market analysis to the most promising "urban mines" of Rare Earths, namely:

1. Hard disk drives from laptops and desktop computers
2. Offshore wind turbines
3. Electric vehicles and electric power steering
4. e-bikes and electric power-assisted cycles
5. Motors deployed in industrial applications
6. Air conditioning compressors
7. Magnetic separators
8. Industrial robotic motors

The recycling potential and specifics of each market segment (1-8) were thoroughly explored by diving into relevant scientific literature, white papers and European open-access databases. The information drawn from these sources, was complemented by up-to-date insights from industry experts, gathered through interviews and surveys. For each EoL product, a dedicated chapter was compiled summarising the conditions prevalent in its respective market segment – with an aim to assess how "fit" the product is for recycling and REE recovery. Finally, the authors ran a comparative assessment of all products taking into consideration the following factors:

- Amount of REE loaded in a product's (sub)components
- Supply of REE from end-of-life products – Expected availability from 2020-2040
- Maximum monetary value of REEs contained in a waste stream
- Maturity of legislation encouraging their recycling
- Availability of collection schemes
- Design compatibility with EoL PM recycling
- Risk for REE reduction/elimination
- Probability of second life out of EU Vs end-of-life in EU

- Possibility of recovering more than one REE from a product- thus, allowing to take advantage of REE4EU's innovative technology that is able to produce rare earth alloys directly from mixed rare earth oxides hence, eliminating the need for downstream separation steps.

The findings presented in this report indicate European EoL EVs as the most relevant feedstock for a future REE recovery plant - with a potential to provide more than 11 ktons of Nd and close to 1 kton of Dy likely to be harvested over the next two decades. In addition, conventional vehicles with Electric Power Steerers (EPS) (estimated Nd content of 5 ktons) could complement EVs as another rich source of secondary REE. Moreover, though the automotive sector seems by far the most promising market segment for REE recycling, residential air conditioners also show potential for cost-effective REE recovery which could translate to approx. 2 ktons of Nd. At the same time, this report acknowledges that other waste streams, for instance offshore wind turbines, may also become important sources of secondary REE, even though - at the moment- they do not score as high as EVs and air conditioners with regard to the aforementioned assessment factors.

To enable future REE recovery from the above EoL products, several technical and systemic barriers must be removed, the most important ones being incompatibility of complex product architecture with existing sorting and recycling infrastructure in Europe, and absent or weak legislation enforcing collection and tracking of secondary REE magnets separately from other secondary materials. In addition, future strategies must also account for external threats. For example, it is uncertain how the launch and uptake of new "REE-free" technologies will affect the dynamics of a nascent secondary REE market. In overall, the results suggest that future REE recovery business cases must incorporate different scenarios for upstream collection rates and fit-for-recycling product designs to allow for a more realistic feasibility analysis.

1. End of Life products for REE recovery – market definition

Rare Earths can be harvested from consumer and industrial products that have ceased to be useful but still have salvage value as secondary material sources. Products reach the end of their life cycle for many reasons: consumer behaviour volatility, disruptive technological innovations, or simply performance degradation over time and subsequent replacement by functionally better products. Emergence of circular economy markets, such as the one of secondary REE, requires reintroduction of End of Life (EoL) products into the business ecosystem.

Building on the findings of the ERECON report, the most interesting post-consumer market segments (for REE recovery) fall under several applications, from automotive to mixed electronics. Given the breadth of these segments as well as the findings of the market analysis, those were further refined based on their estimated REE recyclability potential. Their classification and groupings are listed in Table 1.

Table 1. Product-specific waste streams for REE recovery, as identified by ERECON and REE4EU.

ERECON	**REE4EU**
Hard disk drives, DVD and CD players	Hard disk drives from laptop/desktop computers
Automotive applications	Electric drive motors for EVs and Hybrid cars Electric power steering
Motors in industrial applications	Industrial motors
Loudspeakers	Not covered
Air conditioning compressors	Air conditioning compressors
Magnetic separators	Magnetic separators
Mixed electronics	Hard Disk Drives from laptops/desktops
Electric bicycles	e-bikes and Electric Power Assisted Cycles (EPACs)

Wind turbines	Offshore wind turbines

It should be noted that the market segment of EoL consumer loudspeakers was not analysis owing to the results of of recycling trials carried out by STENA (one of REE4EU's partner) which showed that older models do not contain Nd. If future studies are to consider loudspeakers, STENA advises to focus on small loudspeakers such as those used in LED TVs, flat screens, and i-phones where in those cases Nd magnets are found with a weight between 2 to 6g per speaker element. In addition, loudspeakers for professional use have Nd magnets and could also make part of a future study.

As a first step towards development of robust large scale REE recovery infrastructure, one needs to understand the uncertainties associated with using different EoL products as feedstocks in order to detect future business opportunities and address their respective investment risks. For this purpose, a large amount of information needs to be analysed to have a sufficient judgement basis for prioritising one or more End of Life products over others as feedstocks for REE recovery. Naturally, not the same recycling strategy can apply to all REE-containing EoL products. For example, the selected EoL products have different life cycles: from as short as 5 years (in computer hard disk drives) to lifetimes spanning to more than 2 decades (such as in wind turbines). Another example, the weights of their contained REE alloys can range from a few grams (in consumer electronics) to a high as 1,000 - 2,000 kg (as in the case of permeant magnet generators of modern offshore turbines). In overall, REE material flows, economic and technical viability of producing secondary REE, legislation associated with collection and planning at EU level are all factors that will ultimately determine their "fit" for use as secondary REE sources.

2. End of Life products for REE recovery – market analysis

Section 2 lays the foundations for a future cost and benefits assessment associated to different EoL products containing REE that can be used as feedstock for a future REE recovery plant in Europe. The market of REE-rich EoL products, as defined in Section 1, is significantly heterogenous. The identified products differ in many aspects, for example in terms of lifetime, REE amount, geographic distribution over the EU, etc. A market segmentation was performed along three axes – application, geographical resource allocation and temporal resource allocation (elaborated in Sections 2.1, 2.2, and 2.3, respectively). Key information is summarised for each EoL product (Section 2.1) and is later distilled into Sections 2.2 and 2.3.

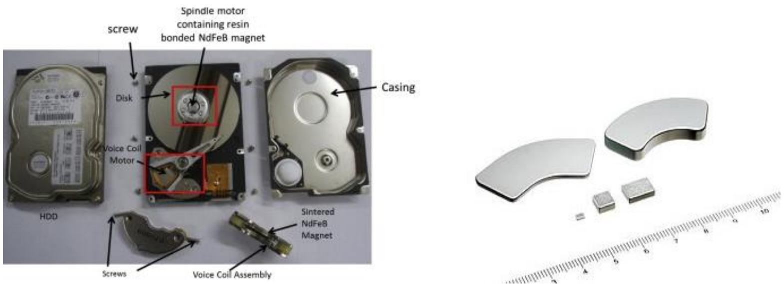
2.1 Segmentation of secondary REE market by EoL product

For each of the identified applications, a dedicated market overview was built following a common template which encompasses:

- Description of the application
- REE content per unit and outlook thereof
- Availability of EoL product in Europe and/or the world over time
- Allocation of EoL product to EU member states (if available)
- Availability and extent of collection measures
- Barriers to recycling
- Expert insight

2.1.1 EoL Hard Disk Drives – market overview

Hard Disk Drives – facts & figures	
Application	Used hard disk drives (HDDs) can be sourced from end-of-life desktop and laptop computer devices. It has been more than 60 years since the HDD technology appeared in the market and since then it has gradually evolved into more compact dimensions. Current HDD models have dimensions that range from 5 to 10 cm and weight approximately 50-600 g, depending on the model and whether they are placed in a laptop or a desktop computer device. A HDD's primary function is to

	store data in computers. NdFeB magnets are used to spin the disk where the data is stored. HDDs contain two types of NdFeB magnets: sintered magnets in the voice coil actuator which controls the scanning (See Figure 1) and resin bonded magnets in the spindle motor which spin the disk (Remanence, 2012). The main technology, competitive to HDDs, is solid-state drives (SSDs). Unlike hard disks, SSDs do not contain any moving parts. They are more robust and work faster than HDDs, and for this are often considered to be more practical as compared to their REE-based counterparts. The use of SSDs has been increasing exponentially since 2010 (Schulze & Buchert, 2016). Despite their superior performance, SSDs are more expensive than HDDs on a price-per-gigabyte basis. However, in some computer models, HDDs and SSDs can be used combinedly to reduce the costs. Another threat to HDDs is the disruptive change to the storage market brought about by the emerging cloud storage services. Due to the progressive shift of consumers to cloud data storage systems, the HDD market share has shrunken significantly in Europe and is projected to decrease even further over the coming years.  Figure 1. Sintered and resin bonded NdFeB magnets (left), voice coil actuator magnets used in a HDD (right) (Walton et al., 2015; www.techmetalsresearch.com)
Rare earth magnet content	NdFeB alloy accounts for approx. 3% of a HDD's weight. Yet, a recent paper from Schulze and Buchert (2016) mentioned that HDDs can be an important resource providing large quantities of secondary REE in the short-term. The demand of magnetic material for HDDs is expected to follow closely their production - given that HDDs are in production for decades and the amount of magnet per HDD has not decreased significantly in the past years (Sprecher et al., 2014). Alternative to HDDs, recent "magnet free" SSD technology and cloud data storage systems are continuously expanding their market share. Rademaker et al., (2013) predicted

that by 2030 the use of HDD will drop from 76% to 40% in desktop computers and from 35% to 14% - to even 1% - in laptops.

The weight of NdFeB alloy in HDDs is in the range of 2 g to 18 g (PMDM and Seagate HDD technical data sheet; Habib et al., 2015) as shown in Table 2. REE permanent magnets contain about 31-32 wt% REEs (Yang et al., 2017). Neodymium (Nd) in particular, was reported as 30% of the total NdFeB magnet weight (Rademaker et al., 2013). Dysprosium (Dy) is not used in the composition of HDD magnets. It is assumed that laptops deploy lighter HDDs models than those of desktop computers. Thus, it is estimated that a laptop and a desktop computer contain approx. 0,5 g and 6 g of Nd, respectively.

Table 2. NdFeB magnet and Nd weight in a standard laptop and desktop computer

NdFeB Magnet (g) in a laptop	Nd (g) (1) in a laptop	NdFeB Magnet (g) in a desktop	Nd (g) (1) in a desktop	Ref.
2	0.6	15	4.5	Rademaker et al., 2013
2.5	0.75	18	5.5	Sprecher et al., 2014
2.75	0.8	13	4	Habib et al., 2015

(1) Nd represents 30% in NdFeB composition

Sprecher et al. (2014) has foreseen that under present conditions, Nd recovery from HDDs might be the most feasible pathway towards large scale of recycling of Nd. This is due to the relatively simpler separation of their magnets from the rest of the HDD components as compared to other applications. NdFeB alloys can attach to the ferrous surfaces due to their magnetism once the HDD has been opened (Habib et al., 2015). REE exist as powder in HDD magnets and can be directly reprocessed from the alloy into new sintered magnets with magnetic properties close to the performance of the original magnets or into cheaper resin-bonded magnets of lower magnetic quality (Sprecher et al., 2014).

Availability as EoL product

Generally, a HDD's useful life timespan depends on the lifetime of the computer which contains it. A laptop in commonly used for up to 5 years whereas desktop computer models can be used even longer, such as 8 years (Rademaker et al., 2013). Due to their relatively short usage time, End of Life HHDs are already abundantly available in the global market and could theoretically, serve as a source of secondary Nd. Table 3 presents the expected availability of secondary Nd from EoL HDDs at global scale as presented in two milestone peer-reviewed papers.

Table 3. Global supply of secondary Nd in tons from end of life HDDs

	2015		2020		2025		2030		2015 - 2030	
	Low (1)	High	Low	High	Low	High	Low	High	Low	High
Nd(2)	310	345	355	400	290	360	240	360	1195	1465
Nd(3)	300	470	221	410	152	380	137	380	810	1640

(1) Low represents low NdFeB demand scenario and high represents high NdFeB demand scenario.

(2) (Schulze & Buchert, 2016). Excluding losses from collection, disassembly and recycling (60% overall collection rate, 40% loss during disassembly, 90% recycling material efficiency).

(3) (Rademaker et al., 2013). (*) This paper did not compare low and high demand scenarios. The authors assumed recycling rates of 64% in 2015, 54% in 2020, 40% in 2025 and 36% in 2030. In this report, these conversion rates are considered as a low demand scenario. For the high demand Nd scenario, it was assumed that all the available Nd could be recycled at 100% rate.

In addition to the global figures provided above, this market analysis also estimates the amount of secondary Nd available in the Europe. The basis of the relevant calculations is the weight of HDDs collected as fraction of electrical and electronic equipment waste (WEEE). Approximately, 9 million tons of WEEE are generated annually in Europe (Eurostat, 2016). Of this amount, the European Electronics Recycler Association (EERA) declared that approximately 2,5 million tons are collected, registered and processed annually in Europe. This is less than one third of the total WEEE generated in the EU. The rest is unfortunately not processed or even registered for some reasons which will be discussed in the next section. In Europe, around 16% to 20% of the total registered WEEE is IT and communication equipment waste which is composed of desktop, laptop computers and cell phones (Cui and Roven, 2011). This fraction of collected WEEE amounts to approximately 454 kton EoL laptops, desktop computers and cell phones per year in Europe.

Eurostat (2016) provides the list of collected IT and telecommunication waste generated in each EU member state country between 2005 and 2014. According to Eurostat, most of the EU countries, apart from Italy, Romania, Iceland and Croatia, have reported the IT and telecommunication waste collected between 2008 and 2013. Between 2008 and 2013, 620 kton (±43 kton) of IT and communication waste has been generated on average every year in Europe. In 2013, almost all EU countries (except for Italy and Romania) reported the amount of IT and telecommunication waste which was collected and processed. Prior to 2008, missing values corresponding to different countries occur more frequently. An additional point of uncertainty is that - in the website of Eurostat - the composition of IT and communication waste is not clearly defined. However, in the book "A handbook for waste management" authored by Cui and Roven (2011), it is mentioned that the content of IT and communication waste collected in Europe covers laptops, desktop computers and mobile phones.

Since for 2013 there are available WEEE figures for most of the countries and the amount of waste collected was relatively constant between 2008 and 2013 (SD=7%), the estimations for WEEE were based on data collected for this specific year. In 2013, the total amount of IT and communication waste collected in Europe was 585 kton. Unfortunately, there is no information on how much of this waste corresponds to EoL computers and cell phones. Figures for the stock levels of appliances in households and businesses are generally unavailable, especially in a harmonized manner. On the other hand, considering the similar diffusion of computers in developed countries, it is assumed that the percentage of IT and communication waste in European WEEE is like that of USA.

In 2010, the Environmental Protection Agency, USA reported separately the amount of computer and mobile waste. According to EPA (EPA, 2011), 142,000 computers and 416,000 mobile devices were being trashed or recycled every day in the USA (www.epa.gov). The weight of a desktop and a laptop computer is approximately 9 and 3 kg, respectively. Under the assumption that most of the discarded computers are laptops, a unit of computer waste weights around 5 kg. By this, it is deducted that 142,000 computers would weight around 710 kton which corresponds to 90% of the total IT and communication waste reported in the US in 2011. This percentage value seems reasonable as the total weight of 416,000 mobile phones would be 83,2 kton which correspond to 10% of the total WEEE amount (a mobile phone weights approximately 0.2 kg).

Based on this percentage, the estimated weight of EoL laptops and desktop computers in Europe in 2013 could be up to 524 kton (90% of 585 kton collected waste). Figure 2 illustrates the potential of secondary Nd (in tons) from collected

EoL computers contained in EU countries in 2013 (only top 12 countries are shown). A HDD weighs approximately 0.2 kg in a laptop and 0.6 kg in a desktop computer. In both cases, a HDD is 7% of the total weight of a computer. As mentioned earlier, NdFeB alloy is around 3% of a HDD weight. Consequently, 524 kton computer waste contain 1,048 ton of NdFeB alloy (314 tons of Nd). This figure – corresponding to European EoL HDDs – appears to be quite high compared to the global estimates presented in Table 1. That could be explained by the fact that this analysis assumes that 90% of collected IT and communication waste are EoL computers. Also, additional disassembly and recovery inefficiencies have not been considered as these can differ widely between different papers and can distort the estimation.

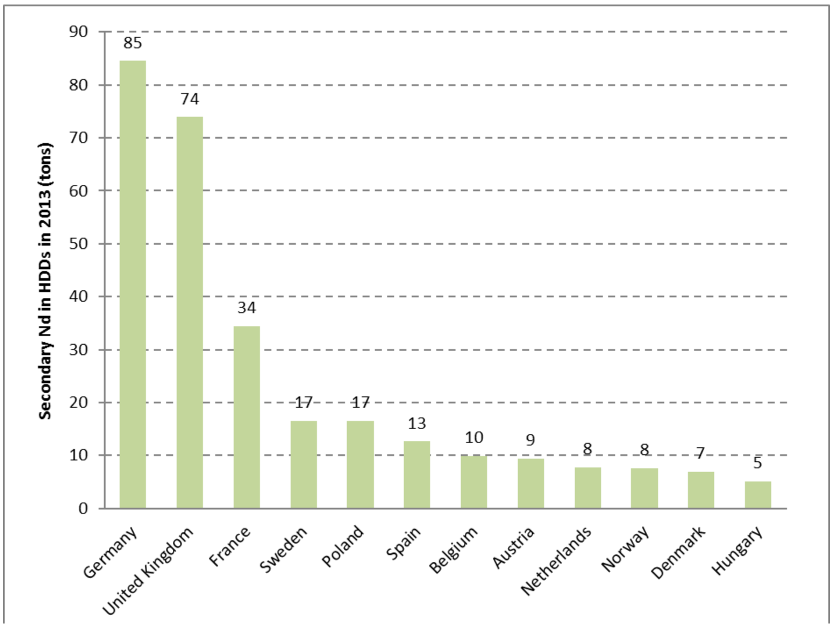
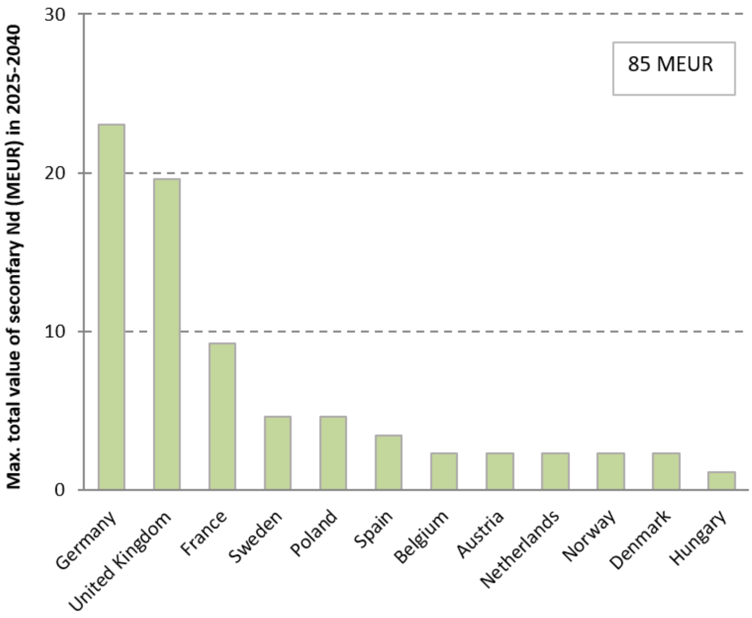
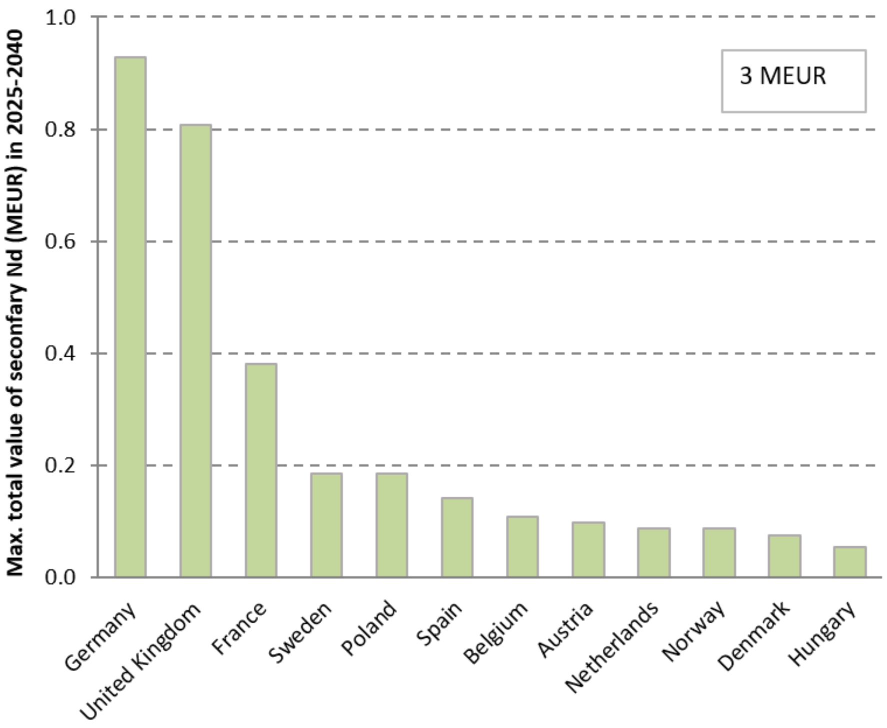


Figure 2. Secondary Nd contained in collected laptop and desktop computer waste in the EU (Year of reference: 2013).

The trend depicted in *Figure 2* shows that secondary Nd from HDDs is quite homogenously “spread” in the EU, which is in accord to the fact that the number of computers discarded in a developed country is roughly proportional to the population. For example, Germany is the most populous member state country and could be the predominant source of secondary Nd from HDDs. On the other hand, it should be noted that dependence on IT and communication equipment index is another important parameter to quantify the amount of WEEE. Population in Sweden, for example, is not very high, however, computer per household ratio in Sweden is 2.7, the highest in the EU (Eurostat, 2013) and higher than Germany (1.8).

Figure 3 illustrates the potential value of secondary Nd contained in collected EoL HDDs. The economic crisis in China during 2011-2012, caused the price of Nd to skyrocket - from 12 €/kg in 2009 to 271 €/ kg in 2012 (Charalampides et al., 2015). Based on these prices, the total value of secondary Nd in Europe – only considering 2013 - could amount between 3-85 MEUR.



	 *Figure 3. Estimated secondary Nd in HDDs in EU member states in 2013 : (a) for € 271/kg of Nd (b) for € 12/kg of Nd.*
Collection measures	In the review by Schulze and Buchert (2016), the collection and disassembly rate of HDDs was assumed to be 60% with a 92% recycling rate. Rademaker et al. (2013) predicted collection rates of HDD 30 - 40% depending on the region. However, according to information obtained from the European Commission regulations and European Electronics Recyclers Association, only 30% of the generated WEEE is collected in Europe. The main reason behind this low collection rate of WEEE is the limited liability of electric and electronic manufacturers for their products after the end of their useful life. According to Directive 2002/96/EC, manufacturers are not obliged to collect EoL electronic and electric equipment they have sold, although they are obliged to handle collected WEEE returned to them (Karavida and Nommik, 2015). Due to lack of collection measurements, electronic waste is regularly exported from Europe primarily to three regions: South China, North India and Pakistan, and West Africa (specifically Ghana) (www.greenpeace.org). This illegal transport might apparently be as high as 50%. It is believed that the trade started in the early 1990s by EU companies to avoid handling of hazardous waste generated during

	the e-waste processing. Yet, there are some companies taking initiatives to increase the collection and recycling of HDDs. For example, Dell covers the cost of home-pick and shipping of their products to their recycling center. Another example is HP, which during the past 20 years, has expanded its collection and recycling operations to more than 40 world regions by encouraging costumers to return their old computers (www.recycling-guide.org.uk).
Barriers to recycling	The management of End of Life HDDs is regulated by Directive 2012/19/EU, which enables the creation of collection schemes through which consumers can return their WEEE free of charge. These schemes aim to increase the recycling of WEEE and/or re-use. Directive 2012/19/EU defines 10 categories of electrical and electronic equipment covered by the Directive: 1. Large household appliances 2. Small household appliances 3. IT and telecommunications equipment 4. Consumer equipment and photovoltaic panels 5. Lighting equipment 6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools) 7. Toys, leisure and sports equipment 8. Medical devices (with the exception of all implanted and infected products) 9. Monitoring and control instruments 10. Automatic dispensers This directive introduces a stepped increase in collection targets that will take effect in 2016 and 2019. Furthermore, from 2018, its current scope will be extended from its present restricted scope to all categories of WEEE. Consequently, the definition and number of the categories will change. However, the existing directive does not set recycling quotas for specific materials contained in the WEE. That could partially explain the fact that, despite the establishment of a regulatory framework, the collection rate of wasted HDDs is limited. According to the CWIT (Countering WEEE Illegal Trade) report published in 2015, only 35%

(3.3 million tons) of all WEEE waste discarded in 2012 was officially collected and recycled in accord with the regulations in Europe. The rest 65% (6.15 million tons) was handled in different ways (Figure 4): 3.15 million tons was collected and treated by unregistered enterprises, round 1.5 million tons was transported to outside of Europe, mainly Africa, India and China by unregistered enterprises and, approximately, 750,000 tons were disposed to residual waste by individuals and therefore ended up in landfills or incinerators. Finally, another 750,000 tons were scavenged for valuable parts (CWIT, 2015).

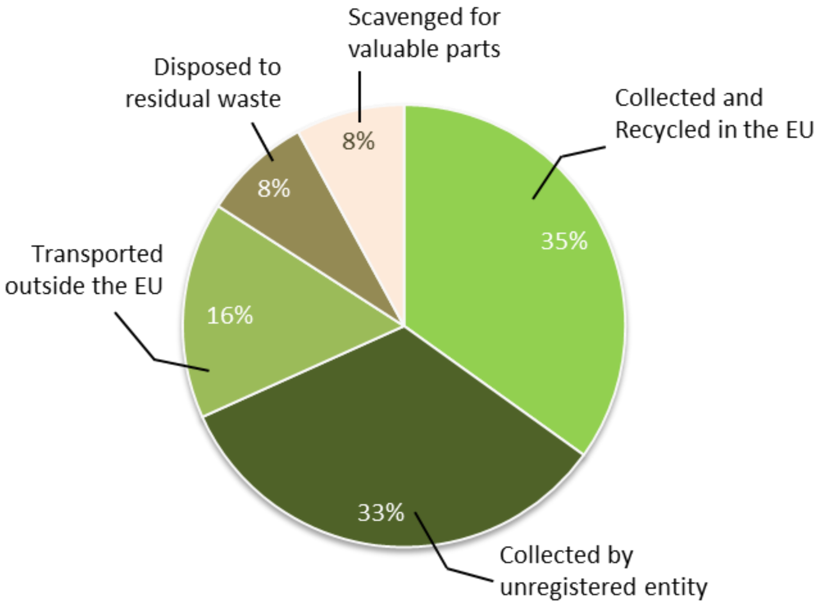


Figure 4. EoL routes of WEEE in Europe in 2012

REE-rich powder or small pieces that are recycled from HDDs can be recovered and adapted to another application (Binnemans et al., 2013). In practice, however, there are certain hurdles preventing recycling of their NdFeB alloys. Firstly, REE in HDDs are present in very low quantities and therefore, necessitate cautious and thoroughly designed recycling procedures to ensure minimal losses during disassembly. According to Yang et al. (2017), one of the main challenges for recycling NdFeB magnets from consumer products is the up-concentration of small NdFeB magnets in diversified scrap, such as those of WEEE. EoL electronic waste (HDDs included) is normally shredded after removal of hazardous components. After shredding, their permanent magnetism causes them to attach to ferrous scrap (steel). At present, almost all small permanent magnets used in consumer electronics, after collection and shredding operation, are lost into ferrous and non-ferrous scrap waste streams. In this operation mode, the REEs in the permanent magnets have very low concentration and are very difficult to be up-concentrated (e.g. by the steel industry) for economic recovery. Recently, Nguye et al. (2017) concluded that adding REE recovery to an e-waste base process in an HDD recycling plant was profitable. The study also concluded that REE recovery has a moderate impact on the profitability of HDDs recycling and could account for 13% of the revenue of a large HDD recycling facility.

Dismantling and separate processing of NdFeB magnets from their end-use products can be a more preferred option over shredding. However, it remains a technological and logistic challenge for the existing system though pre-dismantling has been reported by some companies. In the Netherlands, Van Gansewinkel Group (VGG) operates a small shredder for HDD shredding (data destruction). The Hitachi Group (Japan) developed a mechanical dismantling and separation technique for NdFeB magnets in HDDs and air conditioners, using a rotational dram. Through vibration and impact by tumbling, the screws fixing the HDD casing become loose, and the magnets can be separated out of the casing in about 30 min. The apparatus can process 100 HDDs per batch and 200 HDDs per hour, much faster than manual dismantling at a rate of 12 units per hour. To date, information on the technology's commercialization and operation has not been reported to the public (Yang et al., 2017)

A non-exhaustive list of important HDD manufacturers in Europe can be found below:

- Freecom (Germany)
- Trekstor (Germany)
- PM DM (Germany)

The largest hard disk manufacturers are based in the USA, South Korea and Japan. In fact, three main parent companies: Western Digital, Seagate and Toshiba own most of HDD manufacturing companies in Europe. Because of declining trends of HDD usage (linked to the competition from SDD and cloud data storage systems), several HDD manufacturers are gradually downscaling or stopping their production.

Expert insight	It was not possible to include direct interviews with industrial stakeholders (able to provide insight on the recyclability of HDDs). However, CEA, one of REE4EU's partner has conducted an in-depth analysis for many EoL products belonging to the WEEE waste category. The report states that "after analysis, … the cost-efficient recycling of such items (HDDs) requires new automated dismantling technologies to achieve higher throughput compared to manual dismantling. As such, HDD recycling is something where the entire value chain must adapt and thus large uncertainties remain about the extent to which recyclers will adopt such new technologies. Early efforts have been made in Japan since 2013 to recycle HDDs". According to STENA, recycling of the HDD materials including aluminium and other metals, can be a profitable business today with the potential to become even more so through automated disassembly. STENA has installed an automated line for the extraction of the magnet from HDDs as part of the REMANANCE EU project in their plant in Halmstad (Sweden).
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2.1.2 EoL Offshore Wind Turbines – market overview

Offshore Wind Turbines – facts & figures	
Application	Wind turbines compose one of the fastest growing markets with a demand for Nd, one of the most essential rare earth elements (REEs) (Lucas et al., 2015). In a typical wind turbine, mechanical energy is converted to electricity by the use of a Permanent Magnet Generator (PMG). A PMG is composed of a mixture of steel, copper (Cu), boron (B) together with neodymium (Nd) and sometimes dysprosium (Dy). Early models of wind turbines contained trace amounts of Dy. Today, Dy has been replaced almost completely by Nd in commercial wind turbines. Consequently, recycling of wind turbines for recovery of Dy is of limited commercial potential. Apart from PMG, there are two alternative generator technologies deployed by wind turbines for electricity generation: gearbox and superconductor generators. Gearbox generators (GG) are made of magnetic steel, copper, and silica and do not contain REEs. GGs are cheaper than PMGs but operate at lower efficiencies and have shorter life span in comparison to PMGs. Nevertheless, GG remains a widely adopted technology in wind turbine manufacture. The second technology, superconductor generator (SG), deploys wire materials suitable for high temperature and ceramics - again without the need of REEs – but it is still at development phase. The first wind turbines deploying superconductor generators was demonstrated by Theva in 2015 in Germany. It is worth mentioning that the cumulative revenue potential for superconducting wind turbines is expected to grow rapidly from 2016 onwards for Europe. PMG generators are preferred in offshore wind turbines because of their robustness and longer time of uninterrupted operation without the need for maintenance. Onshore wind turbines are usually coupled with less costly gearbox generators which require frequent handling. Since access to onshore wind turbines generators is easier than offshore, frequent handling is not considered as costly procedure, therefore it is

likely that a large fraction does not contain PMGs. Given this particularity, EoL off-shore wind turbines will be considered in the estimations of Nd potential.

Rare earth magnet content

Nd content in PMGs differs based on magnet type. In the first type of PMG (most common) magnets are used to directly convert mechanical to electrical energy and an average of 0.2 kg neodymium per kW installed power is assumed (Zepf, 2016). In the second type, a hybrid-drive system uses a combination of PMG and gearbox. For hybrid technology, 0.06 kg neodymium per kW can be expected (Zepf, 2016). Table 4 shows a few examples of the REE content of different PMG generators.

As it can be seen in Table 4, the NdFeB alloy quantity varies with the power rating of a turbine. Over the past 20 years, the dimensions of off-shore wind turbines and generators have been up scaled causing a drastic increase of the mass of NdFeB alloy in PMGs - sometimes in the order of hundreds of kg. The amount of NdFeB magnet used by different manufacturers is shown in Table 5.

Table 4. NdFeB PM content in PMG generators

Power (MW)	NdFeB Magnet (kg)	NdFeB per kW (kg)	Nd per kW (kg) (1)	Ref.
3.5	2000	0.6	0.2	Lucas et al., 2015
1.5	350	0.2	0.06	European Parliament briefing, 2013
1	700	0.7	0.15	Rademaker et al., 2013(2)

(1) Nd represents 30% in NdFeB composition.

(2) Paper which models the various estimations in the EU-27 member states.

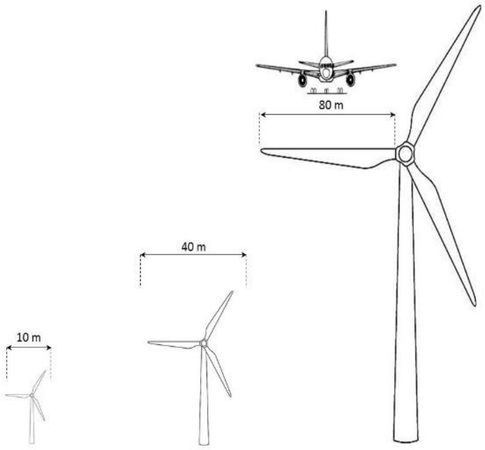


Figure 5. Progressive increase of rotor diameter in wind turbines (1980-2010)

Table 5. Evolution of offshore wind turbine models

Power Output [1]	30 kW	500 kW	6 MW
Year	<2000	2004	2013
PMG	0 (gearbox tech.)	~ 0.4 ton[1,2]	~ 3 tons[1,2]
NdFeB	No potential for recycling	0.8 kg/kW	0.4 kg/kW[3]
Expected end of life	-	2030	2040

(1) Power outputs were chosen as exemplary information provided in wind turbine company catalogues.
(2) Constantinides, S. (2016).
(3) Yang et al. (2017)

Along with the wind turbine dimensions, the REE composition has also evolved over the years. As mentioned earlier, manufacturers have been systematically reducing Dy by replacing it with Nd (Schulze & Buchert, 2016). Siemens, one of the three leading companies in the field of wind energy, announced complete elimination of the element from its offshore wind turbine models by 2017.

Availability as EoL product

Offshore wind turbines using REEs entered the market in the early 2000s (Wind Europe). If the wind turbine is refurbished and reinstalled as a second hand, its lifetime is estimated to last around 15 years due to potential reduce in quality of materials (Rademaker et al., 2013). The maximum lifetime of an offshore wind turbine deploying PMG is estimated to be 25 years. Therefore, one can expect that EoL PMGs from wind turbines will be available after 2025 at significant quantities.

The cumulative offshore wind power installation in Europe was 11,0273 GW till the end of 2015. Approximately 69% of the offshore wind turbines are installed in the North Sea, 17% in the Irish Sea, 13% in the Baltic Sea and less than 1% in the Atlantic Ocean (www.windeurope.org). The total offshore wind turbine installation is 8% of the total wind power installations in Europe (www.windeurope.org; www.gwec.net). Lucas et al. (2015) assumed slightly higher 10% PMG use in wind turbines. According to the European Wind Energy Association, the share of offshore turbines increased by 40% over 2015 (www.windeurope.org). The estimated cumulative recyclable Nd in the Europe total offshore wind turbine installations (11GW) amounts to 772 tons. This second hand Nd will be available for recycling from beginning 2025 till 2040.

This estimation seems indeed in line with the scenarios presented by Schulze and Buchert (2016) and Rademaker et al., (2013). The predictions on global available secondary REE from wind turbines by these two papers are presented in Table 6. According to Schulze and Buchert (2016), till 2030, the global available Nd from EoL wind turbines will range from 425 and 645 tons, excluding losses from collection, disassembly and recycling (20%). According to Rademaker et al., (2013), in the high demand scenario, 1,080 ton of secondary Nd would be theoretically available for recovery during 2015-2030.

Table 6. Global supply of secondary Nd and Dy from end of life PMGs

	2015		**2020**		**2025**		**2030**		**2015 - 2030**	
Unit (t)	**Low [(1)]**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Total Low**	**Total High**
Nd[(2)]	2	2	16	18	92	115	315	510	425	645
Nd[(3)]	- [(4)]	0	-	0	8	80	100	1000	108	1080
Dy[(2)]	0	0	2	3	13	16	42	60	57	79
Dy[(3)]	-	0	-	0	2	20	21	210	23	230

(1) "Low" and "high" correspond to low NdFeB and high NdFeB demand scenarios, respectively.

(2) Schulze & Buchert, 2016. Excluding losses from collection disassembly and recycling.

(3) Rademaker et al., 2013.

(4) This paper did not compare low and high demand scenarios. The authors assumed that only 1% of the total available Nd and Dy can be recycled in 2025 and 10% in 2030. "High demand" scenario was set to reflect 100% Nd recycling rate.

Although Germany remains the EU country with the largest wind turbine installed capacity, the UK leads the offshore wind turbine market (in terms of installed capacity). In 2015, the UK had 5.06 GW offshore wind turbine capacity representing 46% of the total European installations. Next in line were Germany (3.3 GW), Denmark (1.3 GW), Belgium (0.7 GW) and the Netherlands (0.4 GW). Sweden, Finland, Ireland, Spain, Norway and Portugal also produce offshore wind power, albeit their total capacity remains at much lower levels (0.3 GW). Figure 6 represents the potential amount of Nd that is theoretically available in the EU member state countries. The estimated values refer to the total amount that can be harvested from 2025-2040 (proportional to the cumulative installed offshore wind turbine capacity). UK and Germany hold the greatest potential of secondary Nd with 354 and 231 tons, respectively. It can be assumed that locations in the UK and Germany could be more suitable for centralized Nd recovery from offshore wind turbines since they account for 76 % of the total European installations (www.windeurope.org).

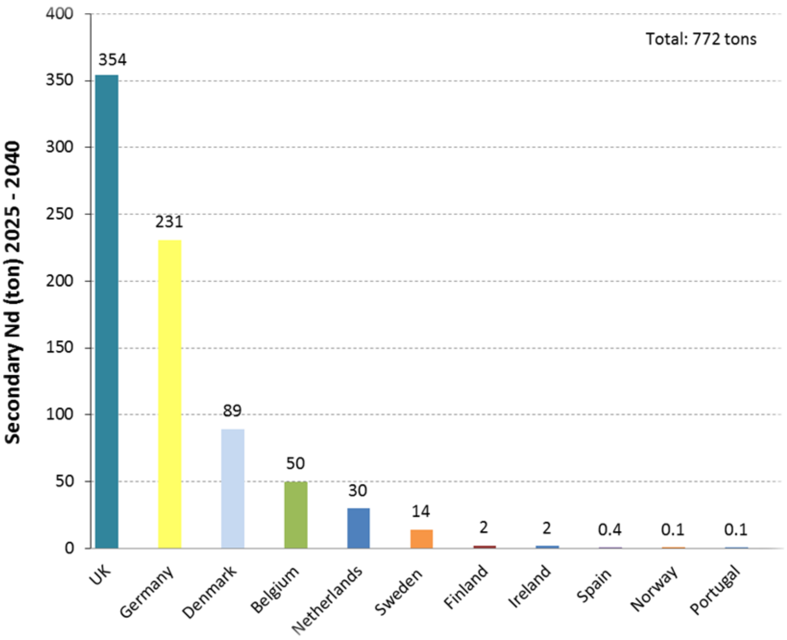
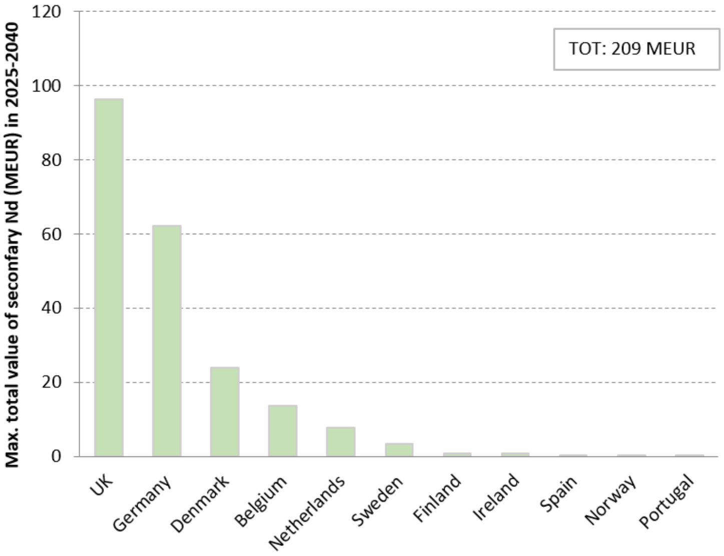


Figure 6. Cumulative quantity of secondary Nd contained in offshore wind turbine installations in the EU

Constantinides (2016) reported that the wind turbine capacity in Europe is expected to grow at a high rate and peak around mid-2020s. This assumption is further corroborated by the constantly positive investment trend in offshore wind turbine installations in Europe. The net capacity of wind turbines installed in 2015 was double of the one during 2014. Indicatively, in 2015 alone €13.3bn were raised for new asset investments of offshore wind farms (www.windeurope.org). Assuming that the average useful lifetime of off-shore wind turbines is 25 years, it is expected their availability as EoL products will peak around 2050.

(a) For Nd price: € 271/kg



(b) For Nd price: € 12/kg

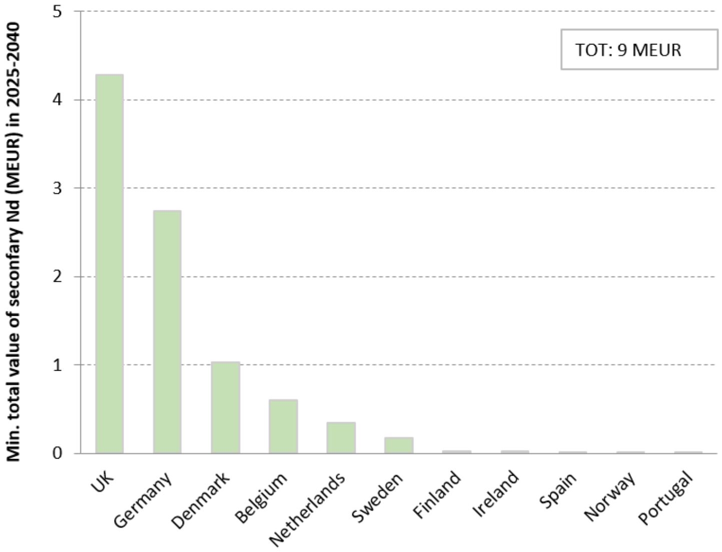
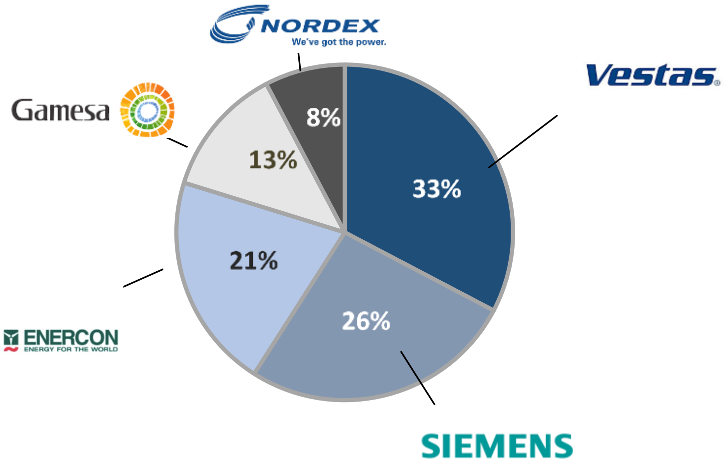


Figure 7. Potential secondary Nd in the EU member states in 2025 -2040:(a) for € 271/kg of Nd (b) for € 12/kg of Nd

Figure 7 above represents estimated ranges of theoretical monetary value of secondary Nd for the EU member state countries that have offshore wind turbine

	investments. Assuming that Nd prices in the next 20 years will range from € 12-271/kg, then the total theoretical revenue potential for secondary Nd in Europe would be fall around 9 -209 MEUR.
Collection measures	In the coming decade, nearly 10 offshore wind farms will need to be repowered or decommissioned. The first offshore wind energy decommissioning took place in 2016, Yttre Stengrud, a 10 MW project with five 2 MW turbines which operated for more than a decade, significantly less than the expected lifetime of 20–25 years. In the EU, the principle “the polluter pays” applies meaning that the wind farm owners are the primary responsible ones for leaving the site in a similar condition as it was before the deployment of the project (Topham & McMillan, 2017). This means that ensuring a sustainable supply of EoL offshore turbines would be quite challenging as their timing of collection (as individual parts) will depend on the case-by-case incentive for an owner to proceed with decommissioning (Ozment & Tremwell, 2007).
Barriers to recycling	WTs primarily consist of steel, aluminium, copper, glass fibre (GF), polyester, carbon fibre (CF) and epoxy. Whilst the average recyclability across the components of a modern WT has been calculated to be 80% by mass, the composite WT blades present a challenge for waste management. To date, end-of-life waste management for the wind energy industry is only weakly regulated at EU level (Cherrington et al., 2012) In addition, because the wind turbine industry is relatively young, there is little practical experience in the removal and recycling of wind turbines. This is particularly true of offshore wind turbines, which are a recent technology. Turbines that are considered too old or too small for mature markets such as Denmark and Germany are refurbished and sold in less mature second-hand markets such as Latin America. This second-hand market has recently surged (Andersen et al., 2014) causing a loss of high value REEs from Europe. At the time of this report, there was no publicly available information on the fraction of EoL offshore wind turbines exported from Europe. In theory, Nd content in wind turbines will be relatively easier to separate in comparison to other EoL products due to the size of their magnets. That is because large, easily accessible magnets, such as the ones in PMGs, could be more easily dismantled and even reusable in their current shape and form (Yang et al., 2017). Direct maintenance and re-use of magnets (in current form and shape) is indicated as the most economical option due to low energy input, no consumption of chemicals

	and no waste generation (Binneman et al., 2013). However, as the size of offshore wind turbines continues to increase, this option might become less feasible. Another issue impeding the direct reuse of PMGs is that the turbines produced in the future can have different shapes and sizes requiring magnets with different properties (Karavida & Nõmmik, 2015).
Expert insight	The leading European manufacturers and their share in Europe in 2014 as reported by the Joint Research Center of the European Commission is presented hereunder, in Figure 8. Vestas and Siemens held the greatest market share in 2014. Enercon, which follows, is no longer producing wind turbines with PMGs (according to the findings of the market analysis and the interviews). Therefore, Enercon is not a stakeholder that can directly benefit from the output of the REE4EU project. The other three important European manufacturers are Acciona (Spain), Alstom (France) and RePower (Switzerland).  *Figure 8. The leading wind turbine manufacturers in Europe* Key messages from interviews conducted with a key stakeholder (large manufacturer of wind turbines) are: Q1: What is the quantity of NdFeB and Nd in a typical wind turbine generator? As far as we know the quantity is changing as the technology on wind turbines progresses. We also found out that Dy is systematically removed from the permanent magnet generators. Would you confirm that information? A1: "*The numbers you provided in your analysis (0.14 to 0,5 Kg of Nd /KW) are not far off. Of course, in the case of hybrid-drive system that could be a factor of 10 less.*

Q2: Since when are Nd and Dy used in wind turbine generators? We found out that their use for commercial models started in the beginning of 2000s but can you define the entry year (for your company) ?

A2: *"We have started with our PMG turbines in 2008 and we supplied our first PMG turbine in 2010"*

Q3: What is the lifetime of permanent magnet generators in wind turbines? Is there any recycling approach that you are planning to take in the future?

A3: *"We are interested in designing magnets with reduced sizes that can be easily recycled. Design for recyclability is an important topic. For instance, we could imagine a modular turbine in the future, where the old PMG modules are extracted and directly placed in the new turbines. This will minimize the recovery cost of REE".*

Q4: Are rare earth elements still common in new generation wind turbines? Or is a new technology growing causing their elimination? What is your general view on the use of Nd and Dy in future wind turbines?

A4: *"The focus on non-REE design is forced by the market. The new designs are focused on lower grade or Dy-free turbines".*

Q5: Lastly, can you share your view on the collection and recycling rate of these elements (specifically from wind turbines)? To our knowledge, no recycling system has been developed to recover REEs from wind turbines and the turbines are sold as second-hand goods in the international market. However, we are wondering if you would have any other information about their recycling opportunities.

A5: *"We are not aware of important regulations to collect and recycle REE. There are some recommendations concerning recycling of wind turbines such as the ones that are being pushed by the Ellen Macarthur foundation".*

Q6: What are the important parameters that could enhance the chance to recover REE from wind turbines? What's in your opinion the importance of the REE4EU project?

A6: *"For manufacturers of wind turbines it is important to have a balance between the cost of a new design for recyclability and if, after a new design, it's economically feasible to recover this material".*

“For manufacture, it’s important to have a fixed price of REE instead of a price highly instable. Hopefully the REE4EU project could show that recycled REE with stable and reasonable prices compared to the market can be provided”.

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2.1.3 EoL (Electric) vehicles and cycles – market overview

(Electric) vehicles and cycles – facts & figures

Application	Several rare earth elements (REEs) are being used in vehicles and cycles. This market segment is dominated by electric power steering (EPS) and electric drive motors for electric vehicles (EVs) and hybrid cars. Other products also include motors from electric cycles (EPACs, e-bikes) and Light Electric Vehicles (LEVs) The main REE used is Nd, in combination with Dy which is essential for high temperature applications (Yang et al., 2017). <u>Electric power steering (EPS) for cars</u> For cars, steering is either unaided (small cars), hydraulic assisted or electric powered. EPS started to gain ground in the beginning of this century. The market share of EPS in 2005 was around 25%, in 2011 it increased to 60% and by 2018, it is projected to reach around 80%.

Electric drive motors for EVs and Hybrid cars

The market share of electric vehicles (EVs) is rapidly growing with sales of 770,000 units globally (2016). EVs are expected to dominate the passenger cars market within 10-20 years. Besides EVs (battery electric vehicles, plug-in electric vehicles, fuel cell electric vehicles), hybrid cars also deploy electric drive motors. In 2016, almost all commercially available EV models contained REE PM-based electric motors with the notable exception of Tesla EVs which deploy PM-free induction engines. Important therefore to note that a REE-free alternative is available for EVs.

Permanent magnet synchronous and induction motors are the most common motor types in electric vehicles. Magnets are either mounted on the surface (surface-mounted permanent magnets, SPM) or in pockets close to the rotor surface (integrated permanent magnets, IPM), and require different dismantling techniques (Elwert at al., 2015). Stated advantage of PM motors is their higher efficiency. Nevertheless, future unfavorable prices or limited unavailability of REEs could turn PM-based EV manufacturers to REE-free models. Given the very recent breakthrough of the EV technology, predictions for market evolution of EVs with REE should be made cautiously.

Electric bicycles (EPACs, e-bikes) and Light Electric Vehicles (LEVs) e-motors

Electric bicycle and/or LEV (Light Electric Vehicle of weight less than or equal to 400 kg) is a term, which covers two different concepts of vehicles with an auxiliary electric motor:

1) cycles[1] equipped with an auxiliary electric motor that can be exclusively propelled by that motor. The cyclist is not necessarily required to pedal. These vehicles are generally called “e-bikes”.

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[1] Pedelecs and E-bikes are not always two-wheeled. There are also vehicles with 3 wheels. Legal definitions have the term “cycles” in order to cover all vehicles, irrespective of their number of wheels

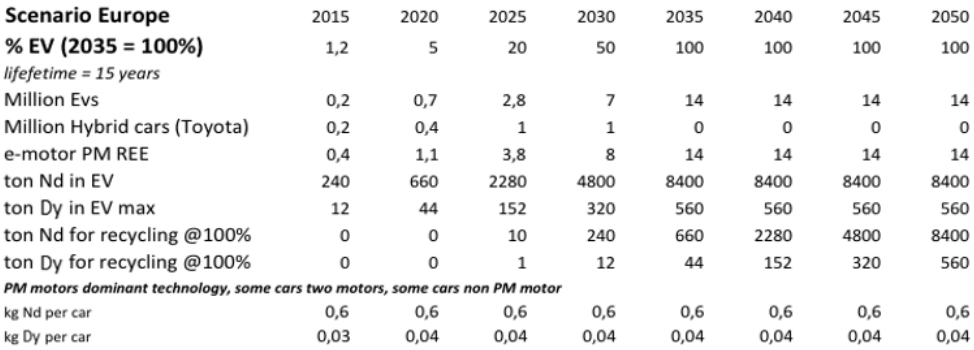
	2) cycles equipped with an auxiliary motor that cannot be exclusively propelled by that motor. Only when the cyclist pedals, does the motor assist. These vehicles are generally called pedelecs. Pedelecs can be considered a type of low-powered e-bike. Currently, electric cycles are mostly used in Northern Europe (80% of electric cycles are located in Germany, Netherlands, Belgium, France) but the market is far from saturated and their numbers are increasing in all countries. Approximately 8 million e-bikes are estimated to exist in Europe, having a net increase of 1.35 million units in 2015 alone (Conebi, 2016) and 20-30% growth per year. REEs in batteries for hybrid electric vehicles (HEVs) Until recently and to a limited extent, REE-based batteries were used for HEVs, mostly produced by Toyota. However, NiMH batteries for electric vehicles are being rapidly displaced by lithium-ion batteries which do not contain REEs. For this reason, market research into the existing HEV fleet containing REEs was not conducted.
Rare earth magnet content	Electric drive motors Published estimates of permanent magnet content per motor unit vary significantly from source to source. However, recent technological developments have resulted in lower PM content per unit of power (kW) as well as elimination or reduction of the Dy. Characteristically, in 2012, Nissan reported that its Nissan LEAF uses 40% less dysprosium (added to improve heat resistance) following changes in their permanent magnet manufacture lines. The amount of REE in motors is correlated to the required magnetic field which is determines the rated power rating of the respective motor.). For electric cycles, the latter is limited to 250 W while in electric vehicles (HEVs, PEHVs and EVs), PM motor rating ranges between 35kW and 150 kW with an estimated Nd content of 0.25 to 1.1 kg. Typically, the amount of Dy in car drive motors is estimated as a percentage of Nd (5 to 10%). In the near future, higher power motors will penetrate the market e.g. Tesla has already commercialized a car model of 568 kW (2 non-PM motors). The lifetime of PM motor in electric vehicles is at least equal to the useful life of the vehicle (14 years in Europe).

	For EPACs (electric power assisted cycles), Dy relative content is lower, (in the range of 2 to 4%) (Bafang communication with AVERE). The PMs in electric cycle motors weight 300-350 gr and contain approximately 30 g of Nd (Bosch communication to AVERE, Yang et al. 2017). Besides PMs in e-motors, magnets are also used in speed sensors for bicycles. This application was not investigated further as it comprises a very small fraction of magnets used in bicycles. Recycling however is relatively easy as the magnets are not glued (Bosch). The lifetime of electric cycles is estimated at 7 years (Bosch). Electric Power Steering (EPS) motors for cars In conventional automobiles, approximately 250 g of PMs (used in small motors and sensors) are used per car (Yang et al., 2017). It is estimated that for EPS, approximately 100 g of PM is being used per car, containing around 30 g Nd and up to 3 g of Dy. In Europe, 14 million new cars are being sold every year, a figure which is expected to increase slowly in the coming decade. If by 2020, as predicted, 70 -80% of these cars deploy EPS, this would translate to an annual demand of 300 tons of Nd. In addition, 15 to 30 ton Dy would also be available, though the Dy content in EPS is continuously decreasing and could be eliminated in the future. No correction has been made for the fact that a certain percentage of cars is exported out of the EU so, the actual volume available through recycling will be lower. The volumes do not reflect any other vehicle types.
Availability as EoL product	Nd and Dy penetration scenarios for vehicles Future market penetration scenarios for Europe have been considered for 3 applications of PM motors in vehicles: 1) e-drive motors in cars (EV and Hybrid), 2) e-drive motors in electric cycles (e-bikes and EPACs) and 3) e-motors for EPS in cars. The COP21 agreement requires virtually decarbonization of road transport by 2050 (fleet level). Therefore, in car-related applications (1,3), two scenarios were defined, one assuming 100% EV market penetration by 2035 and another assuming 50% penetration with hybrid cars partially accounting for the remaining part. The number of REE containing motors is set as equal to the number of new cars (currently, all electric car models with the exception of Tesla contain REE PM

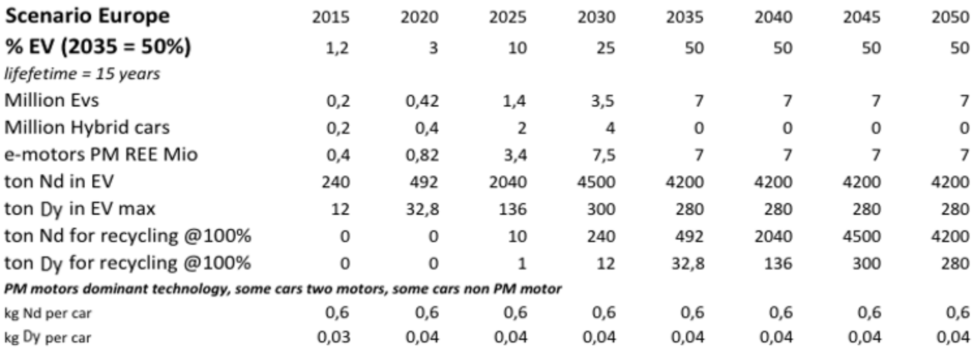
containing e-motors). At present, mainly small and medium (REE containing) cars are on the road and thus, their motor size is relatively small. As models of higher power ratings will be introduced in the coming years, it is presumed that efficiencies in REE use will compensate for higher power motors. It is assumed that these effects will cancel each other. Finally, 100% recycling rates were assumed (elaborated in section "Availability of collection measures").

1. EVs - 100% and 50% market penetration.

To estimate the amount of REE that can be harvested from electric vehicles, two "maturity level" scenarios were conceptualized: one for 3 million and another for 6 million EVs, respectively. Regarding light electric vehicles (LEVs), their market share is still very limited, with sales of only thousands of vehicles per year. Scooter sales in Europe in 2015 were 670,000 (source: Piaggio). Nevertheless, it can be expected that most two wheelers or light vehicles for cities will be replaced in the future by their electric counterparts. Ongoing technology R&D, pressure for short-term air quality improvement in cities and GHG reduction in the long term, significant or full penetration of EVs is a realistic scenario.

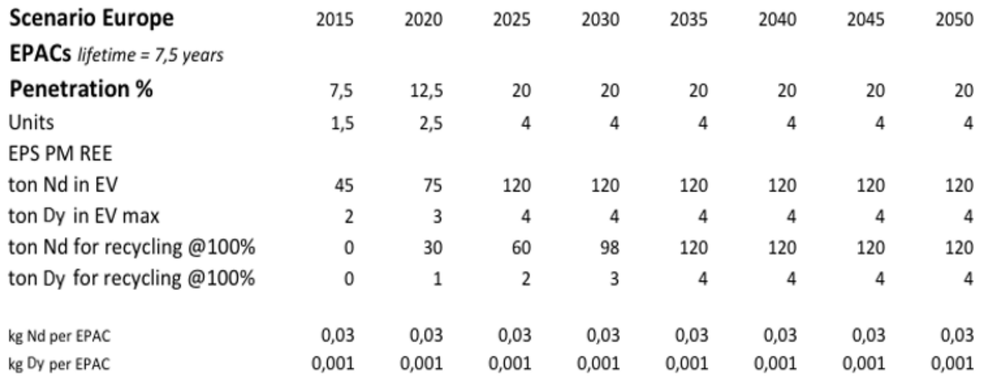


Scenario Europe	2015	2020	2025	2030	2035	2040	2045	2050
% EV (2035 = 100%)	1,2	5	20	50	100	100	100	100
lifefetime = 15 years								
Million Evs	0,2	0,7	2,8	7	14	14	14	14
Million Hybrid cars (Toyota)	0,2	0,4	1	1	0	0	0	0
e-motor PM REE	0,4	1,1	3,8	8	14	14	14	14
ton Nd in EV	240	660	2280	4800	8400	8400	8400	8400
ton Dy in EV max	12	44	152	320	560	560	560	560
ton Nd for recycling @100%	0	0	10	240	660	2280	4800	8400
ton Dy for recycling @100%	0	0	1	12	44	152	320	560
PM motors dominant technology, some cars two motors, some cars non PM motor								
kg Nd per car	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
kg Dy per car	0,03	0,04	0,04	0,04	0,04	0,04	0,04	0,04



Scenario Europe	2015	2020	2025	2030	2035	2040	2045	2050
% EV (2035 = 50%)	1,2	3	10	25	50	50	50	50
lifefetime = 15 years								
Million Evs	0,2	0,42	1,4	3,5	7	7	7	7
Million Hybrid cars	0,2	0,4	2	4	0	0	0	0
e-motors PM REE Mio	0,4	0,82	3,4	7,5	7	7	7	7
ton Nd in EV	240	492	2040	4500	4200	4200	4200	4200
ton Dy in EV max	12	32,8	136	300	280	280	280	280
ton Nd for recycling @100%	0	0	10	240	492	2040	4500	4200
ton Dy for recycling @100%	0	0	1	12	32,8	136	300	280
PM motors dominant technology, some cars two motors, some cars non PM motor								
kg Nd per car	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
kg Dy per car	0,03	0,04	0,04	0,04	0,04	0,04	0,04	0,04

2. electric cycles (EPACs, e-bikes)

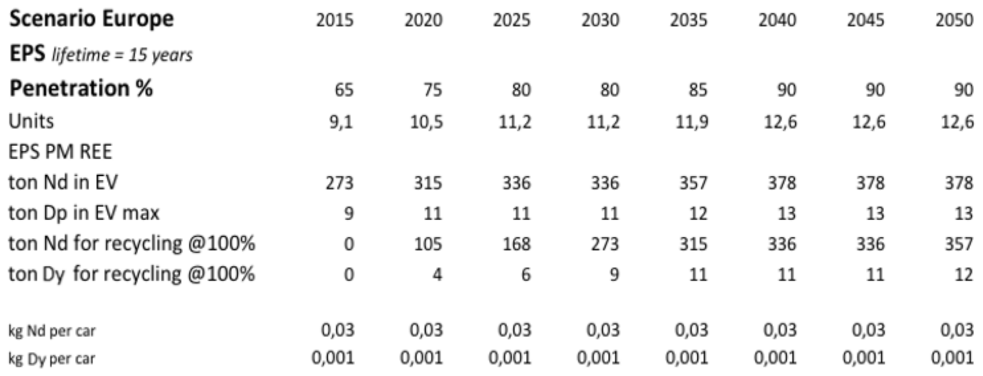


Scenario Europe	2015	2020	2025	2030	2035	2040	2045	2050
EPACs *lifetime = 7,5 years*								
Penetration %	7,5	12,5	20	20	20	20	20	20
Units	1,5	2,5	4	4	4	4	4	4
EPS PM REE								
ton Nd in EV	45	75	120	120	120	120	120	120
ton Dy in EV max	2	3	4	4	4	4	4	4
ton Nd for recycling @100%	0	30	60	98	120	120	120	120
ton Dy for recycling @100%	0	1	2	3	4	4	4	4
kg Nd per EPAC	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
kg Dy per EPAC	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001

E-bike recycling presents a shorter-term opportunity for recovery of Nd and Dy. AVERE estimated that by 2025-2030, approx. 100 tons of secondary Nd will be available on account of a 4 million “fleet” already on the road with half the useful life of cars.

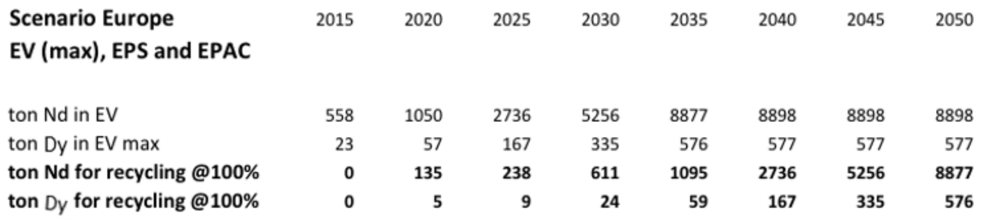
3. EPS for cars

The use of EPS in cars is already widespread with a penetration of more than 50% and expected to grow rapidly to 80% or more. This offers a certain scenario for availability in the years to come as the technology has started to be implemented in the beginnings of this century.



Scenario Europe	2015	2020	2025	2030	2035	2040	2045	2050
EPS *lifetime = 15 years*								
Penetration %	65	75	80	80	85	90	90	90
Units	9,1	10,5	11,2	11,2	11,9	12,6	12,6	12,6
EPS PM REE								
ton Nd in EV	273	315	336	336	357	378	378	378
ton Dp in EV max	9	11	11	11	12	13	13	13
ton Nd for recycling @100%	0	105	168	273	315	336	336	357
ton Dy for recycling @100%	0	4	6	9	11	11	11	12
kg Nd per car	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
kg Dy per car	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001

4. All vehicle scenarios combined



Scenario Europe	2015	2020	2025	2030	2035	2040	2045	2050
EV (max), EPS and EPAC								
ton Nd in EV	558	1050	2736	5256	8877	8898	8898	8898
ton Dy in EV max	23	57	167	335	576	577	577	577
ton Nd for recycling @100%	**0**	**135**	**238**	**611**	**1095**	**2736**	**5256**	**8877**
ton Dy for recycling @100%	**0**	**5**	**9**	**24**	**59**	**167**	**335**	**576**

Collection measures

EoL Cars

End-of-life cars are already collected for recycling by 100% as this is an obligation. However, this does not concern cars being exported outside Europe.

EoL electric cycles

Waste legislation governing electric cycles differs depending on the categorization of the vehicles. Electric cycles are excluded from Regulation 168/2013 by means of article 2(h). More specifically, "pedal cycles with pedal assistance which are equipped with an auxiliary electric motor having a maximum continuous rated power of less than or equal to 250 W, where the output of the motor is cut off when the cyclist stops pedaling and is otherwise progressively reduced and finally cut off before the vehicle speed reaches 25 km/h;" are subject to Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Furthermore, article 2.4 of the same Directive states: "(…). In addition to the equipment specified in paragraph 3, from 15 August 2018, this Directive shall not apply to the following EEE: means of transport for persons or goods, excluding electric two-wheel vehicles which are not type-approved;" Evidently, it is not clear which category e-bikes belong to and subsequently, whether their disposal comes under the WEEE Directive (since 13 August 2012) or will be regulated (on 15 August 2018). EU members appear to apply different interpretations of the Directive as well. For example, in Belgium, the collective scheme Recupel classifies electric bicycles under "Toys, leisure and sports equipment".

All electric cycles that have a higher speed than 25 km/h and or more motor output than 250W fall in the scope of Regulation 168/2013 and are therefore categorized as L-category vehicles. Thus, they come under Directive 2008/98/EC on waste (Waste Framework Directive). The Directive does not hold any collection and treatment obligations tailored to electric bicycles.

On the other hand, all types of electric cycles are subject to Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 about their waste batteries and accumulators.

Bosch indicated that both EPACs as well as their e-motors (when handled as individual parts) are partially recycled by recycling service providers. That is if they

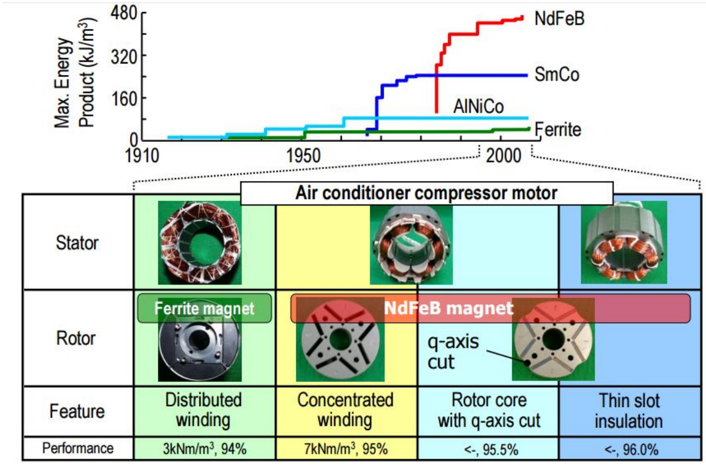
	are collected via dealer service centers. However, magnets are not collected as such at this stage as there is also no specific recycling process for these.
Barriers to recycling	The REE content in EVs is higher compared to this of conventional automobiles. Recycling of EVs mainly consists of de-pollution, dismantling, shredding and post-shredding sorting. Firstly, they are de-polluted in authorized treatment facilities in order to extract potentially hazardous components and toxic materials such as operating liquids, airbags and batteries. Furthermore, specific parts are dismantled either because of their material value (i.e., catalysts), re-use (i.e., engines, tires, electronics) or bad recyclability in the following process steps. Following the dismantling, the ELVs are usually shredded and processed with magnetic (iron concentrate), eddy-current (mixed non-iron metal concentrate) and density separators (plastic, dust, light materials). For a long time, the auto shredder residue (ASR), mainly light components and metals as well as glass-rich shredder sand, was landfilled (Elwert *et al.,* 2015). Difficulties for the recycling of PMs in vehicles arise at multiple levels. Firstly, magnets in conventional cars are not pre-dismantled and car waste is generally "treated" by shredding followed by physical separation (e.g. size, magnetic behaviors etc.). This practice causes significant losses of PMs to ferrous or non-ferrous scrap in a manner similar to the permanent magnets in Hard Disk Drives (Rawson, University of Birmingham, DEMETER H2020 project, Yang et al., 2017). Also, recovering motor PMs and channeling them to REE recovery requires that the magnet carrying parts (the rotors) are separated during disassembly (Elwert *at al*., 2015). If necessary, the magnets must be uncovered prior to extraction, e.g., by removal of the bandage in case of SPM rotors. There is little information regarding the disassembly of ELV motor and the value of their specific parts. The research project "Recycling of components and strategic metals from electric drive motors—MORE" modeled several scenarios for the disassembly of permanent magnet motors from ELVs down to the rotor/stator level. They considered German labor costs, decentral/central processing and different permanent magnet motor types (MORE Final Report, 2014) and concluded that the disassembly of the magnet-bearing rotor is already profitable today, mainly because of the stators' high copper wire content, even if the REEs are not recycled (Elwert *at al*., 2015).

	However, in the MORE project, it was observed that e-motors differ considerably in size, weight and geometry. A uniform dismantling process will therefore require major effort and redesign of the dismantling process. It is crucial for the future recycling of PMs from e-motors to evaluate if and how their design can be adapted to facilitate PM recycling or, alternatively, how the recycling process can be adapted to suit the design. Commercial attractiveness of recovery of e-motors and PMs and recycling of the PMs will determine the success in absence of requirements (Directives, legislation). It is possible that high Nd potential estimated for high penetration rates of EVs / hybrid cars will urge policymakers to develop legislative framework that will support and enforce Nd recovery. Moreover, the early availability of substantial amounts of REE-based PMs from EPACs and EPS motors could favor the set-up of collecting schemes for such end-of-life PMs.
Expert insight	**Key messages from interviews conducted with key stakeholders:** *“e-motors are difficult to disassemble”* *“not designed for recycling”,* *“PMs are glued to stator and very difficult to remove”*
References	♻ Alonso, E., Sherman, A. M., Wallington, T. J., Everson, M. P., Field, F. R., Roth, R., & Kirchain, R. E. (2012). Evaluating rare earth element availability: A case with revolutionary demand from clean technologies. Environmental science and technology, 46, 3406-3414. Retrieved September 18, 2017 from http://pubs.acs.org/doi/pdf/10.1021/es203518d ♻ Bast, U. Recycling von Komponenten und Strategischen Metallen aus Elektrischen Fahrantrieben: MORE (Motor Recycling). Final Research Report. 2014. Accessed on 21 September 2017 at http://edok01.tib.uni-hannover.de/edoks/e01fb15/826920594.pdf ♻ Binnemans, K., Jones, P., T., Blanpain B., Van Gerven, T., Yang Y., Walton, A., Buchert, M., 2013; Recycling of rare earths: critical review in Journal of Cleaner Production, 51, 1-22. ♻ Conebi: Confederation of the European Bicycle Industry, statistics year report July 2016.

	♻ Elwert, T.; Goldmann, D.; Römer, F.; Buchert, M.; Merz, C.; Schueler, D.; Sutter, J. Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles. Recycling 2016, 1, 25-60. ♻ European Bicycle Market. 2016 edition Industry & Market Profile. Retrieved July 21, 2017 from : http://www.conebi.eu/wp-content/uploads/2016/09/European-Bicycle-Industry-and-Market-Profile-2016-with-2015-data-.pdf ♻ Miller M. John., Oak Ridge National Laboratory, 2013 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting. May 15, 2013 ♻ PRESTO (Promoting Cycling for Everyone as a Daily Transport Mode) Legislation Fact Sheet, Retrieved April 28, 2017 from : https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/presto_fact_sheet_legislation_en.pdf ♻ Yang, Y., Walton, A., Sheridan, R. et al. J. Sustain. Metall. (2017) REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review. 3: 122. doi:10.1007/s40831-016-0090-4

2.1.4 EoL Air conditioners – market overview

Air conditioners – facts & figures	
Application	Air conditioning is the process of altering the properties of air (primarily temperature and humidity) to achieve more comfortable conditions, typically in controlled spaces where humans or animals reside. They are used both in industrial and domestic settings. Air conditioners control a room's temperature by compressing and expanding gas, which serves as a heat exchange medium. Gas compressors are the core of air conditioning (Bast et al., 2015). Compressor efficiency has a great impact on the overall efficiency of air conditioning. Stable and efficient operation of compressors reduces the friction between the overall system's operating parts and prevents expansion of the refrigerant. Incorporation

	of rare earth magnets into the design of air conditioners allows for high energy efficiencies which have increased significantly over the last 25 years (as shown in Figure 9) (Mikami, 2012). Air conditioners deploy rare earth magnets in their compressor motors (typically three or four). Having a magnetic field 10 times stronger than this of ordinary magnets, NdFeB PMs greatly enhance the operational efficiency of the air conditioners.  *Figure 9. Evolution of energy performance of air conditioners* REEs of air conditioning units will naturally become available for recovery after the product has reached end of life. SaveEnergy123, states that the "lifespan" of a central air conditioner is about 15 to 20 years. Riano & Binnemans (2016) assumed a lifetime of 12 years for air conditioners and a standard deviation of 3 years. This study assumes the same average air conditioner lifespan (12 years).
Rare earth magnet content	The NdFeB content in air conditioning varies according to their type of applications. Domestic air conditioners have an average NdFeB content of about 100-500 gr, while air conditioners for industrial applications contain 250-330 gr of NdFeB (Bast et al., 2015; Habib et al., 2014; Isfatuni et al., 2013.). Efficiency standards for air-conditioning units are continuously being raised to achieve GHG emission targets (Mikami, 2012; Yu, 2014), and it is expected that efficient NdFeB-based compressors (containing Dy) will support this transition (Frontier Rare Earths,2012; Minowa, 2008). Consequently, the global demand for NdFeB magnets used in air-conditioning systems is expected to increase. (Benecki, 2013; Shaw & Constantinides, 2012.)

	Experts in the REE4EU consortium confirmed that PMs of air conditioners motors can also contain Dy. According to Schulze & Buchert (2016), the dysprosium content for NdFeB magnets used in air conditioners is estimated as 3-7 weight % in the literature and is expected to drop to 2.5-3% by 2015 (Seo & Morimoto, 2014).
Availability as EoL product	The management of WEEE is currently regulated by Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). The first WEEE Directive (Directive 2002/96/EC) entered force in February 2003. The Directive provided for the creation of collection schemes where consumers return their WEEE free of charge. These schemes aim to increase the recycling of WEEE and/or re-use. Directive 2002/96/EC was repealed on 15 February 2014 and was replaced by Directive 2012/19/EU on waste electrical and electronic equipment (WEEE), which introduces a stepped increase in collection targets that will take effect in 2016 and 2019. Coherently with Annex I, air conditioners fall into the category of “large household appliances” (including large cooling appliances, refrigerators, freezers, washing machines, clothes dryers, dish washing machines, cooking, electric stoves, electric hot plates, microwaves, electric heating appliances, electric radiators, electric fans, air conditioner appliances and other fanning, exhaust ventilation and conditioning equipment - listed in Figure 10). In 2018, the current scope of the Directive will be extended from its present restricted scope to include all categories of WEEE, and consequently the definition and number of the categories will change.

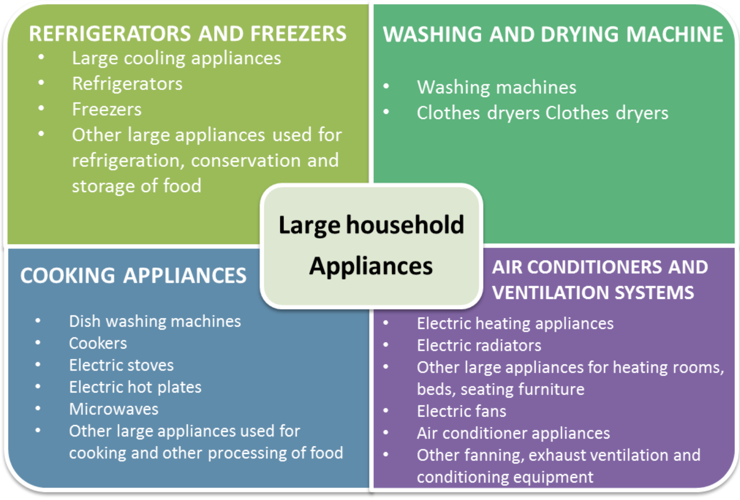
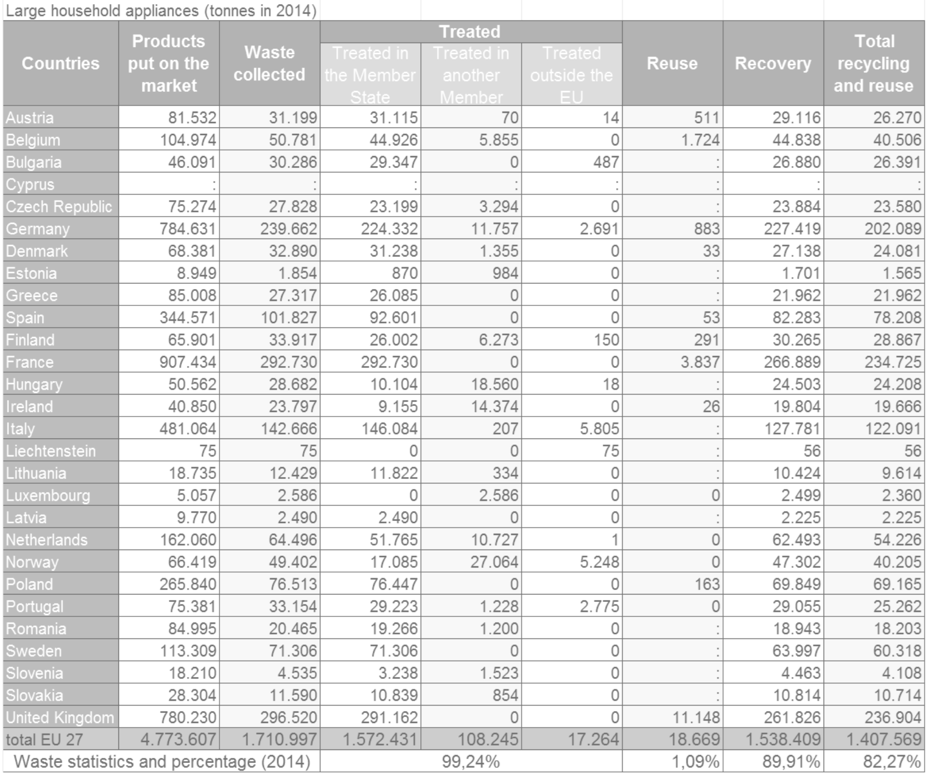


Figure 10. Classification of WEEE according to Directive 2012/19/EU (cf. Annexes I and II)

According to the Commission Decision 2005/396/EC, Member States have the obligation to annually report to the Commission their performance in terms of WEEE collection, re-use, recycling and / or recovery within 18 months of the end of the reference year. The following table (Table 7) shows the geographic allocation of large household appliances collected in the EU during 2014 (the most recent data set in Eurostat). In that year approximately 4.7 billion tonnes of “Large Households Appliance” entered the EU27, 36% of which were collected as waste. Almost all collected EoL large household appliances were recycled and a small percentage (less than 2%) was reused. Among end-of-life (EoL) home appliances, air conditioners have the highest REE harvesting potential as they have a relatively high amount of embedded REE magnets (contain almost a 4-fold equivalent content of neodymium compared to washing, drying machines, refrigerators and freezers).

Table 7. Eurostat Data - Large household appliances – 2014.



Large household appliances (tonnes in 2014)

Countries	Products put on the market	Waste collected	Treated			Reuse	Recovery	Total recycling and reuse
			Treated in the Member State	Treated in another Member	Treated outside the EU			
Austria	81.532	31.199	31.115	70	14	511	29.116	26.270
Belgium	104.974	50.781	44.926	5.855	0	1.724	44.838	40.506
Bulgaria	46.091	30.286	29.347	0	487	:	26.880	26.391
Cyprus	:	:	:	:	:	:	:	:
Czech Republic	75.274	27.828	23.199	3.294	0	:	23.884	23.580
Germany	784.631	239.662	224.332	11.757	2.691	883	227.419	202.089
Denmark	68.381	32.890	31.238	1.355	0	33	27.138	24.081
Estonia	8.949	1.854	870	984	0	:	1.701	1.565
Greece	85.008	27.317	26.085	0	0	:	21.962	21.962
Spain	344.571	101.827	92.601	0	0	53	82.283	78.208
Finland	65.901	33.917	26.002	6.273	150	291	30.265	28.867
France	907.434	292.730	292.730	0	0	3.837	266.889	234.725
Hungary	50.562	28.682	10.104	18.560	18	:	24.503	24.208
Ireland	40.850	23.797	9.155	14.374	0	26	19.804	19.666
Italy	481.064	142.666	146.084	207	5.805	:	127.781	122.091
Liechtenstein	75	75	0	0	75	:	56	56
Lithuania	18.735	12.429	11.822	334	0	:	10.424	9.614
Luxembourg	5.057	2.586	0	2.586	0	0	2.499	2.360
Latvia	9.770	2.490	2.490	0	0	:	2.225	2.225
Netherlands	162.060	64.496	51.765	10.727	1	0	62.493	54.226
Norway	66.419	49.402	17.085	27.064	5.248	0	47.302	40.205
Poland	265.840	76.513	76.447	0	0	163	69.849	69.165
Portugal	75.381	33.154	29.223	1.228	2.775	0	29.055	25.262
Romania	84.995	20.465	19.266	1.200	0	:	18.943	18.203
Sweden	113.309	71.306	71.306	0	0	:	63.997	60.318
Slovenia	18.210	4.535	3.238	1.523	0	:	4.463	4.108
Slovakia	28.304	11.590	10.839	854	0	:	10.814	10.714
United Kingdom	780.230	296.520	291.162	0	0	11.148	261.826	236.904
total EU 27	4.773.607	1.710.997	1.572.431	108.245	17.264	18.669	1.538.409	1.407.569
Waste statistics and percentage (2014)			99,24%			1,09%	89,91%	82,27%

Air conditioning market at global and European scale

Global demand for air conditioning units is projected to have a robust growth in the following years. The Berkeley report projects that the world is poised to install 700 million air conditioners by 2030, and 1.6 billion of them by 2050. That would translate to an average compound annual growth rate of 4.22% on a world basis. China, Southeast Asia and India comprise the largest portion of air conditioning global market. It is estimated that more than 4,000 tons of NdFeB were used for air conditioners in 2014. An increase in NdFeB demand is associated with the growing market for inverter air conditioners in China (Frontier Rare Earths, 2012).

Till 2030, the global available NdFeB in end of life domestic air conditioners is estimated to be around 7480 ton, excluding losses from collection, disassembly and recycling (20%) (Schulze and Buchert, 2015). The authors assumed an average 250 g magnet weight per unit and assumed an average lifetime of 12 years (3 years standard deviation) (See Table 8)

Table 8. Global supply of secondary NdFeB from end of life air conditioners in tonnes

	2015	2020	2025	2030	2015 - 2030

Unit (t)	Low 1)	High	Low	High	Low	High	Low	High	Total Low	Total High
NdFeB(2)	490	865	655	1880	890	4320	1330	7480	3365	14545

(1) Low represents low NdFeB demand scenario and high represents high NdFeB demand scenario.

(2) Schulze & Buchert (2016). Excluding losses from collection, disassembly and recycling (20%).

The European market for air-conditioning is relatively young and still growing substantially. As reported by the Joint Research Centre of the European Commission, 2.6 million air conditioning units were sold in 2007 on the EU-27 market contributing to an existing stock of air- of over 25 million units in 2008 (Bertoldi & Atanasiu, 2009]. The market analysis considered residential Room Air Conditioners (RAC) of up to 12 kW. However, this study did not specify what percentage of the stock was reaching the end of its life the same year. More recent information concerning the global and regional AC demand was published by the Japan Refrigeration and Air Conditioning Industry Association (JRAIA) which collected data for window type and small-sized split type ACs as well as residential-use multi systems (See Figure 11). Generally, there is a lack of reliable information on the market share of NdFeB-based air-conditioning systems.

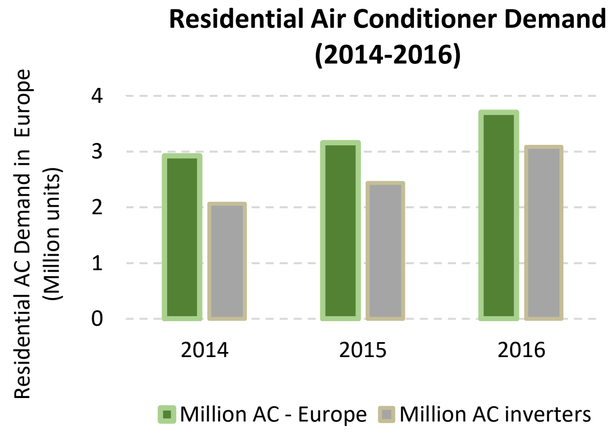


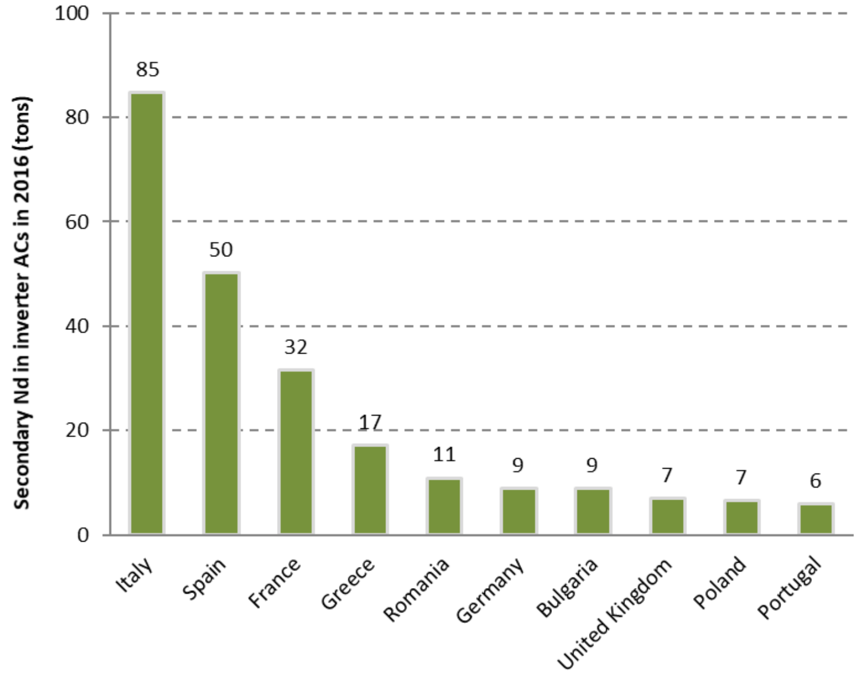
Figure 11. Estimated demand for room air conditioners in Europe during 2014-2016 (excl. Russia, Turkey) (Source: JRAIA)

Due to the very limited availability of public information for EoL air conditioners, estimating the content of secondary NdFeB draws upon multiple assumptions and sources of data. More specifically:

- The scope of the estimation was limited to residential air conditioners as there was no quantitative information on the number of industrial ACs in Europe. In addition, residential air conditioners are more likely to enter EU’s recycling scheme as “large household appliances”.

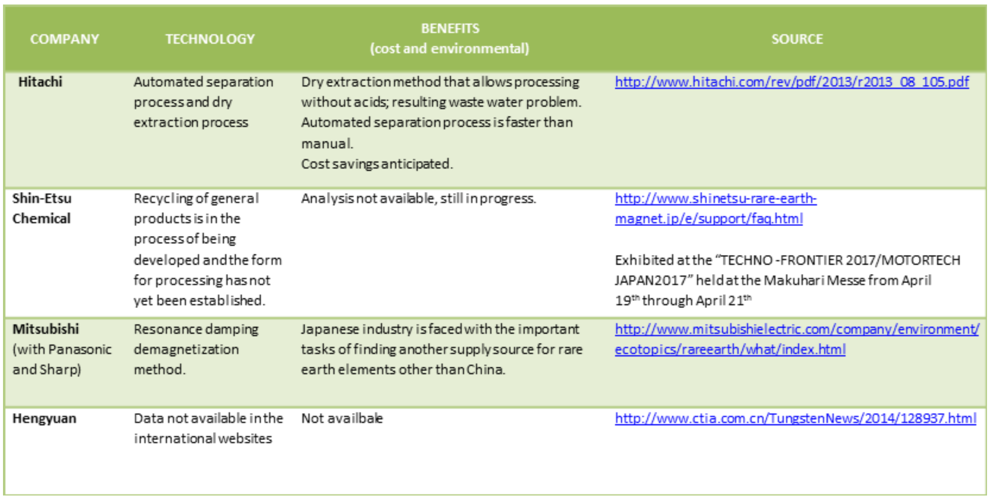
- Following the assumption of Schulze & Buchert (2016), Residential air conditioner units with inverter technology (Daikin Global, 2015) are used as a basis for the scenario calculation, assuming those figures can be used as an indication for the market size of NdFeB-based air conditioner compressor motors. The Inverter technology (DC) is the latest evolution of technology concerning the electro motors of the compressors. AC inverters can vary the speed of the electromotor to adjust the cooling / heating output, thus achieving high energy efficiencies.
- According to Daikin (Daikin, 2015) the market penetration of AC inverters in 2009 and 2015 was 40 and 78%, respectively. We assume a linear increase of market penetration for AC inverters from 2009 to 2015 and due to lack of other information, also for the period of 2016 -2020.
- Inverter Air conditioning units installed in the EU in 2007 were assumed to have an average useful life of 12 years and contain approx. 300 g of NdFeB
- Dy content in AC inverters is considered as 3 % till 2020 dropping linearly to 2% in 2030 (Schulze & Buchert, 2016)
- In line with the statistics of collection for large household appliances, 30% of AC inverters that exit the European market as EoL products are collected, the rest are excluded from the estimation of REE resource potential.
- The European AC demand is assumed to have a flat CAGR of 5% during 2014-2030. Though Schulze & Buchert (2016) assumed a 10% growth rate for years 2013-2030, a more conservative growth rate (close to the global average) was chosen to avoid significant overestimation of REE.
- 100% of the air conditioners entering the market in year n will become EoL products in year (n+12)

With the above as the calculation basis, both the NdFeB demand for inverter ACs and their respective availability as EoL products were estimated. As an example, Figure 12 illustrates the estimated Nd demand for inverter ACs in Europe in 2016. In 2016, Italy and Spain were the largest markets for NdFeB-based residential air conditioners (translating to demand for 85 and 50 ton of Nd, respectively).

	 *Figure 12. Nd demand for residential inverter ACs in EU member state countries (data correspond to top 10 countries)*
Availability of collection measures	*Collection rates of large household appliances and air conditioners in Europe* Estimates for air conditioner collection rates in different countries are given in KPMG (2014). Schulze and Buchert (2016) assumed a 60% collection rate and 90% efficiency during disassembly. **<u>State of the art in collection and recycling of magnets from air conditioners</u>** Despite the challenges, some companies are trying to collect and recycle REE from air conditioners. For instance, the collection and recycling of magnets from air conditioners is already being practiced in Japan, i.e. Hitachi Ltd and Mitsubishi Electric. In 2012, Mitsubishi Electric reported that it is recovering and recycling rare earth magnets from its air conditioners, and Hitachi announced development of a magnet recovery machine for hard disk drives and air conditioners, with the intent to bring the technology into commercial operation. In 2013, Honda announced that it was beginning to recover the rare earth elements from its hybrid car batteries. French chemical company Rhodia has announced multiple rare earth recycling projects. The following table (Table 9) provides a summary of commercial, or soon-to-be commercial, operations by selected companies along with publicized information

on the materials being recovered, the technology to be used, notes concerning to the cost or environmental benefits; and the source of information.

Table 9. Summary of the state-of-the-art in PM recycling



COMPANY	TECHNOLOGY	BENEFITS (cost and environmental)	SOURCE
Hitachi	Automated separation process and dry extraction process	Dry extraction method that allows processing without acids; resulting waste water problem. Automated separation process is faster than manual. Cost savings anticipated.	http://www.hitachi.com/rev/pdf/2013/r2013_08_105.pdf
Shin-Etsu Chemical	Recycling of general products is in the process of being developed and the form for processing has not yet been established.	Analysis not available, still in progress.	http://www.shinetsu-rare-earth-magnet.jp/e/support/faq.html Exhibited at the "TECHNO -FRONTIER 2017/MOTORTECH JAPAN2017" held at the Makuhari Messe from April 19th through April 21th
Mitsubishi (with Panasonic and Sharp)	Resonance damping demagnetization method.	Japanese industry is faced with the important tasks of finding another supply source for rare earth elements other than China.	http://www.mitsubishielectric.com/company/environment/ecotopics/rareearth/what/index.html
Hengyuan	Data not available in the international websites	Not availbale	http://www.ctia.com.cn/TungstenNews/2014/128937.html

The following section gives a brief description of the above-mentioned technologies:

Hitachi Ltd

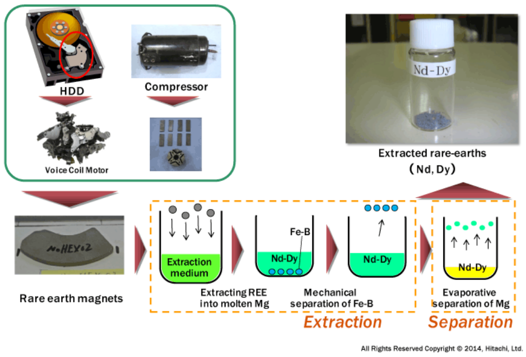


Figure 13. Flow chart of the recycling process of NdFeB magnets at Hitachi Metals (source: Hitachi.com)

In December 2010 Hitachi, Ltd. announced that it had developed a technology for recycling rare earth magnets from hard disk drives (HDD) and compressors from air conditioners and other types of equipment. Specifically, the company developed machinery for separation of rare earth magnets from end-of-life products, from which rare earths could be successfully extracted using an experimental dry process. Though, in the case of compressors the separation process was challenging, the company stated that its new cutting machinery and demagnetizing machinery separation and collection safe and efficient (Figure 13). Moreover, the new dry process, could recover rare earths using a uniquely formulated extraction liquid with high affinity for rare earths. Hitachi stated that they would commence full recycling operations by 2013 after calculating the overall recycling costs and recovery ratio for their developed process.

Shin-Etsu

Shin-Etsu Chemicals owes a Japanese granted patent “T. Hasegawa, K. Hirota, and T. Minowa, JP4296372, 2009” about the recycling of magnets on industrial scale (information available only in Japanese).

Mitsubishi Electric

Mitsubishi Electric’s proprietary technology enables automatic dismantling equipment using a resonance damping demagnetization method. The developed equipment (Figure 14) can automatically dismantle, sort and remove the rare earth magnets used in compressors at a pace of one air conditioning unit every 30 seconds.

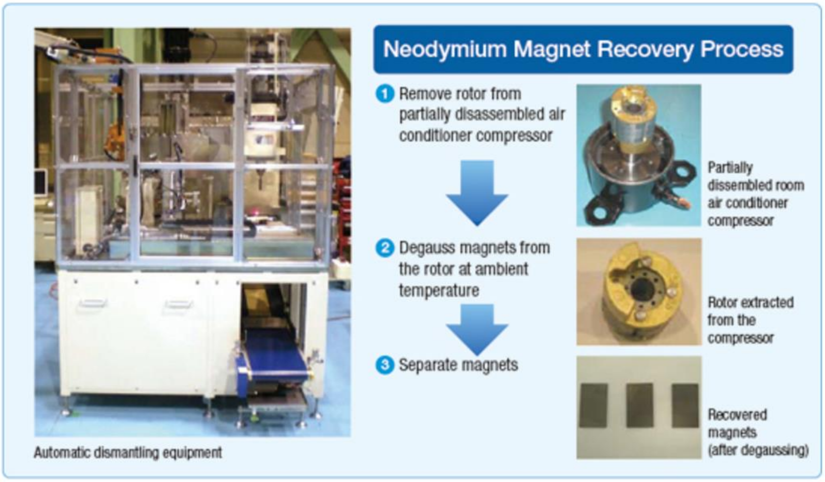


Figure 14. Neodymium Magnet Recovery Process (source: http://www.mitsubishielectric.com)

Hengyuan

On May 2014, Hengyuan Technology Development Co., Ltd. completed the construction of an REE recycling plant capable of recycling 5,000 t Nd-Fe-B magnets / year, after a year of intense construction of smooth operation. The plant was recycling 5.000 tons and 1.500 tons of waste phosphor in this NdFeB waste

	project, located in Ganzhou Shek Pai Village XUNWU County Wenfeng Township. Information concerning recycling of permanent magnets from air conditioner is not available. It is known that Hengyuan raised a total investment of 300 million yuan, and the plant is divided into three building in a comprehensive recycling of 5.000 tons NdFeB waste, 1.500 tons of phosphor waste, 3.000 tons and 1.000 permanent magnet NdFeB magnetic energy efficient motor production line. The company expected to achieve 10 million yuan annual sales income and 400 new job placements.
Barriers to recycling	Room air conditioners have great potential as an untapped deposit of rare earth elements, but the difficulty of removing the rare earth elements from these units can be a critical bottleneck. That is because rare earth magnets used in air conditioners are found inside compressor rotors and are attached to their surrounding components with a rather powerful magnetic force. On top of this, air conditioner compressor rotors are made in a variety of shapes and sizes, making it near impossible to establish a standard method for disassembling the rotor to remove the rare earth magnets inside. This challenge seems to be acknowledged by Mitsubishi, which claimed to have created a database of the shapes and sizes of rotors to easily modify its operations.
Expert insight	In the deliverable “D9.1 Value Chains Stakeholders Analysis Report” a helicopter view on the most relevant stakeholders who are connected to the topic of Rare Earth Elements (REE) in general and more specifically to the air conditioning sectors are well described. T The following 24 companies were identified as main end users of REE (to be used as part of air conditioners): 1. Riello Group 2. VOX 3. Buildingclimate Switzerland 4. ICOM 5. ATIC vzw-asbl 8. Hitachi 9. Guntner 10. Mitsubishi 11. CIAT 12. SWEGON 13. BLAUPUNKT 14. Ariston 19. Bosch Thermotechnik Gmbh 20. Daikin Europe N.V. 21. Ferroli Spa 22. Rhoss

6. SPT
7. EKVU
15. Thermo Group
16. Baltur
17. KGH
18. SSTP
23. ATECYR
24. SELPRO
25. FINVAC

To gather insights regarding the market of EoL air conditioners, members of the four trade associations and federations, namely Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the Association of the European Heating Industry (EHI), were selected as Interviewees for the market analysis. REHVA includes 26 associations from 26 European countries and all its members associations were individually contacted via mail. EHI on the other hand**,** represents and promotes the common interests of 39 market leading companies and 13 associations in the European thermal comfort sector, which produce advanced technologies for heating and cooling in buildings. In EHI's case, a detailed web search has been carried on identifying the member profiles most relevant to REE4EU. In total, 17 members from EHI were selected and contacted. In addition to these contacts, REE4EU also reached out to the 25 industrial stakeholder identified during the project's stakeholder analysis (listed above) Among others, a closer contact has been established with three of the bigger companies, identified as the main actors in Europe: Michele Albieri (R&D Manager, Rhoss), Bosse Andersson (Quality and Environment coordinator, SWEGON) and Antonio Cavaler (Industrial Business Unit R&D Dept Manager - Ferroli).

Every industrial stakeholder received a brief questionnaire with the following questions:

1. *How many air conditioners do you produce annually and what fraction of those have NdFeB-based compressors motors?*
2. *Since when do you use Nd for the manufacture of your compressor motors? What is the NdFeB content in an air conditioner? How many tons of NdFeB are consumed per year?*
3. *We found out that the lifespan of air conditioner ranges between 15 to 20 year. Could you share specific details for the lifetime of the motors? Can the rotor be considered as spare part with a shorter lifetime?*

4. *What is the end of lifetime of parts containing rare earth elements in air conditioners? Is there any recycling approach that your association is planning to conduct in the future?*
5. *Will rare earth elements also have a strong presence in subsequent commercial air conditioner models? Or will new technological advances decrease or even eliminate their use? What is the general view of your company for the prospect of Nd as a raw material for future air conditioners?*

In summary, the findings from the REE4Eu survey showed that:

- Air conditioner producers are the end users of REE elements and they purchase motors already made by other industries Therefore, they can be considered as indirect promoters of REE4EU's business case by influencing the REE intensive product manufacturers (in this case the motor producers).
- EBM-PAPST, Euromotors Italy (EMI) and MS-Schramberg are the predominant suppliers of electrical motors for air conditioning compressors in Europe and they represent the biggest "Motors in industrial applications" producers;
- At the time of the interviews, the interviewees were not actively pursuing solutions alternative to disposal for EoL compressors as the disposal of EoL air conditioners is currently managed by consumers. For example, Ferroli is directly involved in the disposal for only 1-2% of all engines from their returned machines. However, they do plan for future recycling and are taking certain steps towards supporting recycling. Swegon for example, makes BUILDING PRODUCT DECLARATION (BPD) in compliance with the guidelines of the Ecocycle Council. This document illustrates the environmental properties of built-in materials and products, therefore being a reference document in the case of future measures, such as demolition or waste management.
- Most of the compressor suppliers are located outside the EU, especially for the large industries. In general, one of the interviewed stakeholders that is producing more than 30.000 air conditioner units/year, procures only 5-10% of its compressors from EU companies – though this

	percentage can increase up to 40% for the small producers of air conditioners. • If motors containing recycled REE have the same efficiency and cost as their counterparts with primary REE, then recycled REE-based PMs can be an acceptable solution for the interviewed stakeholders. In this regard, Antonio Cavaler says “Ferroli S.p.A is definitely interested in alternatives to rare earths or in using recycled rare earths in order to maintain the same performance or obtain better one and reduce the costs.”
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2.1.5 EoL Magnetic separators – market overview

Magnetic separators – facts & figures

Application	Magnetic separation equipment uses magnetic force to detect and separate magnetically susceptible material from a mixture. The rare-earth magnet content is available in various concentrations (in accordance to the magnetic strength requirements) and it typically contains Neodymium-boron-iron. Magnetic separators are frequently deployed in several types of industries such as chemicals, coal, food, glass, mineral processing, packaging, pharmaceuticals, plastic and rubber, and recycling. Through the removal of ferrous and para-magnetic contamination, magnetic separators ensure product purity and protection of downstream processing equipment from metal damage. For example, high-intensity rare-earth magnetic rods are highly effective in removing ferrous contaminants from free-flowing products such as sugar, grain, tea, plastic granules, chemical powders or liquids. Rare earth magnetic separators are available in several forms, most commonly as: ♻ **Magnetic plate or plate magnet** installed in a chute, spout, or duct, or in suspension over a nonmagnetic conveyor or screen to remove medium and small contaminants (See Figure 15) ♻ **Magnetic grate or grate magnet** consisting of individual tube magnets arranged in a grate assembly that can be installed in a steeply sloped hopper (even one with an odd or irregular shape), floor opening, vertical closed chute, or duct to remove small and fine metal particles or tramp iron from free-flowing products (See Figure 15). ♻ **Magnetic grate in housing** configured as a grate assembly with multiple magnet rows that is installed in a custom-manufactured housing to remove

	ferrous contamination from free-flowing products as they cascade through the grate. • **Magnetic drum separators** used in applications where there is a high throughput of material to be processed and a need to extract smaller ferrous particles from a given product stream. Advances in rare-earth magnetic material properties, magnetic roll and drum designs, and optimization of machine designs have enhanced the technical performance and economic viability of high-intensity magnetic separation in the last few years.  *Figure 15.Examples of magnet plate (left) and magnetic grate(right) type of magnetic separators* Warranties for magnetic separators are typically given for one year; however, in practice, the machines are used much longer. Schultze & Buchert (2016) mentioned that according to one manufacturer, the machines are normally serviced after 5 or 10 years in use, and the magnets then often need to be replaced. A second manufacturer estimated a longer lifetime (12 years).
Rare earth magnet content	Continuous improvement of high energy rare earth permanent magnetic materials has contributed to wide adoption of magnetic separators by several industries. Due to the multiplicity of designs, sizes and intended applications, their REE content varies greatly. Magnetic drum separators, for example, can have a Nd content in the order of 100 kg – 1 ton (personal communication with Commissariat à l'Énergie Atomique) Apart from Nd, magnetic separators also contain Dysprosium (Dy), Praseodymium (Pr) and Terbium (Tb), normally estimated on a weight per weight basis of Nd. The assumptions for Dy, Pr and Tb content by weight in NdFeB magnets was estimated by Schulze and Buchert (2016): for Pr (20% w/w Nd over 2020-2030), Dy (9,7,6% w/w Nd in 2020, 2025 and 2030, respectively) and Tb (1%

over 20120-2030). The same paper also provided estimates of REE demand in EoL magnetic separators for 2020-2030 (Table 10). It should be noted though, that feedback received from Vacuumschmelze (REE4EU consortium member) points to nearly no Dy content in magnetic separators and complete absence of Tb.

Table 10. REE demand for NdFeB PM production channelled to the global magnetic separation market (Schulze & Buchert, 2016)

	2020		2025		2030	
Unit	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario
Nd(t)	1,030	1,200	1,090	1,490	1,160	1,850
Pr(t)	210	245	220	305	235	380
Dy (t)	100	100	95	90	89	69
Tb(t)	9	9	8	8	7	6

Availability as EoL product

Unfortunately, there is very limited information regarding recycling of EoL magnetic separators in the literature (Constantinides, 2012; Schulze & Buchert, 2016). To date, published work gives only an overview of the global market. Therefore, it was not possible to estimate the amount of REEs contained in EoL magnetic separators within Europe. Nevertheless, it is worth noting the trends of future availability even at a global scale. Based on the low scenario estimates for 2020, 2025 and 2030 - provided by Schulze and Buchert (2016)- annual quantities of Nd, Pr and Dy available for recycling worldwide have been intra and extrapolated for the period 2020 and 2040 assuming continuous growth rate as in Table 10. As illustrated in Figure 16 below, available REE quantities in magnetic separators will have a modest growth till 2040 featuring a gradual decrease of Dy. The presented NdFeB quantities hereunder reflect only the upper limit of secondary REE amounts that can be harvested from EoL magnetic separators as they do not consider losses from collection, sorting and disassembly.

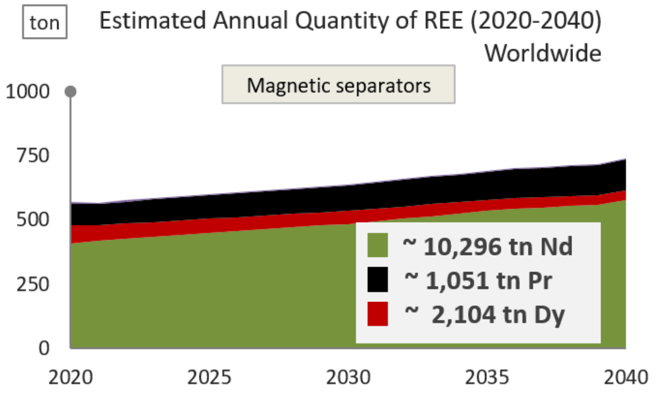

Figure 16.Global supply of REE from NdFeB containing EoL magnetic separators (excluding losses from collection, sorting and disassembly)

Availability of collection measures

To date, EU legislation does not foresee recycling of magnets in magnetic separators, hence rates of collection and losses during disassembly and recycling can only be roughly estimated available. To our knowledge, only one paper ("Scenario estimates of rare earth recycling potentials from NdFeB magnet material" by Schulze and Buchert (2016) indicates a collection rate of 80% and an overall REE extraction efficiency of 59% (Table 11) but the authors do not elaborate further on the basis of these assumptions.

Also, there is no information on the fraction of EoL magnetic separators (magnets) that remains in Europe. When asked on the subject, some of the interviewees confirmed exporting spent permanent magnets from magnetic separators to China. It is likely that due to the value of the particular equipment and the absence of legislation regulating their fate as EoL products, many of them are sold as second-hand goods out of EU markets.

Table 11. According the paper "Scenario estimates of rare earth recycling potentials from NdFeB magnet material" (Rita Schulze, Matthias Buchert, 2016)

Magnetic Separator Lifetime	Collection Rate	Efficiency Rate Disassembly	Efficiency Rate Recycling	Overall REE extraction efficiency
10 years ±2	80%	80%	92%	59°%

Expert insight

Starting from the 16 biggest companies identified by the stakeholder analysis (deliverable D9.1), an email and also a telephone contact was made. In total, 24 organizations were contacted, namely:

1. Älmhults El-Mek AB - Elmemagnets
2. Bakker Magnetics BV
3. Biocare Svenska AB
4. Brugger Magnete
5. Bunting® Magnetics Europe Ltd
6. CALAMIT srl
7. Eclipse Magnetics
8. Eriez Magnetics Europe Ltd
9. ERTEX SCIENTIFIC & PRODUCING LTD
10. Gauss magneti srl
11. GI-DA srl
12. Goudsmith Magnetics
13. IFE Aufbereitungstechnik GmbH
14. IMRO MASCHINENBAU GmbH
15. Magna-c
16. MAGNET PRO
17. Magnetic Separations Ltd.
18. Master Magnets Ltd
19. NEUHÄUSER Magnet- und Fördertechnik GmbH
20. Regulator Cetrisa
21. Steinert
22. STUDIOMAGNETIC
23. The European Magnetism Association
24. The UK Magnetics Society
25. Selter, s.a.

Within the content of REE4EU, the following industrial stakeholders provided insights of the market of magnetic separators: Luis Oliveras (Selter s.a), Carlo Chiarli (STUDIOMAGNETIC), and Roberto Ciambella (Calamit srl).

Every industrial stakeholder received a brief questionnaire with the following main questions:

1. *How many magnetic separators does your company produce (per year) and how many of these are permanent magnets (and not on electromagnets)?*
2. *A wide range of magnetic separator types use NdFeB permanent magnets. What is the NdFeB content in the different separators (i.e. Drum magnetic separators, Magnetic Pulleys, Over Band Magnetic separators, Plate Magnetic separators, Cross Belt magnetic Separators, Pipeline Magnetic Separators, Hump magnetic Separators, permanent suspended Magnetic Separators, others…)? In total, how many tons of NdFeB are consumed per year for magnetic separators' production?*
3. *Precise information about the average lifespan of magnetic separators is difficult to recover. Based on our research, we assume that the average lifespan of magnetic separators is around 10 years.. Can you give an estimate of the average lifespan of magnetic separators? Does it differ for different*

type of separators? How often it is necessary to replace the magnet of the machines?

4. *Does your company plan to recycle spent permanent magnets in the future?*
5. *Are the permanent NdFeB magnets still used in new generation magnetic separators? Is there in the market any alternative technology/product that is expected to eliminate the use of REE? What is the general view of your company on the use of NdFeB magnets in future magnetic separators?*

This survey showed that:

- Magnetic separators are used in a wide variety of applications, though almost always in the industry. Magnetic separators have a wide range of sizes: from a table top version to a large, heavy drum that is used in recycling and other manufacturing applications;
- The permanent magnets and REE must be suitable for their designated use and have a sufficient capacity to enable magnetic separation. To select such a most suitable permanent magnets, when inquiring about separators, conditions such as the purpose of use and property of materials need to be defined, as detailed below: application (improving the grade, collecting useful magnetic substances, etc.); kind, composition and components of raw materials; Grain size of raw materials; water content, raw material temperature; apparent specific gravity (bulk density); Kind, shape and grain size of mixed magnetic substances; amount of raw materials to treat per hour (kg/h, m3/h); amount and ratio of mixed magnetic substances; other special conditions.
- The metallic neodymium has a bright, silvery metallic luster, but as one of the more reactive lanthanide rare-earth metals, it quickly oxidizes in ordinary air. The oxide layer then peel off, exposing the metal to further oxidation. Thus, a centimetre-sized sample of neodymium completely oxidizes within a year. The lifespan of the permanent magnets included into the magnetic separator strongly depends on the installation and the production.
- The neodymium magnets (also called NdFeB) are the most common used magnets in the rare earth magnetic separators;
- The neodymium magnets can be used for separation of either liquid or dry materials (of better or worse bulk properties), they can serve for separation

of magnetic particles from materials transported on conveyor belts or in pipelines. It is possible to place these separators into the hoppers of moulding machines as well as to construct a complete separation line equipped with various kinds of magnetic separators.

- The below table (Table 12) presents estimates of average NdFeB demand by one large European manufacturer of magnetic separators:

Table 12. Estimated annual demand for NdFeB magnets by a large European magnetic separator manufacturer

Magnetic separator type	NdFeB demand annually
Magnetic plate	≈ 400 Kg
Magnetic grate	≈ 60 Kg
Magnetic grate in housing	≈ 450 Kg

- All interviewees would welcome commercialisation of recycled REE-based PMs at the same level of efficiency and minor cost. The market in this field is particularly competitive and the price is the key factor. Despite the scepticism regarding performance of recycled REEs in MS, the recycled rare earths can be better exploited in magnetic separator applications where even a recycled neodymium magnet, classified as medium efficient, can be part of a magnetic separator of good quality.

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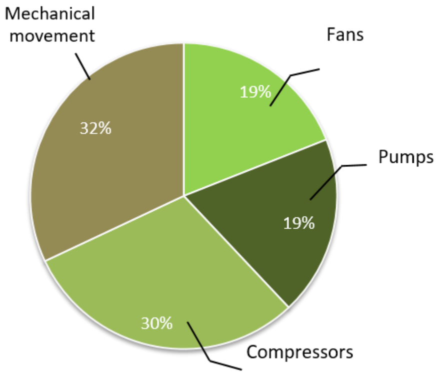
2.1.6 EoL Industrial Motors – market overview

Industrial Motors – facts & figures	
Application	The majority of PM electrical machines (motors, generators) is NdFeB-based (DrivesNControls, 2015). Industrial equipment for which permanent magnet AC and DC motors are suitable include adjustable speed pumps, fans, extruders, conveyers, crane and hoist systems, winders and printing presses (USDOE, 2014). Permanent magnets (instead of electromagnets) are used in applications where precise control and low torque are needed, such as in robotics and servo systems. Factory automation, including robotics and material handling, is currently the largest sector by revenue for PM motors (PR Newswire, 2015b). It is also confirmed by one of the REE4EU partner (VAC) that industrial motors with PMs are mostly used for robotics. The demand for magnets in this group is growing

	exponentially and has been the cause of a rapid increase in dysprosium demand in years 2000–2010 (Mikami,2012). Electric motors are responsible for around 45% of the global power consumption (Waide and Brunner, 2011), which illustrates the need for efficient motors such as rare-earth permanent magnet (REPM) motors. Power specification of PM-based industrial motors varies from 3 – 200 kW. Figure 17 illustrates the percentage breakdown of electricity demand by industrial motors on the basis of end-use application.  *Figure 17. Estimated share of global electricity demand by end-use industrial application* Globally, the use of NdFeB magnets in PM motor applications was predicted to grow at an annual rate of 10.8% from 2014 until 2020 (PR Newswire,2015b). New energy performance standards and rising electricity prices are expected to boost the production of energy efficient motors (GlobeNewswire, 2015).
Rare earth magnet content	Quantitative values for NdFeB-based motors are difficult to obtain due to the diversity of end-use applications. As confirmed by a European motor manufacturer, there is not an average content of REE per motor unit. Generally, neodymium magnet type is the most popular magnet in use, owing to its moderate cost and ability to operate at high temperatures. Dysprosium in industrial motors is estimated as 6% of total magnet content or 20% of the REE content in the magnet (according to Vacuumschmelze). Due to the ongoing HREE reduction efforts, the average dysprosium content is likely to decrease. Pr and Tb are also used in smaller percentages - estimated as 20% and 1% of Nd, respectively by Schulze and Buchert (2016) - but their use is expected to remain stable.

	Currently applications ranging from servo motors to industrial automation are frequently deploying rare-earth magnets. Typically, the use of rare-earth magnets leads to higher performances when compared to REE-free motors of the same size, or enables instead the use of lighter motors of the same rating. There are however commercially available industrial electrical motors wherein NdFeB is substituted with ferrite or ceramic magnets (or other REE-based magnets such as SmCo magnets). Though, SmCo magnets have poorer performance and higher cost than NdFeB , they can withstand higher temperatures. Ferrites ceramic magnets on the other hand, are around 10 times weaker than NdFeb magnets and 2-3 times cheaper.
Availability as EoL product	Permanent Magnet Motor Market Report, published by Allied Market Research, forecasts that the global market is expected to garner $45.3 billion by 2020, registering a CAGR of 11.7% during the period 2014-2020. Motor market data, relating to Europe, were primarily sourced from official EU statistics to ensure coherence with the official information used by the EU industry and trade policy. Prodcom (which stands for Production Communautaire) is the official Eurostat source of statistics on the production of manufactured goods. According to the database, in 2010, over 250 million motors were sold in Europe, 91 % of which were classified in the “low power” range (> 750 W). Direct Current (DC) motors accounted for 56% of the number of low power units sold but more than 37% of these motors were used in automotive applications which are out of the scope of this study, and only 13,1% of the units were sold as Industrial Machinery. Traditionally, conventional brushed DC motors in the medium power range are used in industrial applications requiring accurate torque and/or speed control (e.g. servo drives, traction). Finally, the share of large motors was very small (only 0,01%). The remaining 9% of motors sold were of medium power range. Medium power induction motors above 11 kW are normally repaired at least 2 to up to 4 times during their lifetime. Low power motors are normally not repaired and are replaced upon failure. The reasons is that for smaller motors the repair price can easily exceed this of a new motor as shown in Figure 18.

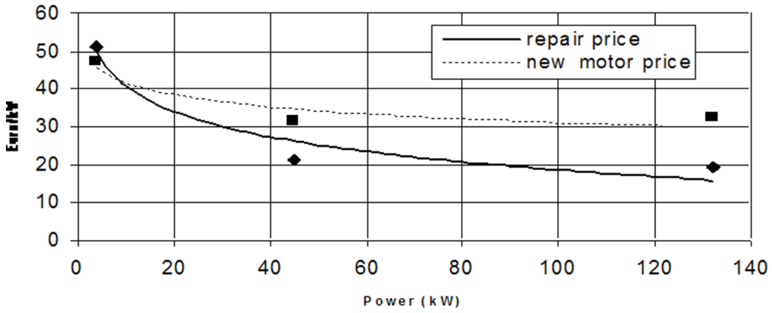


Figure 18. Comparison between repair prices and new motor prices.

For the estimation of the motor scrap in Europe over time a bottom up approach was used starting at the number of motors sold. Assuming an average lifetime of 10, 15 and 20 years for motors in each of the power range (small, medium and large) translates into an annual replacement rate of 10 %; 6,7% and 5% for each of the power ranges, respectively. The average annual scrap potential in Europe was estimated, as shown in Table 13, to be approx. 3,000 items (10% of the sold small motors, 6,7% of the medium and 5% of the large).

Table 13. Estimation of the motor scrap in thousands (EU-28, based on PRODCOM's 2012 dataset)

Motors	Units sold 1000 units	Annual replacement	Service life
Low [< 750w (1)]	169, 029/ 22,143 (2)	10%	10
Medium [0.75< and <375 kw (1)]	1200	6.7%	15
High [>375kw (1)]	10	5%	20

(1) Prodcom codes for Low: 27112300, 27112403, 27111030, 27112230, Medium: 27111053, 27111055, 27111070, 27112405, 27112407, 27112540, High: 27111090, 27112560, 27112590

Availability of collection measures

Broken electric motors from industrial machinery are subject to Directive 2012/19/EU and are classified as "Electrical and electronic tools (with exception of large scale stationary industrial tools)". REE4EU interviewees confirmed that motors containing permanent magnets with REE are treated in the same manner as conventional motors without REE magnets, due to the absence of specific legislation. Therefore, the recycling potential of small and electric motors which contain not only mass metals but also other materials, e.g. REE, is not fully utilised by the prevailing recycling systems. This is also acknowledged by various authors dealing with the subject of REE recycling (Schüler et al., 2011, Tsamis and Coyne, 2014, Binnemans et al., 2013).

End of Life handling and treatment of industrial motors takes place in two stages. At first stage, an inspection is carried out whereby the functionality of the motor is checked. According to the result of the inspection, the motor is classified as suitable either for re-use or disassembly. During the second stage, the motors which are not intended for reuse are disassembled in a robotized automatic station. Schischke et al. (2012) found that broken electric motors from industrial machinery (detected during an inspection) are often recycled in business-to-business schemes or sold abroad to become second-hand machinery. It was also found that some companies already store NdFeB-magnets from broken motors for future recycling.

Table 14. Key assumptions REE supply from EoL NdFeB (Rita Schulze, Matthias Buchert, 2016)

	Efficiency Rate Disassembly	Efficiency Rate Recycling
Other motors	40%	92%

There is very little information on the ease of extracting PM magnets from EoL motors. Schulze & Buchert (2016) assumed a disassembly efficiency of 40% for industrial motors (Table 14) but it is likely that achievable disassembly efficiency rates could be higher for larger magnets.

Expert insight

The market analysis approached the following companies, as those were identified as important REE4EU stakeholders:

1. SERVOTECNICA
2. SINTA
3. ASSOCIAZIONE ITALIANA METALLURGIA
4. FEDERCHIMICA
5. NUOVA CEAM
7. EBM - PAPST
8. TELEQUADRI
9. SICME MOTORI
10. MS-SCHRAMBERG
11. KUBOTA
12. AUER MOTOREN GMBH
13. SAIM SPA
14. ICPE GOELECTRIC
15. MMT - Moving Magnet Technologies S.A.

6. EUROMOTORS

Briefly the queries were about:

- Volumes of produced motors and types thereof in industrial applications
- Quantity of REE-based motors
- State of the art, current and future approaches of recycling REE-based motors.
- Possibility to use recycled REEs.

A closer contact was established with Riccardo Balestra (SC Sviluppo Chimica SPA, member of Federchimica) and Mattia Racca (New Business Development, Sicme Motori).

SC Sviluppo Chimica SPA is a service company aiming to encourage and support the competitiveness of the Chemical Industry, helping to create sustainable value-added, offering products and services such as publications, software management, training modules for Chemical Enterprises and for downstream users of substances, preparations, intermediates and chemicals. Riccardo Balestra already worked for projects focused on similar topic (e.g. neodymium recovery from exhausted permanent magnets - Cerio recovery from end-of-life catalysts - Crystal nano development to replace permanent magnets).

Regarding SICME Motori's feedback, Mattia Racca confirmed that 100% of permanent magnets originate from China; all the motors are NdFeB based and that alternative technologies (e.g. samarium–cobalt, SmCo magnets) are not comparable to neodymium in terms of efficiency and resistance.

For SICME Motori, only 2-3% of its whole production is for industrial application and the consumption of NdFeB equals 1200 - 1300 kg per year. A robust variability

	into the production has been also confirmed by Mattia Racca: motors produced by SICME can contain from 10kg - 100kg of NdFeB.
References	♻ Allied Market Research. Permanent Magnet Motor Market. Accessed 10.08.15 from Accessed 10.08.15 from http://www.drivesncontrols.com/news/fullstory.php/aid/4693/Permanent magnet motor market heads above $45bn.html. ♻ DrivesNControls, 2015. Permanent Magnet Motor Market Heads Above $45bn: 15January,2015. Accessed 10.08.15 from http://www.drivesncontrols.com/news/fullstory.php/aid/4693/Permanent magnet motor market heads above $45bn.html. ♻ GlobeNewswire, 2015. Global Electric Motors Market Reaches Worth $120.68Billion by 2019, at a CAGR of 6.3% By Transparency Market Research (accessed29.07.15) http://finance.yahoo.com/news/global-electric-motors-market-reaches-111132034.html. ♻ EuP Lot 30: Electric Motors and Drives, task 2: Economic and Market, http://www.eup-network.de/fileadmin/user_upload/EuP-LOT-30-Task-2-April-2014.pdf ♻ European Commission: Statistics on the production of manufactured goods. http://ec.europa.eu/eurostat/web/prodcom/data/database. ♻ Mikami, H., 2012. Technologies to replace rare earth elements: Hitachi. World Manuf. Forum, 2012 (accessed 27.07.15) http://www.ims.org/wp-content/uploads/2012/10/Session7a 01 Mikami Hiroyuki Technologies to replacerare earth elements.pdf. ♻ Schischke, K., Hohwieler, E., Feitscher, R., König, J., Kreuschner, s., Wilpert, P. & Nissen, N. 2012. Machine tools and related machinery. Energy-Using Product Group Analysis Lot 5. Berlin: Fraunhofer Institute for Reliability and Microintegration, IZM. ♻ Schüler, D., Buchert, M., Liu, R., Dittrich, S. & Merz, C. 2011. Study on Rare Earths and Their Recycling. Darmstadt: Öko-Institut. ♻ Tsamis, a. & Coyne, m. 2014. Recovery of Rare Earths from Electronic wastes: An opportunity for High-Tech SMEs. Brussels: European Parliament. ♻ USDOE, 2014. Premium Efficiency Motor Selection nd Application Guide: A Guidebook for Industry (accessed 29.07.15) http://energy.gov/sites/prod/files/2014/04/f15/amo motors handbook web.pdf. ♻ Waide, P., Brunner, C.U., 2011. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. OECD/IEA (accessed 29.07.15) http://www.iea.org/Textbase/npsum/ee for electricsystemssum.pdf.

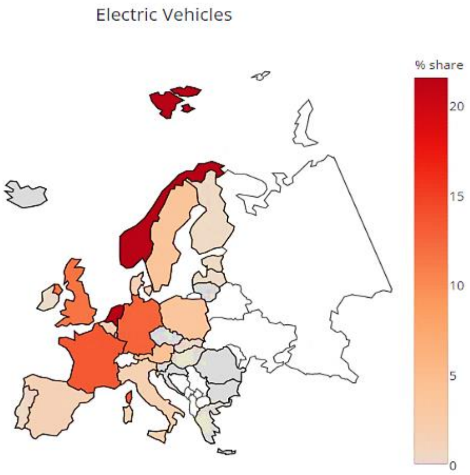
2.2 Segmentation of secondary REE market by regional resource potential

Knowing the cross-EU spread of REE-based EoL products can be useful to identify relatively near-future opportunities for recycling synergies between EU regions. Generally, the more “concentrated” a waste stream is, the simpler the logistics required. For instance, shorter distance of end users from sorting and processing sites will result in lower variable transportation expenses, such as fuel and vehicle maintenance. In this market analysis, the geographical segmentation of the secondary REE market was done at EU country level as it is deemed important from a logistics point of view, to have a preliminary mapping of “hot” regions which hold high fraction of REEs contained in the examined waste stream e.g. EoL HDDs.

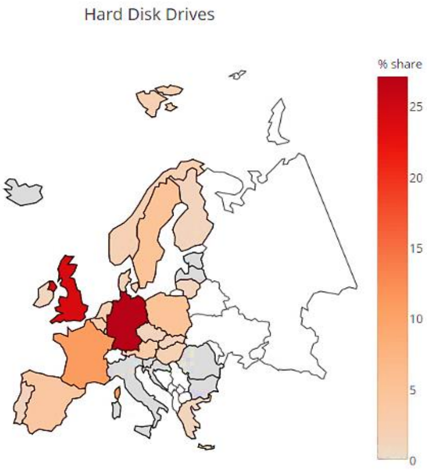
Key output of the geographic secondary REE market segmentation are the choropleth maps that were created for each EoL product (*Figure 19*). Map regions were shaded in proportion to the percentage of REE-based EoL product units allocated to the respective country. “Plotly”, an online tool (https://plot.ly/) was used to create the choropleth maps. The data for each EoL product correspond to material flows of one reference year i.e. the most recent year wherein information was available. The colour scales (displayed on the right of each map), were automatically optimized for each map. Rather than using actual values for each EoL product, colouring reflects normalized values (% market share) which allows a more clear-cut comparison between countries. It was not possible to find country-specific data for magnetic separators and industrial motors, so the figure illustrates the geographic allocation of HDDs, offshore wind turbines, electric vehicles and air conditioners.

As shown in the figure, air conditioners and offshore wind turbines tend to be quite concentrated in certain member states. EoL Electric vehicles as well are also expected to be available mainly in north EU, though e-bikes are more “spread” across member states. As expected, there is a tendency for EU markets to become more geographically homogenous as a technology/product penetration increases over the years and the differences observed today could be fast amplified over the next years. Nevertheless, at the moment it appears that the UK and Germany encompass the highest fractions of potential value from recovered REEs. Therefore, a more detailed study is recommended for these countries which could in the future serve as hubs for innovation commercialisation related to REE recycling.

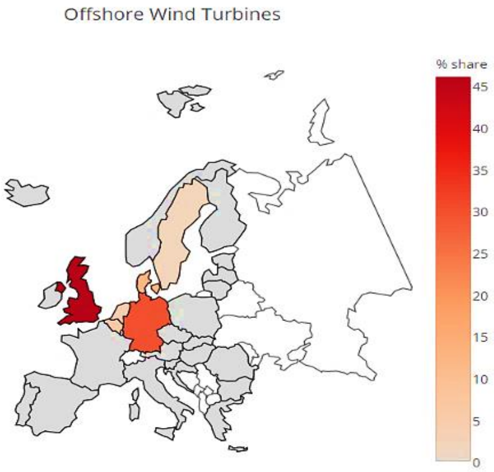
It should be noted, that the segmentation presented below is mono-dimensional i.e. it was done only based on market share corresponding to respective country and does not reflect other important aspects of REE recovery e.g. regulation of disposal, product requirements, competition from other technologies, etc. These types of considerations will be touched in Section 3 of the market analysis.



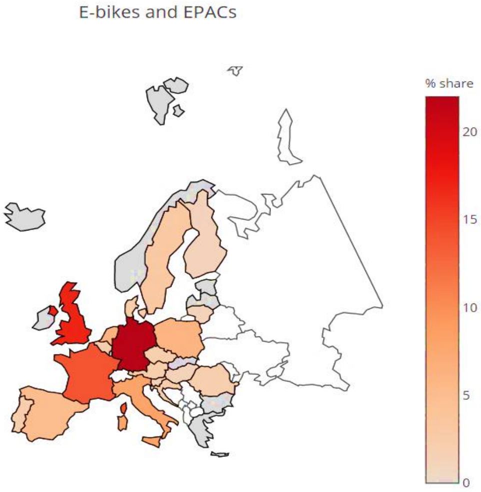
Year of reference: 2013-2014 (Note: Information at country level was not available for Lithuania, Slovenia, Luxembourg, Iceland, Malta and Liechtenstein)



Year of reference: 2013 (Note: Information at country level was not available for Italy and Romania)



Year of reference: 2015



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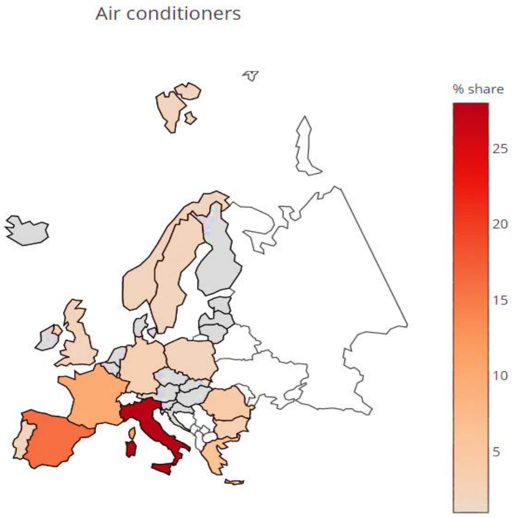


Year of reference: 2015

Figure 19. Percentage market share of REE-rich EoL products showing their cross-EU spread

2.3 Segmentation of secondary REE market by temporal resource allocation

Due to the nature of the resource examined in this market analysis (secondary REE), it is important to have a temporal segmentation of this (future) market indicating when the supply of an EoL product occurs or changes in relation to other EoL products. Particularly if mixed recycling is concerned, the wide discrepancies in the life time of the different EoL products must be carefully considered in preparation for a large-scale recycling investment.

Figure 20 displays the estimated amount of REEs contained in the examined EoL products as percentages of the total amount available in discreet time periods (over 2020-2040). “EV” denotes the motors used in EVs and hybrid vehicles while the PM content for EPS is presented separately. “WT”, “HDD” denote PM from offshore wind turbines and hard disk drives, respectively. It should be noted that the graph gives only a partial view of the projected future market potential since it was not possible to include Europe-specific estimates for magnetic separators and industrial motors.

Newly developed technical applications e.g. offshore wind turbines often have a long lifespan, thereby creating a lag between resource demand and the availability of corresponding scrap materials. As shown below, the available feedstock mix will rapidly diversify after 2025 and the trends of its composition will be shaped by demand for PMs in e-mobility and renewable energy (mainly wind). Automotive applications, in particular, are expected to be the main source of secondary REE after 2030 accounting for more than 70% of the estimated REE contained in EoL products.

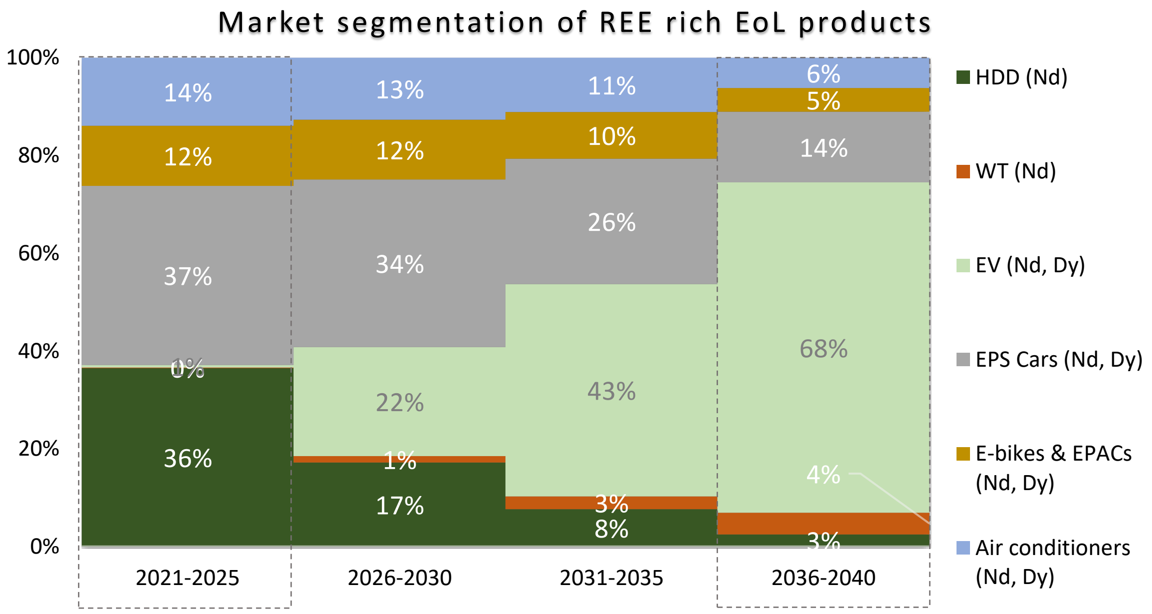
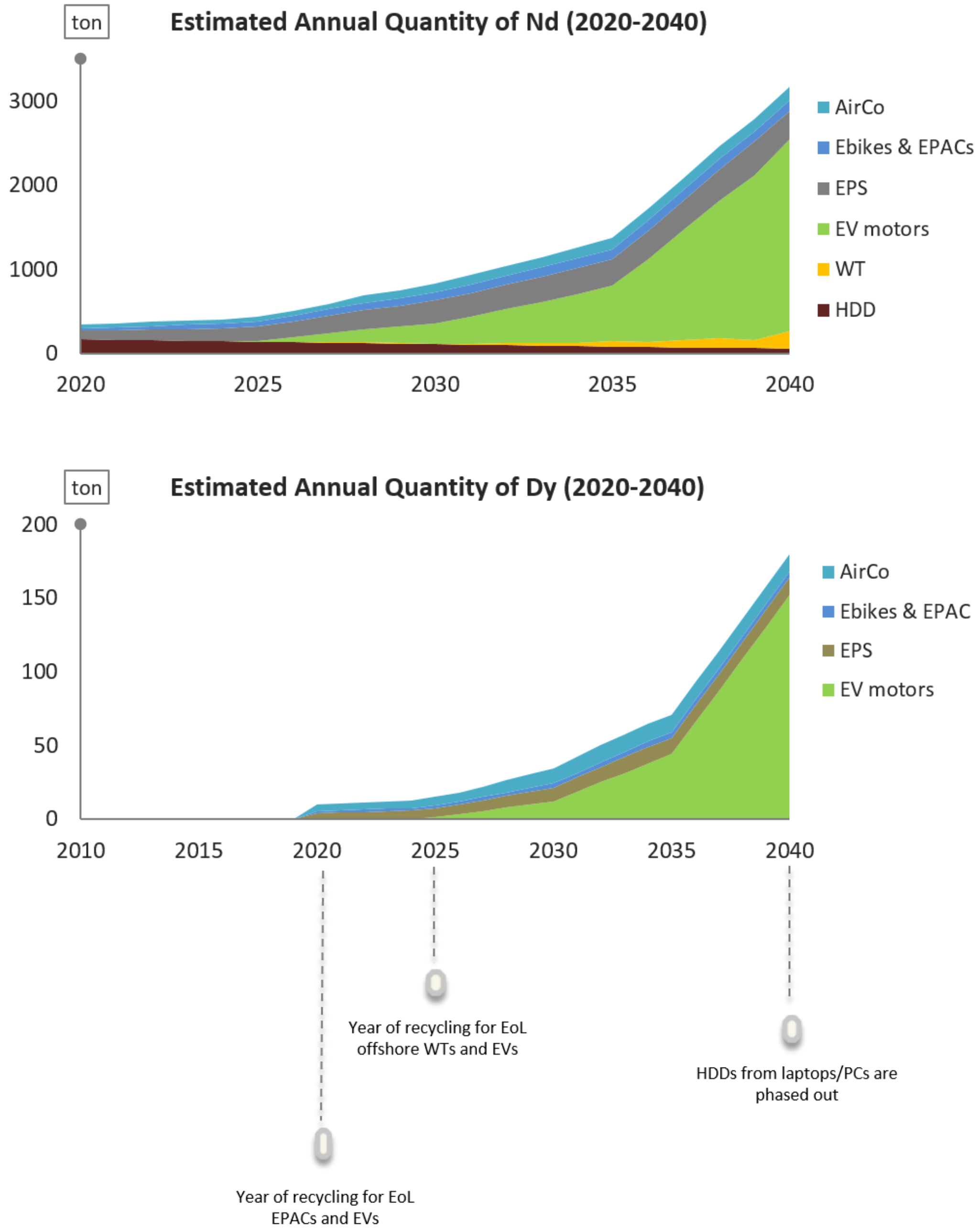


Figure 20. Progressive diversification of secondary REE market over 2020-2040 (reflects bulk quantities of Dy and Nd in EoL products)

For the same period (2020-2040), Figure 21 below shows the REE quantities that can be theoretically harvested from the selected waste streams. Stacked supply curves of Nd and Dy depict annual availability of REEs considering a wide variety of possible feedstocks (EoL products). The share of REEs from automotive applications (namely electric power steering and drive motors) will expand rapidly form 2025 onwards with the electric drive motors being the predominant feedstock for REE recovery. Inverter air conditioners (only residential units were considered) will follow suit.

Residential air conditioners are projected to represent less than 20% of the total available secondary REE resource corresponding to automotive applications during 2020-2040. However, it should be noted that only 30% of available EoL air conditioners were assumed to be collected (in line with Eurostat statistics, elaborated in Section 2.1.4). If that were to change e.g. setting REE recycling quotas or incentivising consumers to return their EoL air conditioners for recycling, then air conditioners market position could be further boosted with respect to automotive applications.

A general observation is that Dy is being gradually eliminated from most EoL products with each new technological cycle. That means that even though dysprosium is a much-prized element today, evidence reviewed in this report suggests that the demand for this element will grow at a slower rate than neodymium over the next decade. Indeed, major motor and generator makers have been designing around the use of dysprosium since 2011, thereby largely reducing global Dy demand. This has major implications for REE4EU as dysprosium will likely not need to be separated from lighter elements e.g. neodymium and praseodymium, by the time magnets from end-of-life hybrid/electric vehicles become available in sufficient quantities to recyclers.



Year of recycling for EoL offshore WTs and EVs

HDDs from laptops/PCs are phased out

Year of recycling for EoL EPACs and EVs

Figure 21. Theoretical REE quantities that can be harvested from EoL products, estimated for the period 2020-2040

3. EoL products for REE recovery – market assessment

3.1 Assessment guidelines

Development of a robust REE recovery infrastructure requires a better understanding of the uncertainties associated with the supply and value of end-of-life products. In this section, the most promising waste streams for the REEEU recycling scheme are assessed by considering quantitative and qualitative indicators. These waste streams refer exclusively to products having reached the end of their life cycle (End-of-life products) that can be processed to deliver rare-earth oxides suitable for reuse in new products.

The assessment was made following two approaches:

- a quantitative assessment meant to highlight the technical aspects of using the respective waste streams as 'feedstock' for a future REE recovery plant
- a qualitative assessment to provide context as to what would be the expected practical issues pertinent to their recycling that are either non-quantifiable or product-specific.

3.2 Quantitative assessment of EoL products

Like most infrastructure investments, a large scale REE recovery plant bears financial risks, mainly due to its significant upfront costs. Therefore, prior to realising such a venture, it is essential to evaluate the technical potential (i.e. availability and time frame) for REE recovery corresponding to each of the identified waste streams. This would primarily allow early elimination of less interesting waste streams. As an added value, the design of unit operations of the future plant could be finetuned to better match the scale, availability and technical features of the most promising feedstock(s), thereby increasing the overall resource efficiency. To that end, a comparative quantitative assessment was conducted across the identified waste streams presenting side-by-side their prospective supply security and REE potential for recovery. The selection of indicators comprises:

- **Amount of REE loaded in a product's (sub)components**

The value of REE recyclates - as a commodity that can be sold back to industry - should not be outweighed by the cost of collecting and processing them. Generally, cost-effective transportation of EoL products to the recovery plant is key for the success of recycling initiatives. Furthermore, high density of REE in a product could facilitate its dismantling and separation and result in low REE percentage losses during processing.

The quantity of REE per unit of product (as presented in Table 15) is a feature inherent to the product's design and function. There are various magnet compositions (number of REE chemical elements, grades, concentration mass percentages, etc.) from EoL product to another or even within the same category. The data presented in the table provide an overview of the current situation as in the future, alloy(s) compositions are expected to change due to fluctuations in raw material prices and finetuning of physical properties. Due to the differences in the composition and structure observed in the identified EoL products, the figures cited below are not meant to be used for direct comparison but rather as an indication of the differences in logistics required to harvest the REE.

Table 15. Comparison of REE quantities contained in a waste stream

	Mass per unit	Notes
♻ **HDDs**	0.6-6 g (Nd)	Weight of HDD is approx. 0.2 kg in a laptop and 0.6 kg in a desktop computer. Desktop and a laptop weight approx. 9 and 3 kg, respectively
♻ **Offshore wind turbines**	200 kg/MW 700 kg Nd	PMGs in offshore wind turbines are in the order of tons
♻ **Electric Power Steering motors for cars**	30 g (Nd) 0 - 3 g (Dy)	Weight of PMs is approx. 0.1 kg New motors do not contain Dy (Vacuumschmelze GmbH, personal communication)
♻ **Electric drive motors for EVs and Hybrid cars**	250-1,100 g (Nd) 80 – 400 g g (Dy)	Approx. 1.2 kg of PMs per car/ Does not include the weight of small motors and sensors
♻ **Electric drive motors for e-bikes and EPACs**	30 g (Nd) 0.6-1.2 g (Dy)	
♻ **Compressor motors of air conditioners**	50-500 g (Nd) 10 – 150 g Dy PM also contain approx.2-3% Dy	3-4 compressors in each air conditioner containing 4 NdFeB magnets each
♻ **Magnetic separators**	Contain only Nd; no Dy Varies widely.	Large magnetic separators are manufactured based on the bespoke needs of the clients

♻ **Industrial motors**	Contains Nd, Dy, Tb and Pr. Dy approx. 6% of total magnet content Pr estimated as 1% of Nd	There is not an average content of REE per unit.

♻ Supply of REE from end-of-life products – Expected availability over 2020-2040

Securing sufficient supply of waste input is critical and depends primarily on two aspects. First, the amount of REEs present in a product's components (see "Weight percentage of REE loaded in a product's (sub)components"). Second, the continuity of supply of certain end-of-life products e.g. supply of REEs contained in off-shore wind turbines is expected to be feasible after 2025 while HDD production is expected to be phased out around 2040.

Figure 22 shows the annual supply curves for each EoL in the period from 2012-2040. In the coming years, availability (in terms of volume) is expected to grow for all the examined EoL products except for HDDs. However, inadequate supply to cover short-term EU needs appears as an unavoidable hurdle, at least till 2030. Possibly, more than one type of feedstock would have to be used for industrial scale recycling (mixed recycling scenario) to balance out shortages of supply along the recovery plant's lifetime. In 2020, approximately 340 t Nd and 5 t of Dy are estimated to be available for recycling. Available quantities of secondary REEs are expected to increase sharply from 2035 onwards, largely due to the rise of green technologies for clean energy and transportation that will create many new "batches "of disposed electric cycles, vehicles and wind turbines.

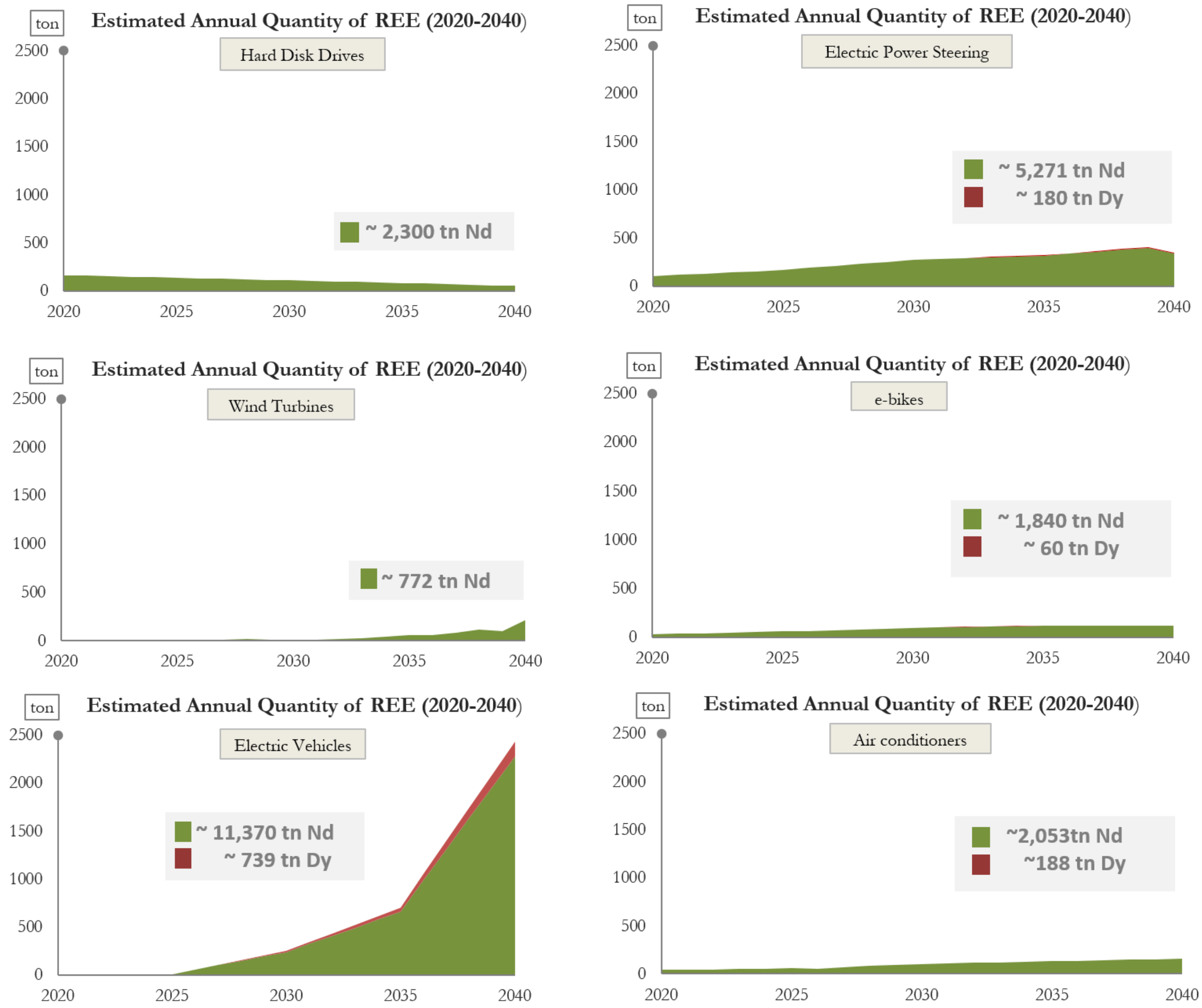


Figure 22. Available REE quantity estimated for the period 2020-2040 for selected End-of-Life products.

Maximum monetary value of REEs contained in a waste stream

In recent years, REE commodity prices have been significantly volatile showing large inter-annual swings. The economic crisis in China during 2011-2012, caused the price of Nd to skyrocket - from €12 /kg in 2009 to €271 / kg in 2011 (Charalampides et al., 2015). To estimate the revenue potential of each EoL product, two representative parameters were used: theoretical maximum and theoretical minimum economic value associated with the REE that could be harvested. Figure 23 illustrates the theoretical ranges of economic value of rare earths contained in the examined EoL products. Price data for REE oxide prices were obtained for two reference years, 2009 (maximum price) and 2012 (minimum price), representing an optimistic pre-"Rare-Earth Crisis" scenario and a conservative post-"Rare-Earth Crisis" scenario.

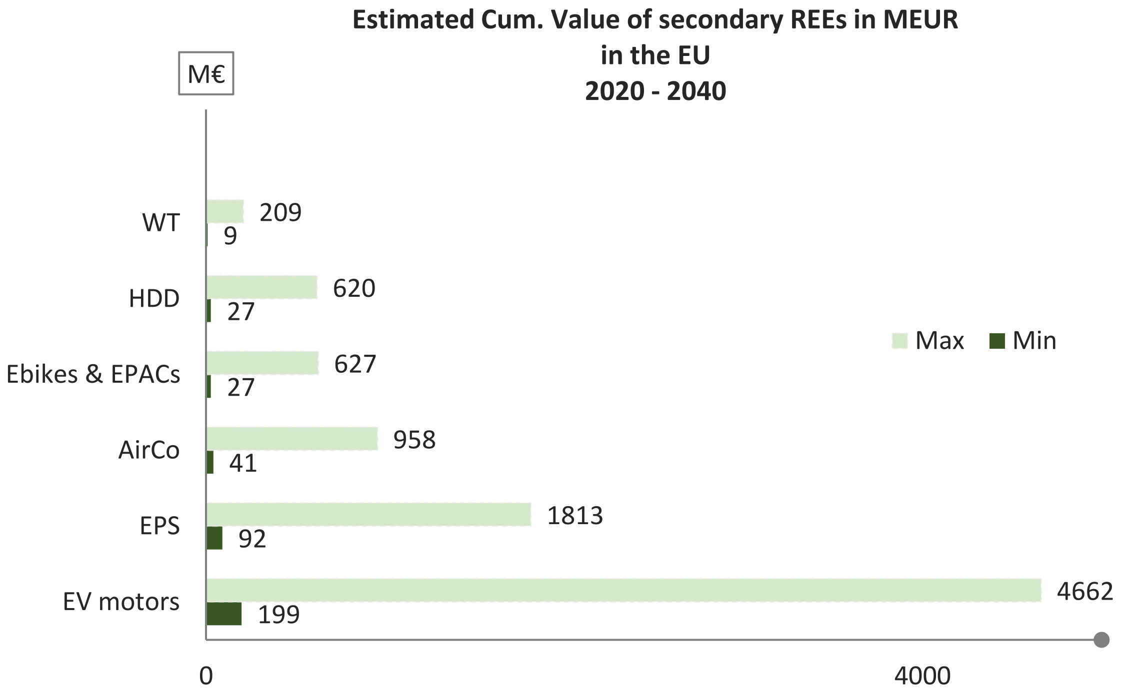


Figure 23. Estimated monetary value of REE contained in a waste stream. Low and high estimates are presented reflecting on the most conservative (1,) and least conservative REE price outlook (2,), respectively.

[1] Maximum prices in €/kg as observed in 2009: Nd (271), Dy (2,139), Pr (248) and Tb (4410)

[2] Minimum prices in €/kg as observed in 2011: Nd (12), Dy (85), Pr (12) and Tb (298) (Original prices in USD $, conversion rates retrieved on October 9th, 2017 from http://usd.fx-exchange.com/)

3.3 Qualitative assessment of EoL products

This section focuses on the incentives and constraints identified for each REE-rich waste streams, namely EoL hard disk drives from laptops/desktops, off-shore wind turbines, electric vehicles, e-bikes and EPACs, motors in industrial applications, air conditioning compressors, magnetic separators, and industrial motors.

The qualitative assessment considers certain non-quantitative indicators which are deemed as strategic for future recycling investments e.g. practical considerations for the disassembly of a waste stream. This approach complements the more “traditional” quantitative comparison in Section 3.2. The indicators, along with the rationale of choosing them, are described in Table 16, below:

Table 16. Qualitative attributes used in the comparative assessment of end-of life products destined for REE recovery

Attribute	Rationale	Score
A. Maturity of legislation	Relevant EU regulation can incentivise collection and REE recovery tailored to a specific waste stream.	Absence of communications/ directives (Low) Communications (Fair) Directives (High)
B. Availability of collection schemes	Existing collection schemes, either public or privately developed imply that there is already a know-how developed on the collection and handling of a waste stream.	no reported scheme (Low) collections scheme(s) under development (Fair) existing scheme (High)
C. Design compatibility with EoL PM recycling	Losses occurring during the disassembly of end-of-life products decrease the REE amount upstream of a subsequent REE recovery plant.	Challenging disassembly and/or extraction of REE-rich components (High) Fairly difficult disassembly and/or extraction of REE-rich components (Fair) Easy disassembly and/or extraction of REE-rich components (Low)
D. Risk for REE reduction/elimination	Future decrease of REEs in existing products can be forced by the market when prices are high. In some cases, a substitute REE-free may be commercially available or under development. Elimination of REEs in product design would impact future REE recovery ventures using the particular EoL product as feedstock.	Existing cost-competitive alternatives with equal or superior performance (High) Substitution possible with higher cost and/or poorer performance (Fair)

		There are currently no commercial substitutes (Low)
E. Probability of second life out of EU Vs end-of-life in EU	While, end-of-life products can be considered as a waste for the EU, they may also carry salvage value as second-hand goods in international markets. Exports of REE-rich EOL products, legal or illegal, represent an opportunity cost for the recycling sector. The existence of strong incentives to divert a waste stream out of the EU can hamper significantly the recovery of REE contained therein.	High probability for second life out of EU (High) Fair probability for second life out of EU (Fair) Low probability for second life out of EU (Low)
F. Co-recycling potential for more than one REE	Notable quantities of more than one REE can be present in a waste stream (for example, EV contain both Nd and Dy). Such cases can further strengthen the value proposition of REE4EU which allows mutual recovery and purification of elements contained in a complex mix.	EoL product only contains one REE in significant quantity (others either non-existent or in trace amounts) (Low) EoL product contains more than one REE (High)

3.3.1 EoL Hard Drives – Levers and hurdles for REE recovery

Table 17. Qualitative assessment for HDDs from desktops and laptops as REE recovery feedstock

REE recovery from EoL Hard Disk Drives		
Maturity of legislation	High	Two directives relevant to waste electrical and electronic equipment (WEEE Directive) are already in place: ♻ February 2003 - Directive 2002/96/EC: Directive on the creation of collection schemes through which consumers can return their WEEE free of charge. (URL, Revised Directive 2012/19/EU effective on 14 February 2014 URL) The amended directive imposes take-back obligations on manufacturers and importers of electrical and electronic products for small products [2] ♻ July 2011 - RoHS Directive: Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (URL)
Availability of collection schemes	High	Large shops selling electrical goods are obliged by EU legislation to accept small e-waste items from customers, such as mobile phones free of charge. Therefore, "collection centres" are theoretically easily accessible to consumers for recycling of their HDDs from laptops and desktops. In addition, large computer manufacturers have developed their own recycling schemes (e.g. DELL URL Lenovo URL)

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[2] WEEE Forum (European Association of Electrical and Electronics Waste Take Back Systems) URL

		However, there is considerable performance variation of existing waste collection schemes across the EU.[3]
Co-recyling potential for more than one REE	Low	HDDs only contain Nd, therefore HDDs do not present an opportunity for mutual recycling of more than one REE.
Design compatibility with EoL PM recovery	Fair	REE exist as powder in HDD magnets which allows relatively simpler separation of the magnets in HDDs comparing to other applications (Sprecher *et al.*, 2014). However, the limited quantity of REEs in HDDs can restrict their harvest when using commonly used equipment and induce losses of initial Nd content.
Risk for REE reduction/elimination	High	The market share of REE-free alternatives to HDD (SSDs and cloud data storage systems) is under expansion. By 2030, HDD use in desktop and laptop computers will have dropped to 40% and to 14% of today's values, respectively.
Probability of second life out of EU Vs end-of-life in EU	High	Despite the development of EU regulations for WEEE recycling, uncontrolled export might be as high as 50% of total waste volumes. China represents the largest downstream destination of EU e-waste export. Most of the illegally imported e-waste enters China's informal refurbishment and recycling sector, which lacks environmental, health and safety standards. It should be noted though, that EU regulations oblige exporters to provide proper documentation for goods being shipped for repair or re-use. The aim is to prevent illegal shipments of e-

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[3] EUROSTAT URL

	waste to developing countries, where workers are sometimes exposed to health hazards

3.3.2 EoL Offshore wind turbines – Levers and hurdles for REE recovery

Table 18. Qualitative assessment for offshore wind turbines as REE recovery feedstock

REE recovery from offshore wind turbines		
Maturity of legislation	Low	To date, there are no important EU regulations (communications or directives) to collect and recycle PMGs from end-of-life wind turbines. A large manufacturer of wind turbines interviewed by REE4EU comments: “We are not aware of important regulations to collect and recycle REE-rich fractions in WTs”
Availability of collection schemes	Low	To date, there are no established PMG collection schemes for end-of-life offshore wind turbines. It is wind farm owners that decide if wind turbine components are collected and recycled. There is only one industrial enterprise that recycles end-of-life turbine blades in Melbeck, Germany. The company shreds the blades and after mixing with other waste material produce a compound that a certain cement producer uses as a substitute fuel.
Co-recyling potential for more than one REE	Fair	Dy may be present in some offshore wind turbines, however, its gradual elimination in new models makes its recovery a relatively short-term opportunity.
Design compatibility with EoL PM recycling	High	Wind turbine’s large size allows for high fraction of NdFeB in PMGs that would most likely facilitate identification, access and disassembly of the NdFeB magnets.
Risk for REE reduction/elimination	High	New off-shore wind turbines are designed to have less REE than previous models. Manufacturers are already reducing Dy by replacing it with Nd (Schulze & Buchert, 2016). For example, Siemens has announced that it will be removing Dy completely from offshore wind turbines by 2017.

		In parallel, an emerging REE-free technology (wind turbines equipped with superconductors), is expected to grow in terms of market size in Europe.
Probability of second life out of EU Vs end-of-life in EU	High	Even though wind turbines are designed to last over two decades, many are made prematurely redundant when wind-farm owners repower projects with bigger, more powerful turbines. This is increasingly the case in countries such as Germany and Denmark, where the windiest sites have already been developed. The export of end-of-life wind turbines (mainly to developing countries) will cause loss of high value REEs.

3.3.3 EoL EVs, Hybrid cars and EPS– Levers and hurdles for REE recovery

Table 19. Qualitative assessment for Electric drive motors for EVs and Hybrid cars as REE recovery feedstock

REE recovery from EoL EVs, hybrid cars and electric power steering motors		
Maturity of legislation	High	Directive 2000/53/EC (Directive 2000/53/EC - the "ELV Directive") on end-of life vehicles sets clear quantified targets (weight-based) for reuse, recycling and recovery of the EoL vehicles and their components.
Availability of collection schemes	High	End-of-life cars and their components are obliged to be collected for recycling, however, this does not apply when cars are exported outside Europe.
Co-recyling potential for more than one REE	High	Both Nd and Dy are available for recovery in the EoL product(s) of this category.
Design compatibility with EoL PM recycling	Fair	Directive 2000/53/EC does not stipulate different treatment for end-of-life e-cars (BEVs and HEVs) vs conventional cars. Conventional cars are not pre-dismantled and are generally recycled by shredding and physical separation (e.g. size, magnetic behaviours etc.). This practice causes significant losses of PMs to ferrous or non-ferrous scrap (similarly to the case of magnets in Hard Disk Drives). The REE content in EVs is relatively large and is normally pre-dismantled, however, the process is challenging when done manually. Separation of PMs from electromotors is difficult because E-motors are not designed considering EoL recycling.
Risk for REE reduction/elimination	Fair	Most EV models of 2016 deployed REE embedded in permanent magnets. However, technology developments have resulted in lower PM content per unit of power (kW) and elimination or reduction of the Dy content from the PM itself. Tesla produces an EV model with induction engine that does not require REEs.

		However, induction engines have slightly lower efficiency and higher cost per kW compared to NdFeB magnet motors.
Probability for second life out of EU Vs end-of-life in EU	Low	Electric vehicles require sophisticated infrastructure (e.g. charging stations), expensive maintenance and spare parts making them less susceptible to illegal export compared to conventional cars. Based on the research conducted for this report, there is no substantial evidence indicating that e-motors from vehicles are exported illegally as such in non-EU countries.

3.3.4 EoL e-bikes and EPACs – Levers and hurdles for REE recovery

Table 20. Qualitative assessment for Electric drive motors in e-bikes and EPACs

REE recovery from e-bikes and EPACs		
Maturity of legislation	Low	It is not clear whether the disposal of ebikes comes under the WEEE Directive (since 13 August 2012) or will be regulated (from 15 August 2018 onwards). EU members apply different interpretations of the Directive. In Belgium, for example, the collective scheme *Recupel* classifies electric bicycles under "Toys, leisure and sports equipment".
Availability of collection schemes	Low	To date, there is no information on running collection schemes for e-bikes. However, components of e-bikes are partially collected for recycling. For example, Directive 2006/66/EC, also known as the Batteries Directive, applies to all batteries and therefore, includes Lithium Ion (Li-ion) and Nickel Metal Hydride (Ni-M-H) batteries commonly used in electric bicycles.
Co-recyling potential for more than one REE	High	Both Nd and Dy are available for recovery in EoL products in this category.
Design compatibility with EoL PM recycling	Fair	There is very limited public information regarding losses of magnet content during disassembly of e-bikes and EPACs and extraction of their motor magnets. The common practice includes removal of batteries followed by mechanical treatment that results in a mixed ferrous stream. Therefore, REE losses occur because the process is focused on the battery removal materials whereas it remains to be investigated whether the design will add significantly to the losses. To date, there is no evidence of a disassembly system tailored to e-drive motors.

Risk for REE reduction/elimination	Low	To date, there are no REE-free alternatives that can offer comparatively efficient solutions.
Probability of second life out of EU Vs end-of-life in EU	Fair	Very little information is available on the illegal export of e-bikes out of Europe. Since they are far easier to be transported and stored than vehicles, it is likely that some EoL ebikes will be channelled out of the EU as illegal waste export.

3.3.5 EoL Air conditioners – Levers and hurdles for REE recovery

Table 21. Qualitative assessment for residential air conditioners as REE recovery feedstock

REE recovery from residential air conditioners		
Maturity of legislation	High	Two directives relevant to waste of electrical and electronic equipment (WEEE Directive) are already in place: ♻ February 2003 - Directive 2002/96/EC: Directive on the creation of collection schemes through which consumers can return their WEEE free of charge. (Revised Directive 2012/19/EU effective on 14 February 2014). The amended directive imposes take-back obligations on manufacturers and importers of electrical and electronic products for small products ♻ July 2011 - RoHS Directive: Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment
Availability of collection schemes	High	The first WEEE Directive (Directive 2002/96/EC) entered into force in February 2003. The Directive focused on the creation of WEEE free-of-charge collection schemes for consumers. These schemes aim to increase WEEE recycling and/or re-use. Directive 2002/96/EC was repealed on 15 February 2014 and was replaced by Directive 2012/19/EU on waste electrical and electronic equipment (WEEE), which steps up collection targets and will take effect in 2016 and 2019. However, waste management differs between countries.
Co-recycling potential for more than one REE	Low	Contains Nd and Dy in high quantities.

Design compatibility with EoL PM recycling	Fair	Rare earth magnets in compressor rotors are strongly attached to their surrounding components. Moreover, the variety of rotor shapes further hinders standardization of rotor disassembly. Mitsubishi Electric's system is the only known industrial case study where a disassembly protocol and technology tailored to end-of-life air conditioners was developed. Its proprietary technology automatically dismantles, sorts and removes the REE magnets at a pace of one air conditioning unit every 30 seconds, (far less than the time estimated by STENA (REE4EU partner) to extract the motor and magnets). However, there is no evidence that Mitsubushi's process can treat mixed brands of air conditioning units or handle motor magnets of different design.
Risk for REE reduction/elimination	Low	Although REE-free alternatives already exist and have been used at massive scale, to the best of our knowledge, there are no REE-free alternatives that can offer comparatively efficient solutions. In addition, efficiency standards for air-conditioning units are continuously being raised to achieve low GHG emission targets. It is expected that efficient NdFeB-based compressors will support this transition. Consequently, the global demand for NdFeB magnets used in air-conditioning systems is expected to increase.
Probability of second life out of EU Vs End of Life in EU	Fair	Air conditioners are legally classified as "Large Household Appliances" under the WEEE Directive. A large portion of this category mix (mainly telecommunication and computer waste) exits the EU as illegal e-waste and enters countries like China and India. Though there are no official statistics regarding the air conditioner fraction of illegal WEEE shipments, it is expected that some of the EoL air conditioners will exit the EU as illegal waste.

3.3.6 EoL Magnetic Separators – Levers and hurdles for REE recovery

Table 22. Qualitative assessment of magnetic separators as REE recovery feedstock

REE recovery from magnetic separators		
Maturity of legislation	Low	To date, there are no important EU regulations (communications or directives) to collect and recycle PMs from end-of-life magnetic separators.
Availability of collection schemes	Low	To date, there are no established collection schemes for end-of-life magnetic separators for which information is publicly available.
Co-recycling potential	Low	Apart from Nd, magnetic separators also contain Dy and Pr. According to Vaccumsmeltze GmbH however, concentrations of Dy and Pr are quite low to enable significant revenues.
Design compatibility with EoL PM recycling	Fair	According to model assumptions developed by Schultze (2016), an overall REE extraction efficiency of 59% and an efficiency rate of disassembly of 80% can be considered.
Risk for REE reduction/elimination	Low	Interviews with stakeholders indicated that no existing technologies exist to replace REE in magnetic separators.
Probability of second life out of EU Vs end-of-life in EU	High	There is no information regarding the fraction of EoL magnetic separators (magnets) that remain in Europe. Interviewees approached by REE4EU representatives confirm exporting spent permanent magnets from magnetic separators to China.

3.3.7 EoL Industrial motors – Levers and hurdles for REE recovery

Table 23. Qualitative assessment of industrial motors as REE recovery feedstock

REE recovery from robotic motors		
Maturity of legislation	High	Broken electric motors from industrial machinery are subject to the WEEE Directive
Availability of collection schemes	Fair	Broken electric motors from industrial machinery are collected as "Electrical and electronic tools (with exception of large scale stationary industrial tools)". Motors containing REE are not treated separately due to the small amounts of PMs. Thus, the recycling potential of small and electric motors which contain not only metals but also other materials, e.g. REE, cannot be fully utilised by the prevailing recycling systems. Nevertheless, companies have been reported to have "hibernating" REE stocks of broken motors in preparation of future recycling incentives.
Co-recycling potential	High	Contain NdFeB permanent magnet at notable quantities as well as Pr an Dy in notable quantities
Design compatibility with EoL PM recycling	Low	The interviewees confirmed that motors containing permanent magnets with REE are treated in the same manner as the conventional motor types without REE magnets. It is expected that the multiplicity of designs and sizes will make it extremely challenging to recover the magnets from EoL robotic motors.
Risk for REE reduction/elimination	Fair	There are commercially available alternatives, but with poorer performance, such as SmCo magnets
Probability of second life out of EU Vs end-of-life in EU	High	Schischke et al. (2012) found that broken electric motors from industrial machinery are often recycled in a business-to-business scheme or sold abroad as part of second-hand machinery.

4. Conclusions

The recovery of REE through urban mining has emerged as a secure source of raw materials for the European industries. The REE4EU consortium aims to aid the decision-making process towards further upscaling of REE recovery and draws the following conclusions from this report:

♻ Relative position of EoL products in a future secondary REE market

Not all magnet-based end-of-life products are equally recyclable. Products can be roughly split into:

- "consumer" appliances: HDDs (Section 2.1.1), e-vehicles, electric power steering and e-bikes (Section 2.1.3) and residential air conditioners (Section 2.1.4)
- "industrial" appliances: offshore wind turbines (Section 2.1.2), magnetic separators (Section 2.1.5), industrial motors (Section 2.1.6)

According to the findings of this report, it appears that EoL consumer products, in particular EVs (complemented by conventional vehicles with electric power steering) and residential air conditioners are expected to be the feedstock of choice for a future REE recovery plant. As previously discussed, automotive EoL products have several attributes that could favour their future recycling e.g. already established collection schemes, maturity of regulations towards their recycling, potential to co-recycle multiple REE, etc. Consequently, future effort at industry and EU policy level should focus on bridging the existing technical and systemic gaps that currently prevent their full valorisation as secondary REE sources.

At the same time, one should not overlook that industrial EoL products (wind turbines, magnetic separators and industrial motors) may also be a promising feedstock for a future REE recovery business. This can be attributed to multiple reasons. For example, the performance specifications of these appliances are such to justify relatively high grade NdFeB magnets, a factor that could offset the "dilution" effect of collecting, sorting and recycling and achieve acceptable quality recyclates. Also, they contain large quantities of magnets that could be more easily identified and retrieved by recyclers minimising the losses during disassembly and extraction. Furthermore, they not only contain one element i.e. Nd but also Dy and other valuable heavy rare earths (namely Pr and Tb) for which REE4EU's technology (able to separate individual elements) presents a unique opportunity for profitable recycling. At current status, however, industrial EoL products they have two important disadvantages. First, large scale appliances, such as drum magnetic separators, used in industrial settings tend to have a long life (>10 years, sometimes reaching >20 years as in the case of wind turbines). Second, there is a severe lack of information to allow estimation of their actual quantities as EoL products or even to have a clear idea of their fate (recycling mode, transport, territory of processing)

In Figure 24, for each of the selected EoL products, a radar chart was developed to facilitate visual comparison of their forecasted “fit” to being as a cost-effective feedstock for REE recovery. For each product, the chart poles represent its estimated performance against potential hurdles/incentives for recycling. It should be noted that the respective scores for each product (See Table A1) were assigned based on the findings presented in Sections 2 and 3 as well as (when information was not available) on logical inferences. More details on the justification of the scores is given in Table A2, in the Appendix.

Figure 24. Qualitative assessment of REE recovery from End of Life products

Technical and systemic gaps hampering large-scale REE recovery from EoL products

Based on the reviewed literature as well as the feedback received from industrial stakeholders, many projected bottlenecks relate to inefficiencies upstream the REE recovery plant. At present, almost all small permanent magnets in EoL consumer products are shredded and lost into ferrous or nonferrous scrap eventually ending up as slag or residues during the recovery processes of major metals. There is currently no known technology to recover such magnets except for upstream separation and subsequent dismantling.

One of the most critical barriers to feasible REE recovery is the lack of economic incentive to selectively collect permanent magnets from EoL consumer products. Manual extraction of REE fractions from EoL products upstream the recovery plant is likely to incur significant labor costs. NdFeB magnets are most often assembled in complex product architectures, making them time-consuming to identify and retrieve due to recycling-unfriendly design, coatings, glue, etc. Increasing the feasibility and cost-effectiveness of this process would require a drastic redesign of presently deployed disassembly and separation practices.

In addition, lack of previous recycling experience can severely undermine the success of business cases focusing on the recycling of certain EoL products. For example, previous research indicates a knowledge gap regarding logistical requirements to reclaim products such as offshore wind turbines – which translates into high uncertainly of costs upstream the REE recovery and consequently a riskier REE venture. Another important issue revealed during the study is the absence of complete and harmonised datasets for industrial products at EoL phase e.g. magnetic separators for estimating the value of these hibernating stocks.

Another key issue lies in the use of REE recyclates for other applications and processes – secondary applications and market development for recycled REE is only in its infancy. Unlike other materials e.g. steel or carbon glass, there is not yet an established supply chain for the uptake of secondary REEs. To date, there is little (if any) demonstration of the performance of "host applications" using recycled PMs. Fully or partially recycled magnets must be tested, characterized and their properties matched up with potential applications. Still, even if these requirements are met, the limited traceability of EoL products e.g. air conditioners and HDDs may discourage future product manufacturers and suppress the prices of REE recyclates further.

Another issue is the unpredictability of the timing and magnitude of the next innovation "wave", particularly for EVs, e-bikes and offshore wind turbines. Markets generally develop with time, for example, disruptive changes can occur due to developments in technology. Replacement of present technologies with others that use far less REEs, will lead to a dramatic fall in the feedstock supply of a future REE recovery plant. In addition, future changes in product design means that EoL magnets themselves will change over time in terms of weight and specifications. As mentioned by one of the interviewees "For a typical lifetime of a motor, perhaps and almost certainly the magnet used into the recycled vehicle won't be use anymore for new vehicles".

♻ Recommended actions towards viable industrial-scale REE recovery

There are only few locations where rare earths are found in high enough concentrations to make extracting them commercially feasible. Supply through a recycling route of REE contained in EoL products could decrease EU's reliance on imported rare earths such as Nd and Dy. Based on the findings of this report, the following set of actions is recommended to set the stage for a future commercial scale REE recovery business case:

- Incentivise research and development of new automated dismantling technologies capable to achieve higher throughput compared to manual dismantling, hence addressing one of the most important bottlenecks of the entire process.
- Promote the creation of new legislation that will explicitly set recycling quotas of REEs in automotive and industrial applications (e.g. wind turbines, electric vehicles) thus enabling recovery of permanent magnets prior to shredding.
- Stimulate sector-wide industry collaboration to better understand the socio-economic implications of the value network required to support large-scale REE recovery. One of the greater challenges of promoting recovery of rare earths is the scarcity of credible data on the practical aspects of recycling. To increase the confidence of prospective investors, REE stakeholders need to jointly benchmark the costs of a large-scale recycling approach in Europe and identify ways of tackling future bottlenecks and risks.

5. Appendix

Table A1. Relative position of EoL products in a future secondary REE market.

	A	B	C	D	E	F	G	H
	EU supportive legislation	Established collection chains	actual composition: >1 REE	recycling-friendly design	REE use in future designs	Unlikely to "leak" out of Europe	High REE content/unit	High revenue potential (2020-2040)
HDD	10	10	0	10	2	5	1	3
WT	2	2	5	10	5	5	10	2
EV	10	10	10	5	5	10	5	10
AirCo	10	10	10	5	10	5	3	5
e-bikes	2	2	10	5	5	5	2	3
MS (*)	2	2	0	10	10	2	8	1
IM (*)	2	2	10	5	5	2	2	1

* Limited information on magnetic separators (“MS”) and industrial motors (“IM”). It is possible that assigned scores are more conservative that in reality

Table A2. Justification of scores assigned to the examined EoL products

	Score justification
A.	10: Directives/Communications, 2: no evidence of recycling-supportive legislation
B	10: mature collection schemes with a clear path from end user to recycler, 2: no evidence of systematic collection
C	10: contains other REEs apart from Nd (e.g. Dy, Pr, Tb), 0: REEs other than Nd are contained in trace amounts
D	10: REE-rich fractions are potentially easy to locate and extract, 5: design features suggest a laborious recovery of REE-rich fractions
E:	10: no evidence of future reduction/elimination of REE content in product, 5: REE use is projected to decrease and/or an REE-free alternative is already commercialised, 2: future design will be REE-free and/or product will be displaced from the market

F	Scores 10,5,2 refer to low, fair and high probability of the product having a second life out of the EU, respectively
G	10: wind turbines, 1: HDDs, intermediate scores were assigned as in Table A1 in the Appendix
H	10: EoL EVs, 1: HDDs, intermediate scores were assigned as in Table A1 in the Appendix