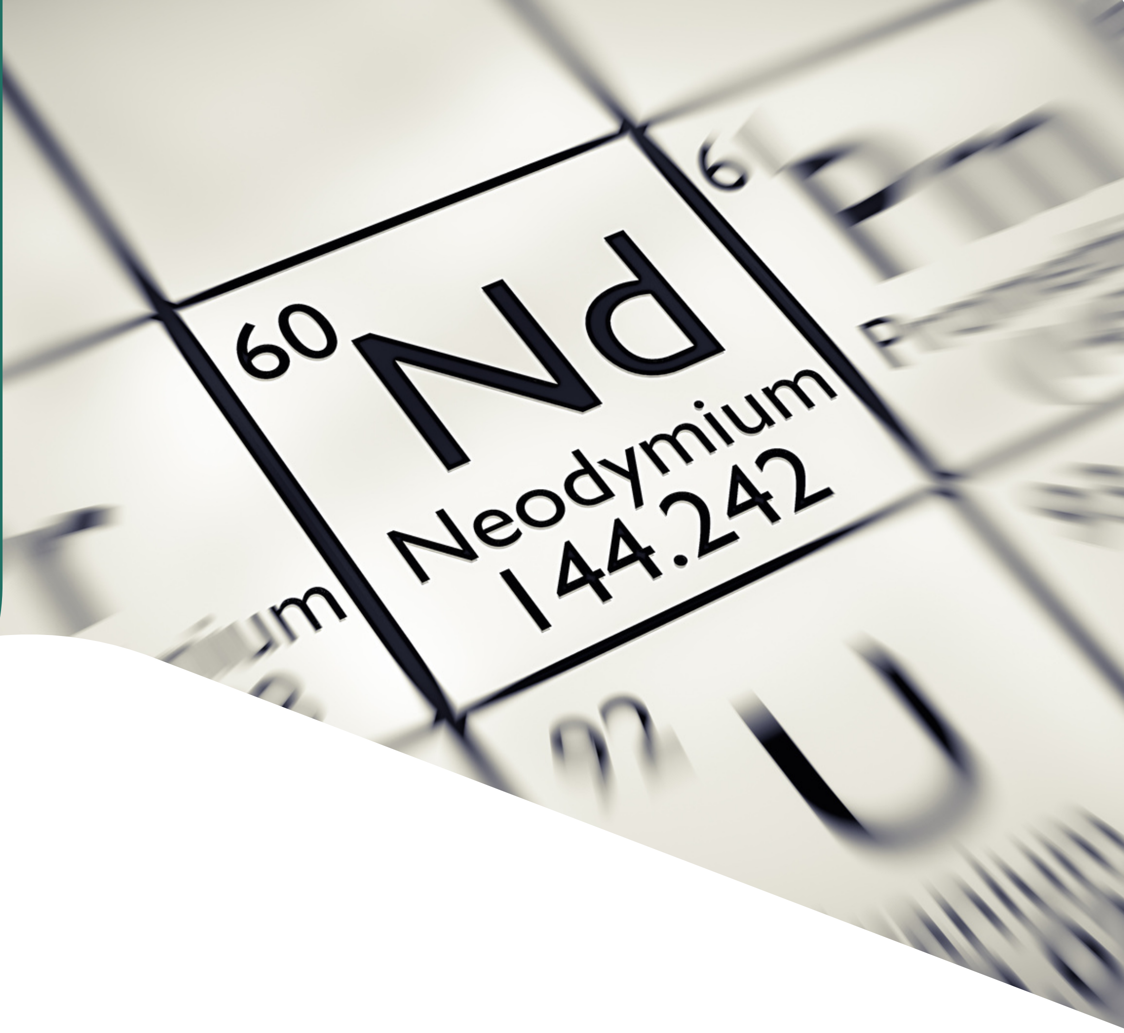

CEPS IN-DEPTH ANALYSIS

DEVELOPING A SUPPLY CHAIN FOR RECYCLED RARE EARTH PERMANENT MAGNETS IN THE EU

Challenges and opportunities

Vasileios Rizos, Edoardo Righetti, Amin Kassab

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SUMMARY

Rare earth elements are of strategically important for the EU to sustain and accelerate its green and digital transition, particularly due to their use in permanent magnets.

Rare earths permanent magnets are critical components of low carbon technologies such as wind turbines and electric vehicles, but also home appliances and consumer electronics. Yet faced with an expected surge in demand, limited domestic manufacturing capacity, high import dependency and rising geopolitical tensions, the EU's ability to meet the future demand for rare earths magnets is at risk.

Recycling can help secure some of this demand. However, permanent magnets recycling is not yet developed at scale in the EU because of a combination of regulatory, financial, supply chain and technological constraints.

Building upon the lessons learnt during the EU-funded INSPIRES project, as well as interviews with experts in the permanent magnets value chain and own quantitative assessments, this research report examines the major barriers hindering the establishment of viable magnets recycling chain in the EU, whilst estimating the extent to which recycling could compensate the upcoming increase in rare earths magnets demand in the foreseeable future.

Tacking stock of the analysis, the report suggests that introduction of product labelling requirements, the development of recycling quotas, the provision of financial support to recycling operations and the establishment of eco-design requirements. These are the critical actions that need to be implemented to ensure the development of magnets recycling in the EU.

Vasileios Rizos is heading the Energy, Resources and Climate Change Unit and is also Head of Sustainable Resources and Circular Economy at CEPS. Edoardo Righetti is Research Assistant and Amin Kassab is Associate Research Assistant in the Energy, Resources and Climate Change Unit at CEPS.

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CEPS ▪ Place du Congrès 1 ▪ B-1000 Brussels ▪ Tel: (32.2) 229.39.11

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EXECUTIVE SUMMARY

The impact of the Covid-19 crisis on supply chains and the new geopolitical environment that has emerged due to the war in Ukraine have sparked a renewed interest in the EU's raw materials agenda.

Rare earth elements (REEs) are among the key materials for which high import dependency – mainly from China - rising geopolitical instability and the projected rapid increase in consumption threaten to expose the EU to potential supply risks. Given their unique properties, REEs have a wide range of military, energy and industrial applications, with permanent magnets representing the largest application. Rare earth permanent magnets are important components for technologies that are driving the energy transition, namely wind turbines and battery electric vehicles. Their use also extends to various other applications including home appliances and consumer electronics.

Recycling rare earth permanent magnets from end-of-life (EoL) products, if systematically implemented, could be among the main avenues for meeting the EU's future REEs' needs and for mitigating supply risks. While significant volumes of EoL magnets from wind turbines and electric vehicles (EVs) are only expected in the medium-to-long term, recycling opportunities may emerge from using Europe's urban mine of other products containing permanent magnets, i.e. home appliances and consumer electronics.

This is the objective of INSPIRES, a project co-funded by the EU, which aims to develop a closed-loop recycling chain for rare earth permanent magnets from disposed of home appliances, by covering all steps of the value chain, from the collection and dismantling of EoL products, to the processing of spent rare earth magnets, the production of recycled magnets and their reuse into new products. This report draws insights from the project's work, desk research and interviews with experts to provide new knowledge and quantitative estimates, and it identifies the principal challenges for developing a supply chain for recycled permanent magnets in the EU.

Although recycling processes for rare earth permanent magnets have been developed over the past few years, our study identifies several barriers that pose challenges for their wider adoption. From a policy perspective, a major barrier observed during the INSPIRES project (and also raised by consulted experts) refers to the lack of clear labelling or marking requirements on products that provide information on magnets. This is an issue for both dismantlers and recyclers who need to manually dismantle the devices to verify the presence, location and type of magnet they're dealing with. Insufficient financial support for recycling processes, the lack of material-specific recycling targets and quotas to boost the development of secondary markets, and the lack of eco-design rules were other key policy-related barriers identified in the analysis.

From an economic perspective, the extraction of magnets from EoL products entails high costs at the expense of developing a viable recycling business case. Low and/or volatile rare earth prices and the challenging competition with extra-EU magnets, and with magnets produced via primary materials pose further economic challenges.

Regarding the supply chain, the EU currently has very limited capacity in several parts of the rare earth permanent magnet supply chain, namely refining, magnet manufacturing and metal making which creates uncertainties for companies wishing to invest in any segment of the process, including recycling. Additional barriers in this area include the lack of transparency and traceability for permanent magnets, possible uncertainties and scepticism about the performance of recycled magnets, a still undeveloped and uncoordinated collection system for EoL products and the current low (and uncertain future) volume of EoL magnets available for recycling. Finally, other critical barriers on the technology front include the challenging extraction of magnets from EoL products, some potential technical limitations of the recycling process (e.g. due to impurities and magnet oxidation) and a general lack of technical knowhow about magnet recycling in the EU compared to other world regions.

Turning to the opportunities that arise from building an effective EU magnet recycling chain , the report provides quantitative estimates about the future demand for magnets and recycling's potential to cover such demand. We estimate that, under different scenarios with varying levels of ambition, recycling could cover between 8 % and 19 % of rare earth magnet material requirements in the short-medium term (i.e. until 2030). Within this timeframe, the key product groups that will provide opportunities for the recycling of rare earth magnets are conventional vehicles, but also Europe's urban mine consisting of home appliances, consumer electronics and audio devices.

Moving beyond 2030, the share of future demand potentially covered through recycling increases, and in 2050 we estimate it could range between 24 % and 48 %. This dynamic is largely due to future market developments: with the upcoming expansion of relatively new markets, such as electromobility and wind turbines, magnet demand will – in fact – significantly outstrip the potential secondary magnet supply in the next five to 10 years.

However, once a larger number of such applications start reaching EoL and demand begins to flatten – i.e. towards the second half of the 2030s – recycling will start to play a larger role. In the longer term, an ever-increasing number of EoL magnets from disposed EVs, electric bicycles and wind turbines would provide important feedstocks of secondary magnet sources.

Taking stock of the above, the report proposes the following recommendations:

R1. Introduce labelling requirements to improve the transparency of EoL magnets. Different types of magnets can be found in disposed of products, and magnets' material compositions – even within the same magnet type – can vary significantly. The recycling of magnets, especially through the 'short loop' hydrogen processing of the magnet scrap (HPMS) process, requires a detailed knowledge of EoL magnet types, composition and the presence of coatings. However, due to the limited availability of such information, companies currently need to manually disassemble the devices to analyse the magnet and determine whether they are fit for the recycling technology. This is a very labour-intensive process. Introducing transparency requirements in the form of a label or marking on products could therefore significantly improve the efficiency of the recycling process. Information about magnets could be collected along the value chain through a digital product passport as is currently being planned for batteries in the context of the Battery Regulation.

R2. Develop recycling quotas and targets for magnets. Establishing a quota on the level of recycled content in new magnets could provide a demand push and help boost the development of markets for secondary magnets. Such quotas could be accompanied by material-specific recovery targets to encourage the recovery of rare earths from EoL applications and support circularity in the sector. The recycling quotas and recovery targets should be ambitious yet realistic, while the industry should be given a trajectory to develop suitable infrastructure and to scale-up recycling processes.

R3. Provide financial support for the establishment of magnet recycling processes in the EU. Currently the processes of disassembling EoL products and extracting the magnets entail high costs, thereby limiting the profitability of the overall recycling process. Moreover, recycled magnets cannot yet compete with magnets produced through virgin materials. Thus, providing financial support and incentives to recyclers could assist the commercialisation and scale-up of the recycling processes. For instance, this could take the form of investment support for new magnet recycling infrastructure, or tax incentives for products containing recycled magnets. Additionally, public R&D funding along the whole permanent magnet value chain should be further increased to fill the gap in technical knowledge with extra-EU producers.

R.4 Establish eco-design requirements to facilitate the extraction of magnets. Accessing rare earth magnets from EoL products represents one of the major technical and economic hurdles for the recycling of magnets. This is because magnet-containing products are not typically designed to take into account the further disassembly and recycling of their components. Introducing eco-design requirements for such products and components could therefore facilitate the extraction process, and improve the business case for magnet recycling.

1. INTRODUCTION

It is widely accepted today that future energy and digital transformation will be accompanied by a soaring demand for raw materials for emerging technologies. Cobalt, lithium, nickel, copper and rare earths are among the elements for which high projected demand and looming supply risks have been extensively documented by various studies (Hund et al., 2020; KU Leuven, 2022). While the challenges of meeting the EU's material needs for batteries has been in the spotlight for many years already, as shown by several established EU initiatives[1], recently the attention of many policymakers and media outlets[2] has been drawn particularly to rare earth-based permanent magnets. The European Commissioner for the Internal Market Thierry Bratton (2022) has highlighted the need to develop an EU value chain for permanent magnets. The new spiral of international tensions caused by the war in Ukraine has also prompted discussions around EU dependency on critical raw materials, including rare earths, in the Council (2022). Securing supply chains for permanent magnets is furthermore emerging as a topic requiring international cooperation as shown by the discussions within the EU–US Trade and Technology Council[3].

Owing to their properties and performance advantages (e.g. high strength and low maintenance requirements) (Raspini et al., 2022; Fujita et al., 2022), rare earth-based permanent magnets have become key components of technologies driving the energy transition namely wind turbines, battery and fuel cell electric vehicles (Gauß et al., 2021). Their use, however, extends to various other applications including home appliances (e.g. refrigerators, washing machines), consumer electronics (e.g. mobile phones, headphones, loudspeakers) and hard disk drives (Yang et al., 2017). As the energy and digital transformations unfold, demand for these magnets is expected to rapidly increase, and with it the need to identify primary and secondary sources of rare earth elements (REEs). This is especially heightened by China's dominance of the rare earth magnets value chain, developed through investments and state financial support over decades (Gauß et al., 2021; Balaram, 2019; Mancheri et al., 2019).

In this context, recovering material from end-of-life (EoL) magnets could be a key option for meeting future needs for REEs and building a viable permanent magnet industry in Europe. However, recycling technologies are not yet economically viable and have not developed at full industrial scale due to several existing barriers (Binnemans et al., 2021; KU Leuven, 2022). In addition, sufficient volumes of (EoL) magnets from wind turbines and electric vehicles (EVs) are only expected in the coming years and decades (KU Leuven, 2022). The latter indicates that opportunities for using Europe's urban mine of other products containing permanent magnets

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[1] One prominent example is the EU Battery Alliance established in October 2017 with the objective to build a coalition of policymakers, major industrial players and scientists to foster the development of a European battery ecosystem (European Commission, 2019).

[2] See for instance articles by Bloomberg and REUTERS.

[3] See the EU-US joint statement following the meeting in France in May 2022.

(i.e. home appliances, consumer electronics) would need to be seized where possible. But, significant uncertainties still exist with regard to the future volumes and streams of EoL magnets, and therefore on the extent to which recycling could tackle the upcoming surge in demand.

The INSPIRES project[4], co-funded by the EU, will test and develop processes for recovering rare earth permanent magnets from home appliances and other devices from Europe's urban mine. Bringing together partners from the whole value chain, the project aims to cover all steps from collection and dismantling of EoL products to processing of recovered rare earth magnets and production of new magnets with recycled content. Drawing from the project's insights, desk research and interviews with experts in the field, this report aims to provide new knowledge, quantitative estimates about the future volumes, and policy recommendations that can inform the development of EU raw material and recycling policies.

Chapter 2 provides an overview of global rare earth reserves and uses, while Chapter 3 presents the current state of the rare earth permanent magnets value chain. Chapter 4 then describes the different circularity and recycling options that exist for magnets. A presentation of barriers for developing a supply chain for recovered rare earth permanent magnets in the EU as observed by project partners and experts in the field then follows (Chapter 5). Chapter 6 provides quantitative estimates about the share of future demand for rare earth magnets that could be covered through recycling magnets from end-of-life products. The report concludes with policy recommendations.

2. RARE EARTHS: RESOURCES AND USES

2.1 Rare earths: reserves and production

The rare earth elements (REEs) are a group of 17 elements of the periodic table – the 15 lanthanides plus yttrium and scandium – that share similar physical and chemical characteristics. Despite their name, the REEs are relatively abundant in nature, where they occur within different types of minerals, such as bastnasite and monazite. However, mineral concentrations enabling a profitable and environmentally sound extraction tend to be less common than for most other minerals, as they only occur under special geological conditions (Kalvig, 2022; Trench, 2019). Based on the atomic weight, the REEs are typically divided into *light* rare earth elements (LREE) and *heavy* rare earth elements (HREEs) (Kalvig, 2022)[5]. The two

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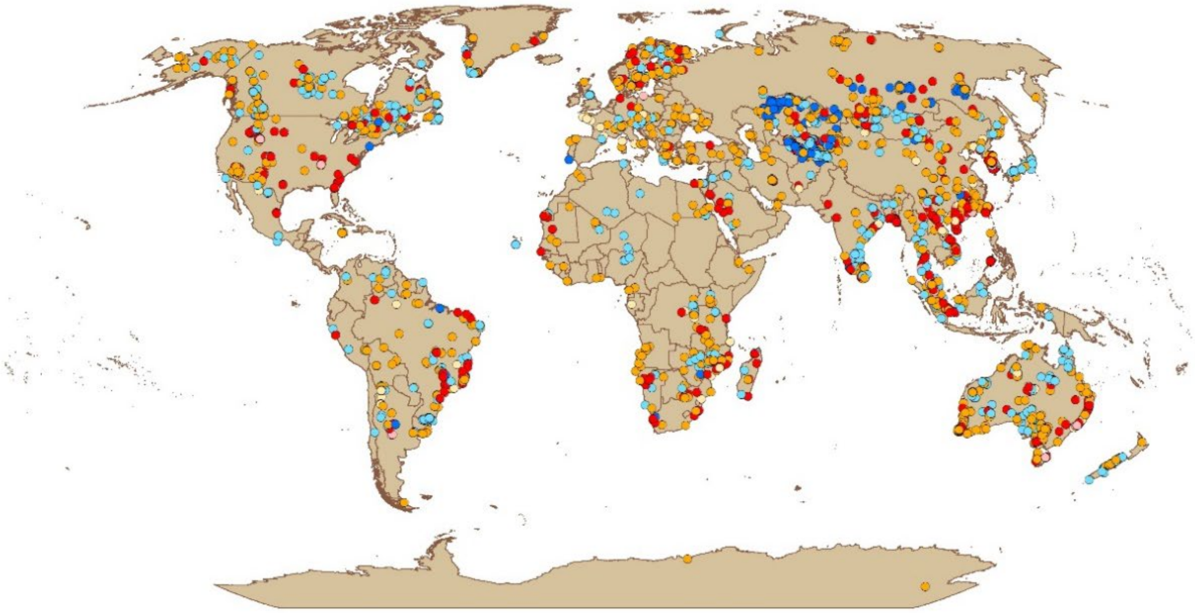
[4] For more info about the project see: https://www.inspires-magnet.eu/.

[5] The LREE group comprises lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium and gadolinium, while the HREE include terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium. Despite having a light atomic weight, yttrium is typically included within the HREE group due to its chemical and physical properties (USGS, 2017).

sub-groups have different properties, different concentrations and, therefore, different market dynamics[6].

As of 2017, a total of over 3 000 million metric tonnes (mt) of total REE resources were estimated in 40 exploration projects around the world (USGS, 2017), while current REE reserves[7] are around 120 million mt (USGS, 2022)[8]. China holds 37 % of global REEs reserves, with the rest largely distributed among Brazil, Russia, and Vietnam. Together, these three countries account for more than half of current global reserves (USGS, 2022). In Europe, significant rare earth reserves are located in Greenland (1.5 million tonnes), and potential rare earth deposits of interest have been identified in Finland, Sweden and other sites in southern and eastern Europe (Goodenough, et al., 2016). The global distribution of rare earth deposits is shown in Figure 1.

Figure 1. Location of global rare earths deposits and occurrences



Source: USGS (2022).

Notes: (light) red dots refer to (possible) deposits, i.e. 'sites or areas with known production, reserves, or resources without regard to size'; (light) orange dots refer to (possible) occurrences, i.e. 'sites or areas without known production, reserves, or resources where geology seems to be fairly well described or where mineralisation was notable enough to result in prospection/exploration'; (light) blue dots refer to (possible) 'sites or areas where REE mineralisation is present but the amount is not considered interesting, has not been studied, or has almost no information available'.

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[6] HREEs tend to be more 'rare' and, therefore, more expensive than LREE (USDE, 2020).

[7] Reserves indicate the part of an identified resource that can be physically and economically extracted at the time of determination. Reserves can be reduced as material is extracted, or at the economic feasibility of extraction in some deposits improves. As such, they are dynamic quantities that may vary over time. Resources refer instead to the concentration of material (USGS, 2022a).

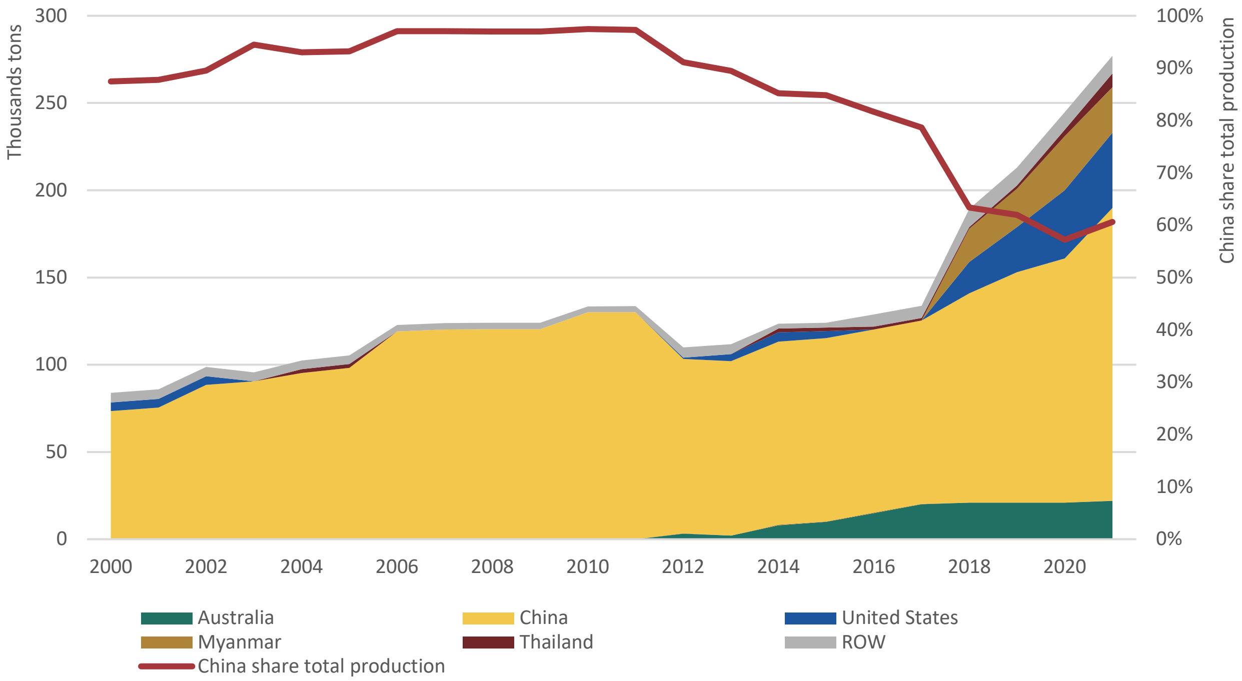
[8] These figures do not account for the roughly 700 million mt of rare earths resources recently discovered in the Turkish regions of Beylikova. With an expected processing capacity 10 000 mt of REO, this deposit could make Tukey the fifth largest REO producer.

In terms of mining production, REEs are today predominantly mined in China (about 60 % of the total), albeit the Chinese share of total supply has been gradually decreasing since 2011, when the country controlled almost all global production (Figure 2). This dynamic has been largely driven by the increase in REE mining outside of China following the 2010-2011 rare earths crisis, when global REE prices spiked due to Chinese export bans.

Other major REE suppliers besides China are the US, with 15 % of world total production (largely from the Mountain Pass mine in California), and Australia, with 8 % of total production (predominantly from the Mount Weld mine) (USGS, 2022; Alves Dias et al., 2020; Kalvig, 2022). Production of rare earth oxides (REO) in Myanmar, which has also substantially increased since 2018 reaching 9 % of global supply, has been largely considered under Chinese sphere of influence (USGS, 2022; King, 2022; Global Witness, 2022). In the EU, aside from a few small active projects in Sweden and Greenland – mostly controlled by Canadian and Australian companies – current rare earth mining production remains negligible (Alves Dias et al., 2021).

As shown in Figure 2, after more than 15 years of only limited growth, global rare earth production has more than doubled over the last five years alone, reaching close to 280 kilotons (kt) in 2021.

Figure 2. REEs global mining production by country (REO equivalent) and Chinese share of total production



Source: USGS (2002 to 2022).

Box 1. Environmental impacts related to rare earths mining

While rare earths have many important applications (see the section below), it should be noted that their extraction and processing is often associated with environmental and social concerns. Over the years, there have been multiple cases of rare earth mining activities leading to significant environmental damage and, therefore, to social distrust. In the 1980s, the leakage of radioactive materials at the Bukit Merah mine in Malaysia was one of the first environmental disasters linked with rare earth mining operations. Extensive mining in the world's largest rare earths site, Bayan Obo (in China) led to a large share of the population leaving the region because of soils becoming infertile. In California, leakages in the wastewater piping system at the Mountain Pass mine in the 1990s were followed by large environmental compliance costs and the subsequent closure of the mine (Ali, 2014).

Although technological improvements have led to a significant reduction in environmental impacts over the past decades, rare earth mining processes can still release toxic metals and chemicals. Mining has an impact on local soils, water systems, wildlife, vegetation and human health, especially through dust containing gamma radiation in mining areas (Balaram, 2019). However, the amount of harm caused by rare earth mining depends on the type of element extracted from different ores. In 2020, Cerium and Neodymium account for the largest share in total energy and water use, as well as CO_2 emissions in global rare earth production. Additionally, the increase in demand for green energy production has led to a hike in the total environmental impacts of rare earth mining over the past decade. In the period from 2010 to 2020, global GHG emissions through rare earth mining increased by 94 % from 79 thousand tonnes CO_2 equivalent to 152 thousand tonnes CO_2 equivalent. Regarding water use for rare earths mining, it is seen that from 0.42 million m^3 in 2010, water consumption almost doubled to 0.82 million m^3 in 2020. These numbers are expected to increase further until 2030, albeit at a smaller pace. Given the geographical concentration of rare earths mining, China accounts for the highest share of these impacts, followed by Myanmar and the US (Golroudbary et al., 2022). The actual environmental impact of rare earths mining strongly depends on the energy mix used in the mining process, whereas the amount of energy required depends strongly on the size and the geological conditions in the mining site (Zapp et al., 2022).

2.2 Rare earths: uses and applications

Thanks to their unique properties, rare earths are used for a wide range of military, energy and industrial applications – from permanent magnets to batteries[9]. Today, permanent magnets represent their largest application, accounting for about 30 % of the global rare earths market volume (Figure 3) and 90 % of the market value (King, 2022; Adamas Intelligence, 2019). However, with the ongoing swift expansion of the electromobility and wind power markets – two of the largest final applications for permanent magnets – the consumption of permanent

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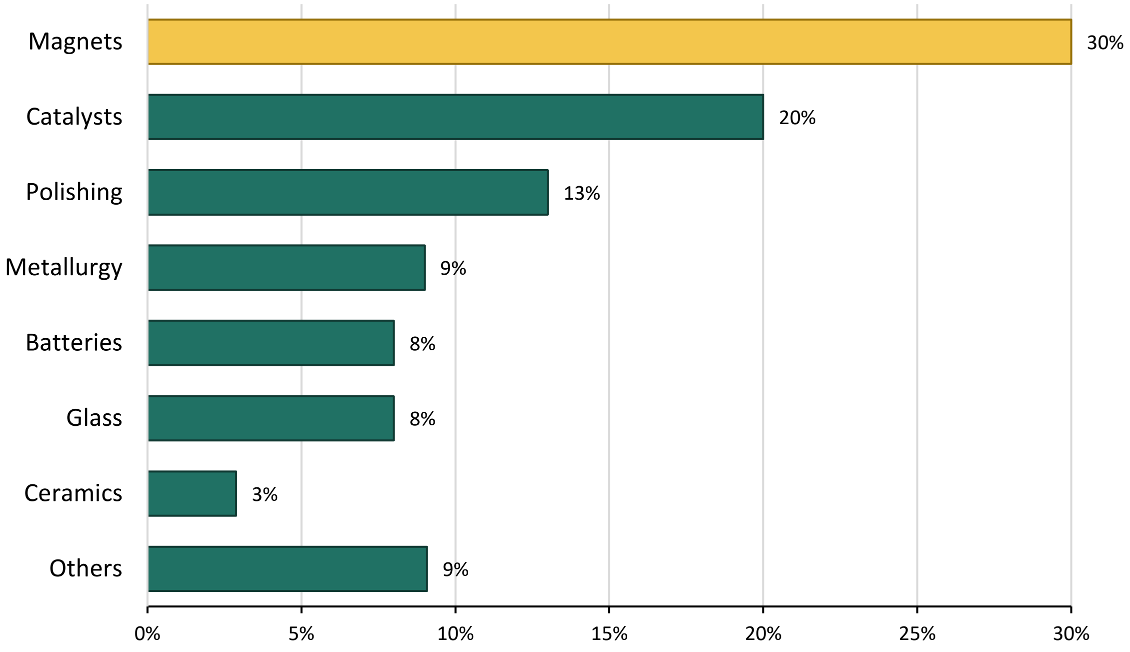
[9] More specifically, rare earths are used for nickel-metal hydride (NiMH) batteries, i.e. rechargeable batteries typically employed for hand tools and electronics (Kalvig, 2022).

magnets compared to total rare earths' consumption is expected to increase even further in the next few years, and potentially lead to shortages in supply (Alves Dias, 2020).

There are many different types of permanent magnet compounds on the market today (see Chapter 3 for further details). When it comes to the most common rare earth-based compound – neodymium-iron-boron (NeFeB) – four REEs are critically important: two LRREs – neodymium (Nd) and praseodymium (Pr), and two HRREs – dysprosium (Dy) and terbium (Tr). Specifically, Nd and Pr are used to confer magnetic properties, while Dy and Tr are used to increase magnet resistance to demagnetisation at high temperatures (USDE, 2020). Rare earth content in NdFeB permanent magnets typically account for about 30 % of their weight, with Nd taking the largest share (about 26 %) (IRENA, 2022; Kalvig, 2022). However, significant variation in terms of rare earth composition may be observed among specific properties required[10].

In addition to permanent magnets, other significant applications requiring REEs include catalysts (used for instance in petroleum refining and vehicle catalytic converters), metal alloys (e.g. for batteries and fuel cells) phosphors (employed amongst others for lasers, fibre optics, displays) ceramics (used for sensors) glass and polishing compounds and defence applications such as satellite communications and aircraft structures (USDE, 2022).

Figure 3. Global REO demand by end-use application (%)



Source: King (2022); IRENA (2022).

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[10] From a review of studies on NdFeB magnets, overall rare earths content was found to range between 28 % to 36 % of magnets' weight, with Nd content varying from 9% to 32%, Dy from 0% to 10%, Pr from 0 % to 6 % and Tb from 0 to 1 %. More details on magnets composition for each product category – specifically Nd and Dy – are reported in Chapter 6.

3. RARE EARTH PERMANENT MAGNET VALUE CHAIN

3.1 Key segments of the value chain and geographical concentration

Figure 4 below illustrates the linear value chain of RE permanent magnets, which can be divided into six main segments: 1) mining of rare earth ores[11], 2) separation of rare earths oxides (REO), 3) refining of rare earth metals and alloys, 4) production of magnets and 5) production of the final magnet application (e.g. electric vehicles or wind turbines). As we will see in Chapter 4, once magnet-containing products reach the end-of-life (EoL) stage, an additional segment can be considered if rare earth magnets are directed towards different circular options and particularly recycling.

The whole RE permanent magnets value chain is highly concentrated in China. With regard to the first step, i.e. mining, as shown in the previous chapter China is responsible for about 60 % of overall global REEs production, with Australia, Myanmar and the US largely covering the remaining share (USGS, 2022). However, as can be seen from Figure 4 below, a large part of the REEs globally extracted are then further processed in China, irrespective of where they are mined (IEA, 2021)[12].

Moving beyond the mining stage, China dominates the midstream and downstream segments of the value chain – i.e. from REO separation up until the magnet production step. The country holds about 87 % of REO separation activities, with the remaining share almost entirely controlled by Malaysia (through the Australian company Lynas – 11 % of the world total) and Estonia (2 %) (IEA, 2021; King, 2022). When it comes to the rare earth metal or alloy-making step (i.e., the reduction of REO into rare earth metals (REM)), China accounts for about 91 % of the whole global capacity, followed by Japan with 7 %. Finally, the Chinese share of rare earth permanent magnet production[13] accounts for 94 % of the world total, with Japan still holding the second largest share (5 %)[14].To date, the EU accounts for 1 % of global RE permanent magnets production (King, 2022).

Overall, the above steps of the value chain of rare earth permanent magnets have been highly concentrated in China, a trend that has been observed since the 1990s. Nevertheless, when it comes to the applications containing permanent magnets the Chinese market share of global

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[11] Rare earths permanent magnets contain several other elements besides REEs that also need to be mined. However, this study the focuses on rare earths only.

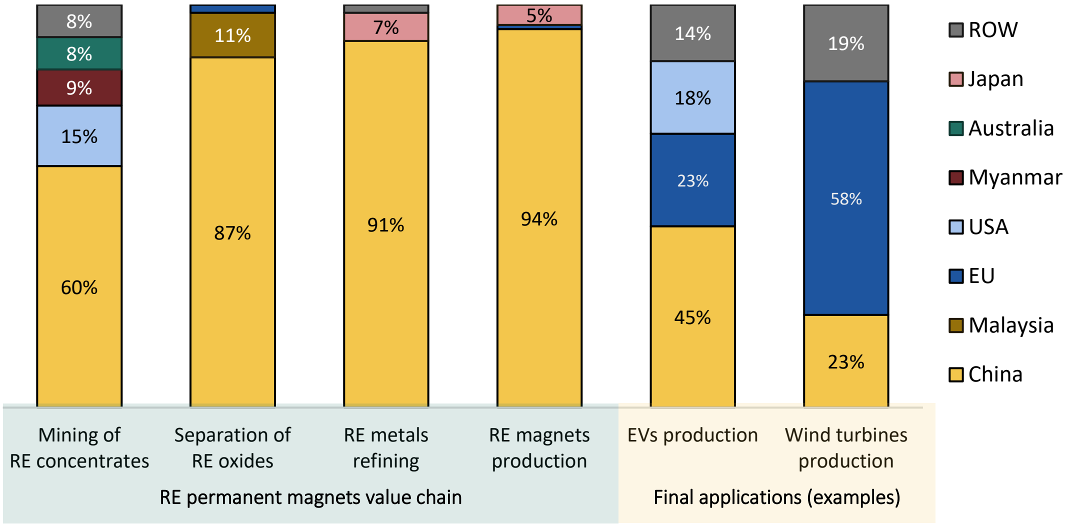
[12] As also underlined by some interviewed industry experts, this trend mirrors Chinese strategy to increase market penetration in segments further downstream in the value chain, which guarantee higher profit margins and lower environmental impacts (Adamas Intelligence, 2020).

[13] This step entails the creation of so called 'super alloys', whereby different REEs and other elements are combined to form the final magnet compound (Kalvig, 2022). Further details on the different compounds and manufacturing processes are reported in the following section.

[14] Japan is specialized in high-grade (i.e., high-performance) rare earth magnets. As of 2018, 36 % of world high-grade permanent magnets were produced in Japan, with China controlling "only" 48 % of this market (Ma & Henderson, 2021).

manufacturing is often significantly lower. In most of these markets, the US and the EU represent the leading producers. In the case of wind turbines, for instance, the EU is the largest manufacturer with 58 % of the overall production, with China at 23 % (Gauss et al., 2021).

Figure 4. Rare earths permanent magnets value chain and final applications, geographical concentration



Own design based on: USGS (2022); IEA (2021); Gauss et al. (2021); King (2022); CMA UK (2022).

3.2 Types and applications of permanent magnets

Permanent magnets vary depending on the grade (i.e., magnetic strength), production process and the material composition. In terms of composition, four major magnetic compounds can be identified in the market: two rare earths based – neodymium-iron-boron (NeFeB) and samarium-cobalt (SmCo) and two non-rare earths based – ferrites and aluminium-nickel-cobalt (AlNiCo). Rare earth permanent magnets are usually preferred due to their higher performances in terms of strength and resistance. Amongst these, NdFeB magnets are the most widely used as they are cheaper and stronger than SmCo[15] (Alves Dias et al., 2020; Kalvig, 2022). Despite having lower performances than all rare earth counterparts, ferrite magnets are the cheapest alternative on the market (Kalvig, 2022), and are therefore preferred for some product categories. As shown in Figure 5, in 2019 NeFeB magnets accounted for 66 % of the whole market, followed by ferrites (31 %) and SmCo (2.2 %) (Ma & Henderson, 2021). The remaining sections of this report will be solely focused on NdFeB magnets which are the most widely used type of magnet and the target of the INSPIRES project.

With regard to the manufacturing process, NdFeB permanent magnets can be produced through either sintering or bonding techniques. The former generates fully dense magnets with high strength-to-weight ratio, therefore ideal for applications where high strength and small size is required (e.g. electric motors, wind turbines and EVs). The latter generates lower performing magnets which can be shaped into different geometries and whose magnetic

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[15] However, SmCo magnets have higher resistance to high temperature and corrosion (Kalvig, 2022).

orientation can be customised depending on product needs. Because of these properties, bonded magnets are typically preferred for smaller applications such as consumer electronics (Ciacci et al., 2019). Today, the market is composed of about 90 % of sintered permanent magnets and 10 % of bonded magnets (Kalvig, 2022).

The range of NdFeB permanent magnet applications is wide and heterogeneous, and includes amongst others consumer electronics, industrial applications, ‘white goods’ (i.e. refrigerators and washing machines), wind turbines and several mobility applications such as electric scooters and bicycles and both internal combustion engine (ICE) and electric vehicles. Data on the disaggregation of (global) NdFeB magnet demand amongst applications are fairly inconsistent in the literature, partly due to discrepancies in categorisation; for instance, USDE (2022) reports industrial motors and consumer electronics as the two major demand applications (30 % and 29 %, respectively), whereas IRENA (2022) identifies consumer electronics and electric vehicles as the largest demand drivers with 20 % and 14 % of the demand.

In the EU, our calculations show that in 2020 the majority of NdFeB magnets were employed in the automotive sector, almost equally among conventional (23 %) and electric (22 %) vehicles, and wind power was the third largest demand segment (15 %)[16]. Irrespective of the above inconsistencies, there seems to be broad consensus over the fact that EVs and wind power are currently the fastest growing segments of NeFeB demand, and will drive a significant expansion in magnet demand in the coming decades.

Figure 5 Permanent magnets market by magnet compound

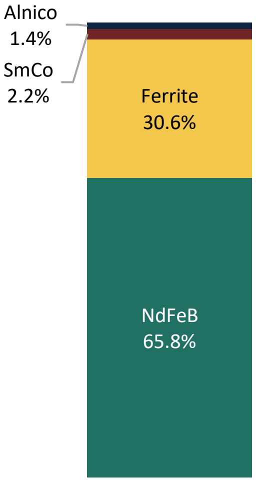
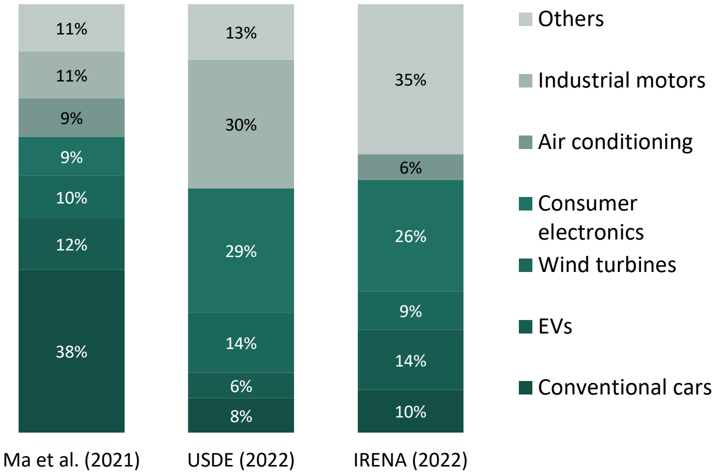


Figure 6 NdFeB magnets applications, different sources



Source: Ma et al. (2021), USDE (2022), IRENA (2022).
Note: In Ma et al. (2021), the ‘industrial products’ category was referred to as ‘industrial products’, and the ‘others’ category include ‘elevators’ (8 %) and ‘others’ (3 %). In USDE (2022), the ‘conventional cars' category considers ‘non-drivetrain motors in vehicles’ and ‘wind turbines’ only include offshore. In IRENA (2022), the ‘conventional cars’ category includes ‘EPS’ (2 %) and ‘other automotive’ (8 %); ‘consumer electronics’ include ‘HDDs’ (3 %), ‘acoustic transducers’ (3 %) and ‘other consumer electronics’ (20 %); ‘Others’ include ‘robotics’ (2 %), ebikes (3 %) and ‘others’ (30 %).

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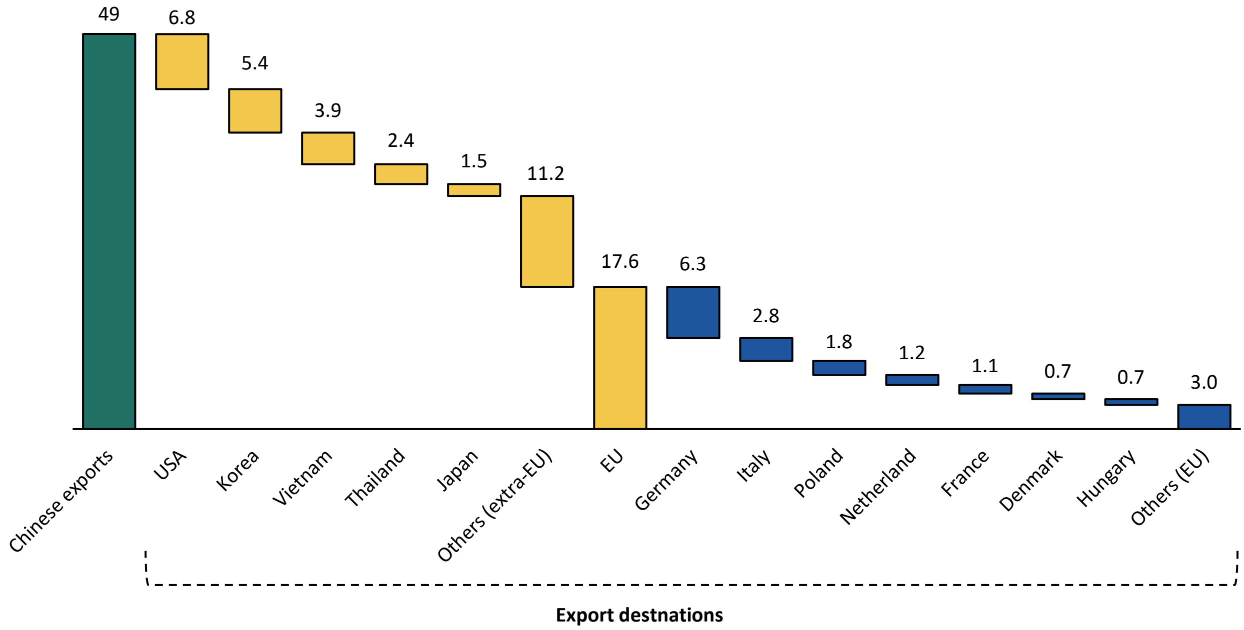
[16] For more details on methodology and assumptions, please refer to Chapter 6.

3.3 Permanent magnet production and trade in the EU

The production capacity of NdFeB permanent magnets in the EU is currently limited. Vacuumschmelze Gmbh & Co (and its subsidiary Neorem Magnets Oy), ThyssenKrupp Material Trading and Magneti Ljubiana represent the only major EU producers of sintered magnets, while EU bonded magnet producers include Grundfos, Magnetfabrik Schramberg, JL Mag and IMA (Gauss et. al, 2021; Kalvig, 2022). Overall EU capacity is about 1 kt, although the actual production output is likely lower and only serves specialised applications (Gauss et al., 2021)[17]. Therefore, the EU meets the vast majority of its permanent magnet needs through imports, almost entirely from China. In 2021, the EU imported about 18 kt of rare earth permanent magnets from China (REIA, 2022) (Fig. 7), which according to Gauss et al. (2021) accounts for about 98 % of the overall EU market. This makes the EU the largest importer of Chinese NdFeB magnets (36 % of the total), followed by the US (14 %) and Korea (11 %). Germany and Italy accounted for the largest share of EU imports (36 % and 16 %, respectively) (Figure 7).

Figure 7. China's rare earth permanent magnet exports and export destinations (kt)



Source: REIA (2022).

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[17] In Estonia, the Canadian Neo Performance Materials – already active in rare earths mineral processing – has recently been awarded a EUR 18.7 million grant to develop vertically integrated rare earths magnets manufacturing capacity, with plans to reach 1 kt production output by 2024 and then further upscale to over 5 kt.

4. CREATING CIRCULARITY ROUTES FOR PERMANENT MAGNETS THROUGH RECYCLING

In view of the future surge in demand for rare earths, the challenges related to RE primary mining[18], and the significant supply risk of REEs, increasing attention has been recently placed on the recovery and recycling of REEs from EoL applications. In particular, due to their widespread and increasing use, growing research has focused on recycling processes of rare earth permanent magnets.

Albeit several recycling processes for NdFeB magnets have been developed over the years, the market commercialisation of recycling operations has been challenging. This is due to a combination of factors, including technical limitations, financial constraints and a limited availability of end-of-life NdFeB magnets. Moreover, sorting and dismantling still represent significant limitations for the development of rare earth recycling operations (Zakotnik et al., 2016). Nevertheless, research and development efforts have significantly intensified over recent years as also shown by the large number of projects in this domain[19]. Given the limited RE mining activity in the EU, it is anticipated that RE recycling will play a fundamental role in complementing primary production in the near future (Filippas et al., 2020; Schulze et al.,2016; Habib et al., 2014a; Rademaker et al., 2013). This section presents the main characteristics of RE-based permanent magnet recycling technologies, their specific advantages as well as potential drawbacks.

REEs from EoL permanent magnets can be recovered through direct and indirect routes. Indirect recycling routes involve the extraction of individual REEs from magnets through chemical processes, while direct recycling routes (also known as ‘closed’, ‘magnet to magnet’ or ‘short route’ processes) encompass processes through which the magnetic material (the alloy) is recovered and directly used for the manufacturing of new magnets.

Indirect recycling routes can be further distinguished based on the chemical process used to separate and extract REs contained in magnets. Notably, the separation step can be based on a hydrometallurgical or pyrometallurgical process, or a combination thereof.

Hydrometallurgical (or ‘wet’) processes represent the more traditional route, as they closely resemble the process to extract REs from mineral ores in the first place (Binnemans et al., 2013). They involve, first, the dissolution of magnets by means of strong mineral acids (so-called leaching process), followed by separation (through solvent extraction, ion exchange or ionic liquid techniques) and further precipitation of REEs (Binnemans et al., 2013; Yang et al., 2017). Such processes provide a high level of flexibility, as the REEs are obtained in high purity solutions that can potentially serve as feedstock for any RE-based application (including new

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[18] See, for instance, the so-called balance problem (Binnemans et al., 2015).

[19] Among the numerous EU initiatives and EU funded projects targeting RE or permanent magnets recycling are REMANANCE, SUSMAGPRO, REproMAG, SecREEts, EREAN, REEcover, REE4EU.

magnets). However, they require large amounts of chemicals and water, generating significant waste treatment costs and posing environmental and safety concerns (Binnemans et al., 2013; Firdaus et al., 2016; Nlebedim et al., 2018; Takeda et al., 2014). Moreover, as also highlighted by interviewed experts, several process steps, relatively long process times and expensive infrastructure are typically required to obtain new magnets (Binnemans et al., 2013; Firdaus et al., 2016)[20].

Pyrometallurgical ('dry') extraction methods have been developed as an alternative to hydrometallurgical ones, to overcome the high consumption of chemicals and wastewater generation, especially in conditions of water scarcity or where waste needs to be curbed (Firdaus et al., 2016). They include a wide range of techniques, which essentially involve the remelting of scrap alloys at elevated temperatures and the subsequent extraction of pure REEs (extractive type processes) or RE-containing alloys (refining type processes) (Rasheed et al., 2021). While available evidence indicates that they have a general lower environmental footprint compared to hydrometallurgical routes, pyrometallurgical processes are considered to be highly energy intensive, they may require highly corrosive gases and generate large volumes of solid waste (Binnemans et al., 2013).

As explained earlier, a second group of REE recovery processes involves the direct reuse of REE magnet alloys for the manufacturing of new magnets (direct recycling route). A promising technology in this area is based on hydrogen decrepitation. Known as Hydrogen Processing of Magnet Scrap (HPMS), this process allows the separation and extraction of magnets from EoL applications in the form of a hydrogenated alloy powder, which can be further treated (and, if needed, blended with virgin REEs) for the production of new magnets (Yang et al., 2017; Walton et al., 2015). The technology has been developed by the University of Birmingham and has so far been tested in the context of hard disk drives (Walton et al., 2015) and automotive rotors (Jönsson et al., 2020). This technology will be the core focus of the INSPIRES project and will be tested, for home appliances, such as tumble driers, consumer electronics and similar devices. Compared to hydro- and pyrometallurgical routes, HPMS is considered to present economic and environmental benefits in terms of lower energy and chemical intensity as well as entailing fewer steps until the final recycling of magnets (Yang et al., 2017). At the same time, however, the process is only practical for applications with a narrow distribution in the composition of their magnets so as not to result in quality downgrades, such as wind turbines or hybrid and electric vehicles (Yang et al., 2017; Binnemans et al., 2013; Ueberschaar, 2015). For other applications, indirect recycling routes or further separation of REEs from the powder obtained through hydrogen processing remain the preferred option (Binnemans et al., 2013).

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[20] In light of the shortcomings of conventional hydrometallurgy, research has also recently developed more sustainable hydrometallurgical recycling methods, for instance requiring less energy input or using less impactful chemical processes. Within this area, the bioleaching (or biohydrometallurgy) process is emerging as a promising path (Magrini et al., 2022).

5. BARRIERS FOR DEVELOPING A SUPPLY CHAIN FOR RECOVERED RARE EARTH PERMANENT MAGNETS IN THE EU

This chapter delves into the key barriers for developing a supply chain for recovered rare earth permanent magnets in the EU. It applies a quantitative analysis based on in-depth perspectives from experts across the value chain.

5.1 Data collection and analysis

Using the 'judgement sampling' method (see Mishra & Alok, 2017; Pratton, 2002;), we built a sample of experts to provide qualitative data on barriers for this analysis. As a first step, we included the partners of the INSPIRES project who provided insights from the different stages of the permanent magnet supply chain and shared the lessons learnt during implementation of the project. To further enrich our findings, we expanded the initial sample with additional experts from academia and industry who had a working knowledge of the rare earth magnets value chain and/or recycling processes. Identification and selection of additional experts was based on recommendations from interviewees themselves, who suggested potential company representatives and academics to be featured in this assessment[21]. In total, the sample has experts from 16 different organisations and covers the full supply chain for recovered rare earth permanent magnets, from collection of end-of-life products, dismantling and extraction of magnets, to production of magnets with recycled content and of new electric motors and end users. Table 1 below presents the list of sampled experts and types of organisations they come from.

Table 1. Sample of interviewed experts

Interview number	Affiliation	Interviewee(s) position
1	Industry	Applications Engineer, R&D Magnetics
2	Academia	Full Professor; Senior Assistant Professor
3	Industry	Technical Director
4	Industry	Head of Department Magnetic Materials
5	Academia / industry	Scientific Director, Head of Innovation and Technology
6	Academia	Associate Professor
7	Industry	Secretary General
8	Industry	Analyst
9	Academia	Researcher
10	Industry	Head of Basic R&D
11	Industry	Manager of waste electrical and electronic equipment
12	Academia	Researcher; Postdoctoral Fellow
13	Industry	Senior Expert Rare Earth Material & Magnets
14	Industry	Leader Project Development; Leader Product Development
15	Academia	Assistant Professor
16	Academia / industry	Consultant and Researcher; Consultant

Source: Own elaboration.

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[21] The method of seeking recommendations by the interviewees for other experts in their network in order to further expand the sample is described in the academic literature on qualitative assessments as 'snowball sampling method' (see Staicu, 2021).

In-depth and semi-structured interviews were employed as the principal method for collecting empirical data on barriers (see Voss, et al., 2002)[22]. Interviews were arranged in an online format and took place in the period between October 2021 and October 2022. Prior to the interviews, experts received a consent form explaining the purposes of the assessment and how collected data would be used, along with a questionnaire. The latter invited interviewees to first describe their experience in the domain of magnets and then identify the key barriers/challenges (policy, financial, technological and market) for developing a viable supply chain for recovered rare earth magnets in the EU. Each interview lasted between 45 and 90 minutes. Experts were also asked to provide perspectives on the prospects of different available recycling technologies and the current geopolitical environment. Such perspectives going beyond core barriers have been fed into other relevant parts of this report.

For each interview the research team prepared a detailed transcript and grouped the identified barriers according to three main categories: policy and regulation, finance and economic factors, supply chain and technology. This categorisation was based on similar work conducted for other sectors (see Rizos et al., 2021) and a literature review of available studies on the recycling of rare earths[23]. The team then prepared a second categorisation level using codes reflecting the more specific content of different barriers. As a next step, the different barriers were introduced in an Excel document according to the above-mentioned categorisation levels in order to identify common barriers and synergies from the data collected from the experts. As shown in Table 1 above, in some cases there was more than one participant per organisation; however, for this analysis barriers were only counted once as coming from one interview per organisation.

5.2 Identified barriers

5.2.1 Policy and regulation barriers

The first key policy-related barrier raised during nine interviews was the lack of labelling or marking requirements providing information on the presence of magnets in the products, their location within the products, the type and composition of magnet employed and the possible coatings used. Experts advised that a ‘digital product passport’ providing a set of relevant data for magnets would ease the process of identification and separation of specific components in discarded products and increase the efficiency of the recycling process.

Lack of sufficient economic incentives for recycling processes was another important barrier mentioned by seven interviewees. The experts specifically highlighted that although technologies exist, economies of scale have not yet been achieved in the EU to build a viable

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[22] Using in-depth interviews for collection of data on barriers to circularity has been applied by several other studies focusing on different sectors, for example electronics (see Rizos et al., 2021; 2022), building sector (see Giorgi et al., 2022) and waste management (see Arena et al., 2021).

[23] See, for instance, Binnemans et al. (2021); Burkhardt et al. (2020); Ilankoon, et al. (2022) ; Yang et al. (2017) ; Sprecher et al. (2014) and Raspini et al. (2022).

business case for the extraction and recycling of magnets. Thus, it was noted that financial incentives are needed until the market for recycled magnets has matured and secondary production can compete with primary production. Some experts made specific reference to the need for financial support also for the refining industry which is almost absent in Europe.

Four experts referred to the absence of targets and quotas in the current legislative framework as another barrier. Among them, two suggested there is a need for material-specific targets for recycling rare earth magnets from products, while two others held that a quota for using a minimum recycled content in new magnets would help create a market for recycled materials. However, the experts cautioned that targets should be introduced through a gradual process to provide room to the industry to build recycling infrastructure and production capacities. Lack of eco-design rules to facilitate the recycling process was another obstacle mentioned during four interviews. The experts specifically suggested that action on the product design front can play a key role in building a viable business case for the recovery of magnets at the end-of-life stage. One specific example noted was that the current design does not favour the disassembly and recycling of magnets is electric vehicle motors.

Three interviewees pointed to the complexity of the current legal framework for moving EoL products that have waste status across borders for the recovery of components and materials. It was argued that in the case of magnets, economies of scale may be achieved through the establishment of a number of dedicated facilities across the EU with the capacity to handle magnets from end-of-life applications. Thus, having a framework in place that facilitates transferring end-of-life products and components to these facilities applying high recycling standards will be important in this regard. While it was generally recognised that funding for projects like INSPIRES has improved the industry knowledge base, three experts noted that more public funding is needed to help overcome barriers for companies investing in recycling technologies. Such funding should not only be geared towards bringing mature solutions to the market but also for basic R&D research looking for new innovations.

5.2.2 Finance and economic barriers

Several barriers of an economic nature emerged during the expert consultations, primarily related to the costly extraction of magnets and the competition with magnets already available on the market. In particular, nine experts pointed out that the high costs involved with the extraction of magnets from EoL products complicates the development of a viable business case for the recycling of rare earth magnets. This was largely attributed to the low concentration and high dispersion of magnets in products, which requires labour intensive and costly dismantling and extraction techniques. In this respect, the (conventional) automotive sector was often mentioned as a magnets-rich sector[24] whose waste magnet streams are currently not intercepted due to the difficulty in accessing them.

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[24] As described in Chapter 6, about 200 grams of auxiliary magnets are usually embedded in each vehicle, distributed among, e.g. EPS systems, electric windows and speakers.

The challenging market competition for recycled magnets was seen as a further major concern. This issue was primarily identified with respect to magnets produced in extra-EU countries, particularly in China. As highlighted by 8 experts, current rare earth magnet production costs in China are significantly lower than in the EU, mainly owing to substantial government subsidies. This competitive advantage leads to an unlevel playing field for EU magnet producers and recyclers. In addition, according to 7 experts, it is difficult for recycled magnets to compete with those manufactured with virgin materials, because of the costly steps involved in the magnet recycling chain. According to some of them, this creates a trade-off between environmental and economic targets for final magnet users, who in some cases are still not willing to pay more for recycled magnets. It is only if the prices of primary materials start to increase, a few noted, that the gap will start closing and recycled magnets will become a viable alternative.

Barriers linked to the REE price dynamics were also noted during the interview consultations. Three experts highlighted that the current low prices of rare earths do not incentivise the development of a recovery chain. This contributes to the difficulty for creating a business case for the recycling of rare earth magnets as noted earlier. In addition, the high price volatility of these metals was mentioned twice as a price-related barrier, as it creates uncertainty and makes it difficult to plan and develop a business plan for the recycling of magnets.

5.2.3 Supply chain barriers

With regard to supply chain barriers, the difficulty in building the whole supply chain for recovered magnets in Europe was noted as a prominent barrier in nine interviews. Experts pointed to a number of key contributing factors. According to four of them, the EU currently has very limited capacity in several segments of the rare earth permanent magnet supply chain. This creates uncertainties for companies wishing to invest in any segment, including recycling. One example is the magnet production step, which as we saw in Chapter 3 is today very limited in the EU and would need to be scaled up to create higher certainty about future demand for rare earth metals. Metal making is another important part of the supply chain which is currently underdeveloped. Two other experts noted that the development of a viable supply chain requires a stable supply of recycled magnets and economies of scale that would create confidence in the market. Building confidence would require time and good cooperation between recyclers and the industry. The availability of certified recycled material can also contribute to this end according to the experts. One other expert noted that that the development of a viable supply chain is hindered by a combination of factors including insufficient demand for recycled magnets coming from the domestic market and lack of eco-design rules to facilitate recovery of magnets.

Lack of transparency about the magnets was mentioned as an obstacle during eight interviews. A key lesson learnt during the INSPIRES project implementation is that identifying whether different household appliances and consumer electronics contain NeFeB permanent magnets requires manually dismantling the collected devices which is a labour-intensive process that cannot be economically viable outside the scope of the EU-funded project. This is the case for a range of different products assessed during the project including washing machines, headphones, laptops, battery-powered hand drills, vacuum cleaners, kitchen appliances and mobile phones. For most of these products, detailed information about their magnet content (i.e. type of magnet, chemical composition) is missing which complicates the work of dismantlers and recyclers. Moreover, even within the same product group (e.g. washing machines) there might be large variation in terms of magnet content depending on, e.g. the origin of the product (e.g. US, Japan and Europe) or the specific model[25].

Six experts identified the perception of recycled magnets as a barrier. Specifically, end users place a strong emphasis on the performance of magnets and thus in some cases they can be sceptical regarding the quality and magnetic properties of magnets with recycled content. Two interviewees indicated that certification from a reliable third party guaranteeing not only the recycled content in magnets but also their properties would help boost market demand for secondary applications.

Three barriers related to the state of the recycling industry and its prospects given current and future volumes were raised during the interviews. The first barrier noted by five experts concerned the recycling chain which is currently underdeveloped with no proper established networks in place. The experts further highlighted that since available volumes are still low the recycling networks have not been properly established and there is a lack of interaction between those who apply the recycling technologies and those who discard products. One specific example noted was wind turbines for which energy operators may have limited knowledge about their full content since they are not the manufacturers. At the end-of-life stage, the turbines are provided to dismantlers and then different parts may end up in different recycling companies that are often specialised and are only interested in certain materials or components. The whole recycling process is disaggregated and there is not yet a viable business model in place where all players can effectively work together. The varied collection approaches for end-of-life products across the EU and the multiplicity of types of magnets installed in different devices were two other contributing factors noted in the interviews. It was also argued that the magnet production industry in Europe is still very small and will need to scale up to create certainty about domestic demand for processed rare earth metals and magnets with recycled content.

The second barrier to the development of a viable recycling industry identified by four experts related to the low volumes of end-of-life products containing NdFeB permanent magnets currently available for recycling which makes the development of a recycling business case challenging. Currently we are still in a transition phase and there is a time gap between the

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[25] Our assessment indicates that any available data from studies and market assessments on adoption rates of NeFeB permanent magnets in products from previous market assessments should be treated with caution. For instance, whereas according to Habib et al (2014b), Sekine et al. (2016) – both referring to the Japanese market – around 25% of washing machines placed in the market contain NdFeB magnets, insights from the INSPIRES work indicate that the figure for devices entering the EU market might be lower.

period when emerging technologies containing large magnets such as EVs and wind turbines enter the market and the time they reach the end-of-life stage on large scale. Certain types of household appliances and consumer electronics offer opportunities for recovering magnets though as explained above there are considerable challenges linked to transparency, varied collection approaches etc. A related third barrier also mentioned by four interviewees referred to uncertainties about future volumes of end-of-life products with magnets which complicates investment decisions. As discussed during the interviews, there is a degree of unpredictability due to the fact that many applications where magnets might be installed such as EVs and wind turbines are relatively new on the market and new estimates regarding their possible life span and applications after the first use continuously emerge. This challenge is further accentuated by the use in different product groups of magnets with varying coating performances. Within INSPIRES, it was observed that such uncertainties about volumes with magnets also apply for large household appliances as producers decide to use different types of magnets depending on the size and power concentration of the device.

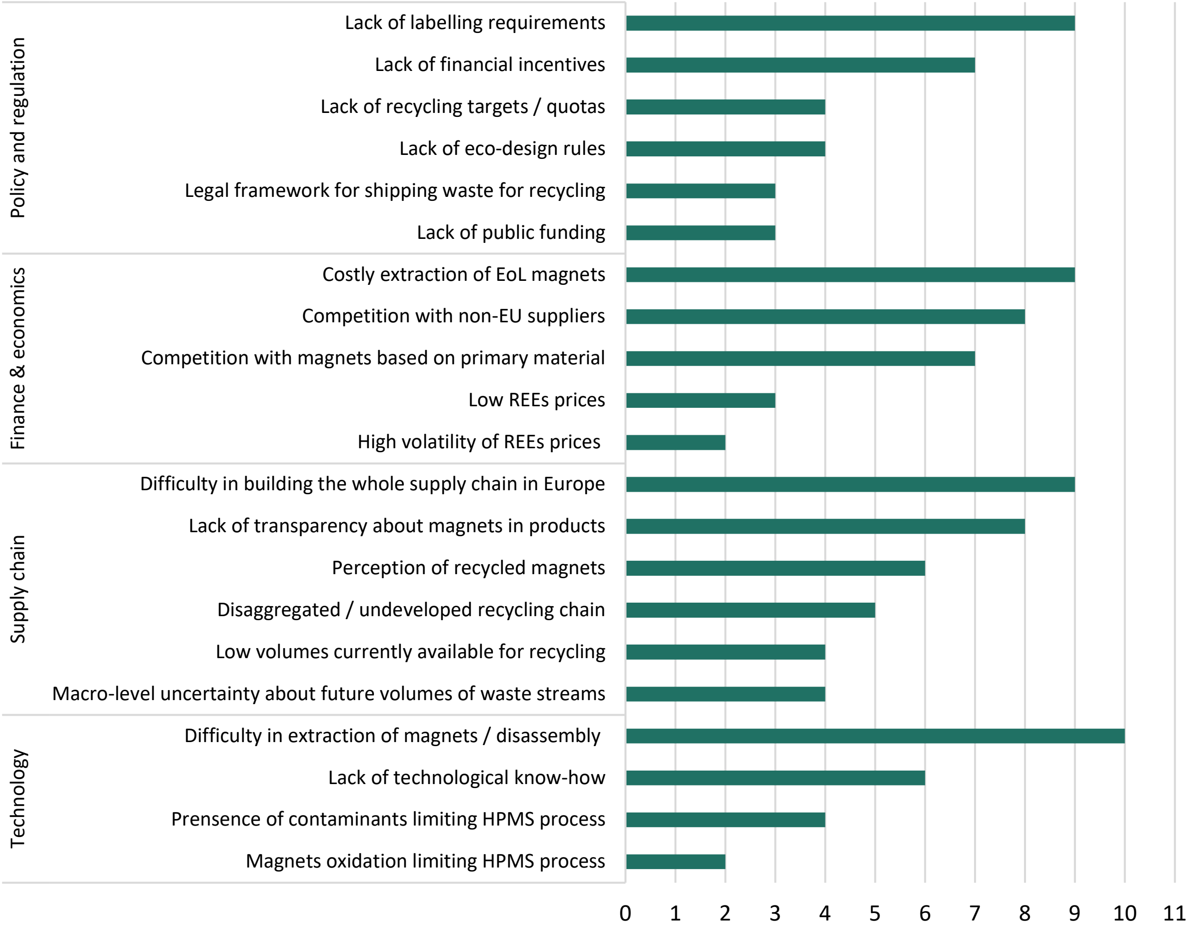
5.2.4 Technological barriers

As outlined in Chapter 4, different recycling routes exist for rare earth permanent magnets. Nonetheless, several technical barriers to the upscaling of a magnets' recycling chain have been acknowledged by interviewed experts. In particular, a major bottleneck was identified at the magnet separation stage. According to 10 interviewed experts, the process of dismantling EoL applications and extracting magnets is technically challenging. This is particularly true for smaller appliances, such as consumer electronics and home appliances, where magnets are typically firmly embedded in the ferrous fraction – often by means of glues – and for which the extraction often results in material losses and/or damage to the magnets themselves. But extraction of magnets emerged as a concern also for larger applications, such as electric vehicles and wind turbines. For the former, obtaining the magnets requires the extraction and dismantling of the motor and of the rotor first, then a process that requires either sophisticated and automated work or a significant amount of manual labour. As for wind turbines, their large magnets tend to be dangerous to handle when still magnetised, so the separation requires on site demagnetisation of magnets. For all these reasons, the magnet-separation step remains a rather complex, labour-intensive and time-consuming activity which, as discussed earlier, can significantly increase the costs of recycling. As underlined by some interviewees, setting more rigid eco-design rules or increased investments in more advanced separation technologies would largely benefit the magnet extraction process.

A second key barrier identified by 6 experts is the general lack of technical know-how on rare earth magnet production and recycling in the EU. Experts highlighted that the EU still lags behind in terms of technical knowledge compared to countries with a traditionally well-established magnet industry, particularly China. Moreover, the majority of R&D on magnets is currently carried out in China, which further increases its competitive advantage with respect to EU producers. In order for the EU to establish a full magnet supply chain, experts flagged that technical knowledge and skills should be further developed in the EU, through e.g. ad hoc education or cooperation with non-EU producers.

Some more specific technical barriers linked to the hydrogen decrepitation (HPMS) employed during the INSPIRES project were also raised during the interviews. The presence of contaminants was indicated as a potential issue for the HPMS process, as it risks degrading the quality of recycled magnets. In particular, the use of magnet coatings – i.e. layers of materials often used to protect magnets from corrosion – were mentioned 4 times as a possible source of contamination in magnet recycling. In fact, whereas some can be easily removed before (e.g. through 'sand blasting') or after (e.g. nickel-based coatings) the recycling process, some tend to decompose into small particles and remain in the form of impurities, affecting the quality of recycled magnets. Residues of glues were also mentioned as a potential source of contamination. Finally, a further issue linked specifically with the HPMS process – mentioned by two experts – is magnet oxidation; over time magnets tend to oxidise, and highly oxidised magnets cannot be processed through HPMS without undergoing significant degradation, or the addition of virgin material.

Figure 8. Major barriers per category



Source: Own elaboration.
Note: The numbers in the figure refer to how many interviewed experts mentioned the respective barriers.

6. ASSESSING THE POTENTIAL OF RECYCLING FOR MEETING FUTURE DEMAND FOR NDFEB PERMANENT MAGNETS

In this chapter, we assess current and future demand for NdFeB permanent magnets from selected product categories in the EU, as well as the potential of recycling for contributing to future demand for magnets. For the latter, two scenarios with different levels of ambition were built upon three key variables: collection rates of EoL products for recycling in the EU, efficiency rates of product disassembly and recycling efficiency rate. As described below, a number of assumptions on the different applications employing NdFeB magnets – based on the literature and interviews with experts – were considered when carrying out the analysis.

This forward-looking exercise serves a twofold purpose. First, it aims to identify some of the major streams of EoL products that could potentially feed the future magnet recycling industry. As discussed in the previous chapter and as raised by various authors[26], the uncertainty regarding the volume and the composition of future EoL streams represents in fact one of the major barriers to the establishment of an NdFeB magnet recycling value chain. Secondly, it provides an indication of the extent to which recycling of magnets could compensate the future increased demand for NdFeB magnets in the EU in the short, medium and long term, provided that the barriers described in the previous section were addressed and that a viable supply chain for recovered magnets was to be established in the EU. The overall objective is to provide useful insights and messages for policymakers designing policies in this field and industry actors making investment decisions in the recycling of NdFeB magnets.

6.1 Methodology for the scenario analysis

The scenario analysis was developed through the following steps. In a first stage, the overall demand of magnets arising from 28 major NdFeB applications was estimated for the years 2020-2050. The applications of interest were selected based on a review of the existing literature on magnets, insights from the INSPIRES projects and inputs from interviewed experts. They are reported in Table 2, aggregated by application category[27].

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[26] See, among others, van Nielen et al. (2021).

[27] Due to the very high number of current NdFeB magnet applications and the limited available data in some cases, it should be noted several of them could not be included in the analysis. As such, the results reported in Chapter 6.3 should not be considered as representative of the entire NdFeB magnet market. Additional applications employing NdFeB magnets which have not been assessed include aeronautics applications, sensors, energy storage systems, other electrical equipment (e.g. electric drills), other consumer electronics (e.g. tablets, game consoles, MP3 players etc.) other industrial applications (e.g. extruders, fans, conveyers, crane and hoist systems, winders and printing presses) and other transport applications (e.g. trains) (Schulze et al., 2016; Elwert et al., 2018; Marscheider-Weidemann et al., 2021).

Table 2. NdFeB magnets containing applications included in the analysis

Application category	Applications
Mobility applications	Conventional vehicles, electric vehicles (EVs), electric bicycles, electric scooters, electric motorcycles
Energy applications	Offshore wind turbines, onshore wind turbines
Consumer electronics	Desktop computers, laptops, smartphones, printers, digital cameras, electric shavers
Acoustic devices	Headphones & earphones, microphones, loudspeakers
Home appliances	Washing and drying machines, air conditioners, refrigerators, dishwashing machines, microwaves, vacuum cleaners
Industrial applications	Industrial motors, industrial pumps, industrial robots
Medical applications	Magnetic resonance imaging (MRI)

Source: Own elaboration.

NdFeB magnets demand for each application (*i*) in year t was determined by the following formula:

$$NdFeB\ magnets\ demand_{i,t} = market\ size_{i,t} * NdFeB\ adoption\ rate_{i,t} * NdFeB\ magnet\ weight_{i,t}$$

where the adoption rate refers to the share of products assessed that actually employ NdFeB magnets[28], the market size indicates the number of units of a product entering the EU market in a specific year and magnet weight express the overall amount of NdFeB magnets contained in said product. Past and current market size of each application were primarily determined based on Prodcom (Eurostat, 2022a) data and through the 'apparent consumption' calculation method (Forti et. al, 2018), whereby market size of application *i* in year *t* is determined by:

$$Market\ size_{i,t} = EU\ production_{i,t} + EU\ imports_{i,t} - EU\ exports\ _{i,t}$$

For some applications, annual sales or installations data (e.g., for wind turbines) from specific institutional sources were used instead of Prodcom to determine past and current market size. In these cases, the alternative source in reported in the assumptions (see Chapter 6.2).

Future market trajectories for each application were estimated based on historical market trends and by means of regression models. More specifically, logistic growth models were employed for emerging low-carbon applications – such as EVs, electric bicycles and wind turbines – for which an initial exponential uptake is expected to occur in the first development years, followed by a gradual market slowdown. Where available, forecasts developed by other authors where also taken into account for these applications. For all others, a simple linear

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[28] As explained in Chapter 3, different types of permanent magnets exist on the market. For the purpose of this analysis, only NdFeB permanent magnets were take into consideration.

regression was used in case of an upward sloping growth path, and an exponential decay model where a decreasing market trajectory was recorded in the past. The projected market developments for all applications are reported in the Appendix.

In a second step, the overall number of magnets reaching end-of-life (EoL) throughout the timeframe of interest was estimated. This quantity, which could be defined as the 'theoretical recycling potential' (TRP) (Reimer et al., 2018; Elwert et al. 2018), gives an indication of the maximum number of magnets available to enter the recycling chain) in any given time.

In a third step, two alternative scenarios – scenario 1 and scenario 2 – were built to estimate the amount of magnet material potentially recovered through recycling in any given year considered (i.e., the magnet secondary supply, or 'practical recycling potential'), with scenario 2 being the more ambitious one. These scenarios were built upon three variables, reflecting the three broad stages of the recycling chain: i) the collection rate, i.e. the share of products reaching end of life that are collected with the intent of being recycled in the EU; ii) the dismantling efficiency rate, which represents the portion of material of interest (in this case, NdFeB magnets) which is successfully extracted during the dismantling process; and iii) the recycling efficiency (or recovery) rate, that is the share of material physically recovered throughout the actual recycling process.

$$\begin{aligned} NdFeB\ magnets\ secondary\ supply_{i,t} \\ = TRP_{i,t} * collection\ rate_i * dismantling\ efficiency\ rate\ _i \\ * recycling\ efficiency\ rate\ _i \end{aligned}$$

Importantly, while product-specific (or product group-specific) collection and extraction efficiency rate were considered throughout the analysis, the same recycling efficiency rates – 85 % for scenario 1 and 99 % for scenario 2 – were applied consistently for all applications assessed.

As a final step, the aggregate NdFeB magnet secondary supply was compared with the aggregate NdFeB demand, in order to assess the extent to which recycling can contribute to future demand for NdFeB magnets.

6.2 Assumptions and variables

6.2.1 Electric vehicles

In our analysis, the electric vehicles (EVs) applications category includes both hybrid (HEVs) and battery electric vehicles (BEVs). Today, between 90 % to 95 % of EVs are typically assumed to use permanent magnet-based motors, due to higher efficiency compared to alternative technologies (Alves Dias et al., 2020; Gauß et al., 2021). On this basis, we assumed that 93 % of EVs use such magnet motors. In terms of vehicle lifetime, figures in the literature range between 10 to 16 years, although the upper bound figure usually accounts for second or more uses of the vehicle (Alves Dias et al., 2020; Gauß et al., 2021; Filippas et al., 2020; Shulze et al., 2016; Sekine et al., 2017). An average lifetime of 13 years was thus assumed for this assessment. Permanent magnets used in EVs weigh between 1.25-2.25 kg with HEVs usually employing lighter ones (Yang et al. 2017; Filippas et al., 2020; Reimer et al, 2018; Sekine et al., 2017). Due to the high operating temperature, EV propulsion motors are among the applications with higher Dy content (Binnemans et al., 2013; Reimer et. al, 2018). For our scenarios, we assumed that EVs use on average 1.9 kg of magnets (which includes auxiliary ones), comprised of 23 % Nd and 6 % Dy.

Historical data on EV sales were retrieved from the European Environmental Agency (2021). Several scenarios on future EV market developments with different levels of ambition were found in the literature. At the lower bound, Wood McKenzie (2020) expects EU EV sales to increase to up to slightly less than 7 million vehicles *per annum* by around 2030, and to stabilise thereafter. Much higher figures are reported by BloombergNEF (2022), which expects sales to exceed 10 million in 2030, and 15 million in 2040. Irrespective of the number of sales, all scenarios report a rapid growth up to 2035, which slows down (or stabilises) afterwards. For our scenario, we assumed intermediate (yet still significant) EV market growth, with annual sales reaching 8 million vehicles in 2030 and stabilising at around 11 million from 2040 onwards[29].

With regard to the variables used for the scenarios, collection rates are generally assumed to range between 90 % and 100 % for both electric and conventional end-of-life vehicles (ELV) (Ciacci et al, 2019; Shulze et al., 2016; Rademaker et al., 2013). Nevertheless, such figures do not usually account for ELV of unknown whereabouts (about one third of the total) and extra-EU export, which based on Mehlhart et al. (2017) we estimate at 15 %-20 % of ELV of known whereabouts. Therefore, a 60 % collection rate for recycling in the EU was assumed for the less optimistic scenario 1, and 90 % for the more ambitious scenario 2. With regard to disassembly efficiency, Shulze et al. (2016) assumes it to reach 90 % which was used for scenario 1. Given that some marginal improvements can be expected with the further establishment of the EV market a 95 % disassembly efficiency rate was assumed for the more ambitious scenario 2.

6.2.2 Wind Turbines

Since the early 2000s, permanent magnets have been increasingly employed for wind turbines, particularly offshore. Thanks to their high strength-to-weight ratio, permanent magnets allow for smaller generators with higher power density and higher efficiency. Moreover, since a direct drive system can be used in place of a gearbox mechanisms, permanent magnet-based generators lead to lower maintenance requirements, which is particularly useful for offshore wind turbines (Centre for Sustainable Energy, 2017). The performance benefits of using permanent magnet-based wind turbines have also been highlighted during the expert interviews. More specifically, there are two types of wind turbine configurations with integrated permanent magnets: direct-drive turbines based on permanent magnet synchronous generators (DD-PMSG) and hybrid drives turbines combining both gearboxes and

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[29] For more details on market evolution, please refer to the Appendix.

(small) permanent magnet generators (GB-PMSG) (Månberger & Stenqvist, 2018; Carrara et. al, 2020). According to Carrara et al. (2020), to date virtually all offshore wind turbines employ one of these two configurations (roughly 75 % DD-PMSG and 25 % GB-PMSG), whereas for onshore wind farms the share is significantly lower (5 % DD-PMSG and 20 % GB-PMSG) (Carrara et al., 2020). However, permanent magnet-based configurations are expected to decline among offshore turbines and increase among onshore ones in the future.

The weight of magnets used within wind turbines can vary greatly, ranging from only 80 kg per MW in hybrid turbines to up to 700 kg/MW for larger turbines (Rademaker et al., 2013; Pavel et al., 2017; Centre for Sustainable Energy, 2017). Unlike other applications considered in this analysis, the average magnet weight in wind turbines was determined on a yearly basis, based on the magnet weights in different sub-technologies as reported by Reimer et al. (2018) (160 kg/MW for hybrid drives turbines, and 650 kg/MW for direct drives turbines) and on the evolution of said sub-technologies as reported by Carrara et al. (2020) in the medium demand scenario[30]. The assumed REE content was 28.5 % of Nd and 4.5 % of Dy (Rabe et al., 2017), while the average lifetime was 25 years for onshore wind turbines, and 30 years for offshore ones (Carrara et al., 2020; Bobba et al, 2020).

In terms of market development, historical data on both onshore and offshore annual installations were retrieved from WindEurope (2017; 2022. Several estimates of future market evolution are available in the literature. For offshore wind, Carrara et al. (2022) [31] estimate annual new installations to reach 9-10 GW in 2026 in their medium- and high-demand scenario, which is in line with figures provided by WindEWurope (2022), and then experience a linear increase of 25-27 GW in 2050. GWEC (2022) foresees a much quicker uptake and estimates that current national and regional target in EU will lead annual offshore installations to exceed 29 GW by 2031. Similar to the EVs, we assumed an intermediate development path based on the above projections. For onshore wind, an intermediate trajectory between the medium and high demand scenarios of Carrara et al. (2022) was taken into account.

As raised by the interviewed experts, recycling rates for wind turbine magnets can be expected to be higher than other applications, as larger magnets will likely be more attractive for recyclers and, despite some technical difficulties (linked to e.g. the need to demagnetise magnets on site), more accessible. In line with figures typically found in the literature, we therefore assumed collection rates ranging between 90 % and 99 %, and disassembly efficiency rates ranging between 90 to 95% (Shulze et al., 2016; Ciacci et al., 2019; Reimer et al., 2018).

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[30] This approach is more straightforward from a material flow analysis standpoint, as it does not require an explicit definition of the adoption rate. However, it should be noted that since NdFeB magnet-free sub-technologies are factored in the calculation, the resulting average does not represent the actual average weight of magnets used in wind turbines. Moreover, since no disaggregation among wind turbines sub-technologies was found for years prior to 2018, the 2020s values were considered for this timeframe. For more details, please refer to the table in the Appendix.

[31] Only the medium and high demand scenario were accounted for in this assessment.

6.2.3 Conventional vehicles

Conventional (i.e., internal combustion engine (ICE)) vehicles contain around 40 'auxiliary' motors equipped with permanent magnets, used amongst others for electric power steering (EPS), starter engines, electric windows and speakers. In total, between 175 and 250 grams of permanent magnets are usually embedded in each vehicle (Yang et al., 2017; Reimer, 2018; Shulze et al., 2016). For our scenarios, we assumed an average magnet content of 225 grams per vehicle, consisting of 28 % Nd and 4 % Dy (Reimer et al., 2018; Sekine et al., 2017). In terms of future market trajectory, in line with the EU's commitment to reach a zero-emission road mobility by 2035[32] we assumed total ICE vehicles sales to linearly decrease from the current 10.5 million (ACEA, 2022; EEA, 2022) to 0 in 2035.

The average lifetime of conventional vehicles is assumed to be 12 years – only slightly lower than EVs (Ciacci et al., 2019). With regard to the adoption rate, based on Habib et al. (2014b) we assumed that the share of vehicles employing NdFeB magnets was 25 % prior to 2005, this then increased to 50 % by 2012 and again to 75 % from 2013 onwards.

Although fairly high recovery and recycling rates are usually reported for ELV[33], such rates do not usually account for magnet material which is often lost within ferrous or non-ferrous scrap during the dismantling process due to low concentration and high dispersion in the vehicles (Yang et. Al., 2017). Therefore, based on Shulze et al. (2016)[34], we assumed the disassembly efficiency rate to range between 40 % and 60 % in the two scenarios. Following the same rationale used for EVs, 60 % and 90 % collection rates was assumed for recycling scenario 1 and 2, respectively.

6.2.4 Consumer electronics

Consumer electronics have long been among the largest applications for NdFeB permanent magnets. In our analysis, this group encompasses smartphones, laptops, desktop computers, printers, digital cameras and electric shavers[35]. In laptop and desktop computers, magnets are mostly used for the voice coil motors in hard disk drives (HDDs), with an average weight of 5 g for laptops and 13 g for desktop computers (Glöser-Chahoud et al., 2016; Sekine et al., 2017; Habib et al., 2014b). In smartphones, about 1 g of magnetic material is usually incorporated in

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[32] As part of the Fit For 55 package, the European Commission included a proposal to revise current CO2 emissions standards for cars and vans, which entail the 100 % emission reduction target to be achieved by 2035. A common agreement on the proposal was reached by the European Council and the European Parliament in October 2022.

[33] Current ELV recovery and recycling rates stand above the targets set by EU legislation, with an average of 95.1 % reuse and recovery rate and 89 % reuse and recycling rate of ELV parts and components (Eurostat, 2021).

[34] In the assessment by Shulze et al. (2016) conventional vehicles magnets are included within the 'other motors category', whose disassembly efficiency rate is assumed at 40%.

[35] It should be noted that several other items – including tablets, MP3 players or other electromechanical hand tools – would likely fall within the group of consumer electronics employing NdFeB magnets. However, due to limited data available on such applications, they have not been included in the assessment. In our study, acoustic devices such as loudspeakers and headphones have been assessed separately within a self-standing application category.

each device, typically along camera lenses and in sound systems (Singh et al., 2018; Glöser-Chahoud et al., 2016; Schulze et al., 2016). In printers and digital cameras, an average permanent magnet content of 15 g and 5 g respectively was assumed (Glöser-Chahoud et al., 2016). Finally, electric shavers were assumed to have 1 g of magnets (Habib et al. 2014b).

In terms of product lifetime, laptop and desktop computers were assumed to last for 7 and 8 years on average, respectively (Habib et al., 2014b; Sekine et al., 2017). For smartphones, the assumed average lifetime was however 3 years (Rizos et al., 2019). Printers were assumed to be disposed after 5 years of use (Song et al., 2016), whereas for digital cameras and electric shavers the average service life was assumed at 6 years for the first (Yamamoto et al., 2021) and 4 years for the latter (Habib et al., 2014b).

Due to their high strength-to-weight ratio, NdFeB magnets are particularly suitable for consumer electronics, and are therefore typically preferred over market alternatives. This leads to relatively high NdFeB magnet adoption rates, compared to other product groups. One notable exception is represented by laptops, for which the use of HDDs has been gradually phased out in favor of NdFeB-free solid-state disks (SSDs) since the early 2010s. Based on previous estimates (Rademaker et al., 2013; Sprecher et al.,2014), we assumed the NdFeB magnet adoption rate among laptops to be 100 % in the years before 2010, and that it will linearly decrease to 10% towards 2050. Electric shavers also seem to show modest adoption rates (25 %, according to Habib et al., 2014b). For all the other electronics considered, a 100 % adoption rate of was assumed (Glöser-Chahoud et al., 2016).

According to Eurostat (2022b) the current collection rate for IT and telecommunication equipment is 60 %, against a target of 85 % set by the Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU). Therefore, these collection rates were respectively assumed in the recycling scenarios 1 and 2, for all the consumer electronics assessed. In terms of disassembly efficiency, fairly high material losses have been reported in the extraction of magnets from laptop and desktop computer HDDs through shredding, usually in the order of 30 %-40 % (Shulze et al., 2016; Sprecher et al., 2014; Yang et al., 2017). However, significantly lower losses (around 10 %) were demonstrated when applying the HPMS process (Walton et al., 2015). Therefore, an extraction efficiency of 60 % was assumed for the less ambitious recycling scenario (1), and of 90 % for the more ambitious one (scenario 2) for these two products. Given the similarity in terms of magnet size and the general lack of data on the extraction of magnets for the other electronics, the same disassembly efficiency rates were applied for the whole product group.

6.2.5 Acoustic devices

Besides the above-mentioned consumer electronics, permanent magnets are also widely employed in acoustic devices such as headphones, microphones and loudspeakers. More specifically, magnets are used for acoustic transducers, i.e. the technologies that convert electric signals into sound and vice versa. The magnet weight in such devices can vary significantly, ranging from 300 grams in large speakers to less than a gram in headphones

(Shulze et al., 2016). For our estimations, we assumed an average of 26 g for loudspeaker magnets (Glöser-Chahoud et al., 2016; Habib et al., 2014b) and 1.65 g for headphone ones (Shulze et al., 2016; Glöser-Chahoud et al., 2016). The magnet content of microphones was assumed to be equal to that of headphones.

There is divergent evidence on the share of acoustic devices employing NdFeB magnets. For headphones, although Glöser-Chahoud et al. (2016) report a 30 % adoption rate, the preliminary insights of the INSPIRES project which involved the practical collection and dismantling of acoustic devices indicated a significantly higher share (80 %). In addition, according to interviewed experts an even larger adoption rate can be foreseen for the newest devices. Based on these insights, an NdFeB magnet adoption rate growing from 30 % in the years prior to 2015 to 80% from 2025 onwards was assumed. Following a similar rationale, a lower yet still increasing adoption rate was assumed for loudspeakers, starting from 15 % in the pre-2015 years and reaching 40 % after 2035 (Glöser-Chahoud et al.,2016; Elwert et al., 2018). Due to the lack of data, the same adoption rate of headphones was assumed for microphones.

The same end-of-life collection rates of consumer electronics were considered when building the recycling scenarios. In terms of dismantling efficiency, insights from the INSPIRES project suggest that extraction of small magnets from headphones could be performed with relatively low material losses (from 5 % to 15 %). However, significantly higher material losses were reported by Shulze et al. (2016) for acoustic transducers. Taking this into account, the same dismantling efficiency rates as consumer electronics were considered for our scenarios (i.e., 60 % and 90 % for the low and high ambition scenarios 1 and 2, respectively).

6.2.6 Home appliances

NdFeB magnets can be found in the motors of a wide range of home appliances. Among these, our analysis includes air conditioners, refrigerators, dishwashers, vacuum cleaners, microwaves and washing and drying machines. Based on preliminary insights from the INSPIRES project and on data retrieved form the literature, we assumed an average magnet content of around 200 g in refrigerators, 325 g in air conditioners, 50 g in dishwashing machines, 135 g in washing and drying machines[36], 80 g in vacuum cleaners and 110 g in microwaves (Habib et al., 2014b; Schulze et al., 2016; Sekine et al., 2017; Yang et al., 2017). In terms of lifetime, washing machines and air conditioners were assumed to last for an average of 12 and 11 years respectively, whereas the useful life of refrigerators was assumed to be15 years (Ciacci et al., 2019; Habib et al., 2014b; Schulze et al., 2016; Sekine et al., 2017). In the absence of data, the lifetime figures for washing machines were applied for dishwashing machines. A lifetime of 8 years was assumed for microwaves (Habib et al., 2014b; Yamamoto et al., 2021), and 7 years for vacuum cleaners (Habib et al., 2014b).

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[36] Habib et al. (2014b) reports an average NdFeB magnet weight of washing machines of 1.04 kg. However, due to significant inconsistency with other available estimates found in the literature, this figure was not considered as the average.

The share of home appliances containing NdFeB magnets is rather uncertain, as it might vary significantly depending on e.g. the geographical scope of interest and on the reference year. As for air conditioners and refrigerators, based on Ciacci (2019) we assumed an adoption rate starting at 1 % in 2000, linearly increasing to 10 % in 2015 and stabilising thereafter. A similar trend was also assumed for washing and drying machines, yet with the rate increasing from 1 % to 25 % in the years between 2000 and 2015 (Ciacci et al., 2019)[37]. Due to the absence of data, the same adoption rate of washing machines was considered for dishwashing machines. Finally, a constant 30 % adoption rate was used for microwaves (Habib et al. 2014b), while an 8 % adoption rate was assumed for vacuum cleaners (Crock, 2016).

According to Eurostat (2022b), 48 % of large household appliances reaching EoL are currently collected for recycling. As these applications fall within the scope of the WEEE Directive, the 85 % collection target set by the Directive was used to calculate the optimistic recycling scenario 2, whereas the current collection rate was assumed for the less optimistic scenario 1. With regard to extraction, the INSPIRES project showed that, when manually dismantled, between 75 % and 85 % of the magnets contained in washing machines can be successfully extracted, the remaining share is typically lost during the process. Thus, such bandwidth was considered for the dismantling efficiency rates in the two scenarios.

6.2.7 Electric bicycles, scooters and motorcycles

According to several interviewed experts, significant short-term growth in demand for permanent magnets is likely to arise from emerging low carbon mobility applications such as electric scooters, electric bicycles and electric motorcycles. Magnet weight in these applications typically range between 60 and 350 g, with an estimated average of 270 g (Shulze et al., 2016; Elwert et al., 2018; Yang et al., 2017). In terms of lifetime, an average of 6 years was assumed for all applications (Ciacci et al., 2019; Shulze et al. 2016).

With regard to the adoption rate, Shulze et al. (2016) assumes that 100 % of electric two-wheel vehicles (i.e., all of the above applications) produced from 2020 onwards employ NdFeB magnets. Elwert et al. (2018) confirm this for electric bicycles only, however mentioning that only half of them were using NdFeB magnets before 2015. Assuming that this assumption can be extended to electric scooters and electric motorcycles as well, we therefore consider the adoption rate of this group of applications to increase from 50 % in the years before 2015 to 75 % in the 2015-2020 period and 100 % from 2020 onwards.

Although electric bicycles and other two-wheel vehicles are not explicitly mentioned within the scope of the WEEE Directive (Directive 2012/19/EU), these applications have often been included in the scope of the WEEE legislation at national level[38]. Thus, in the absence of data

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[37] It should be noted that preliminary results from INPIRES showed that only 2 % of dismantled washing machines and none of dismantled air conditioners contained NdFeB magnets. Nonetheless, since such figure refers to the very specific INSPIRES project context (i.e., the Slovenian market) those figures were not considered as representative of the whole European market.

[38] For instance, this is the case in Germany and the Netherlands.

at EU level, we assumed that the collection rates of these applications will likely mirror those of other EEE in the coming years, especially relatively large ones like home appliances. For this reason, a 50 % collection rate was assumed for the lower bound of the range, and 80 % (as assumed by Shulze et al., 2016) for the upper one. As for the dismantling efficiency, the 90 % rate used by Shulze et al. (2016) was kept for scenario 2, and 75 % – i.e. close to that of home appliances – was instead used for scenario 1.

6.2.8 Industrial applications

Industrial applications employing NdFeB magnets include robots, motors and pumps. For industrial robots, used primarily in the automotive and electronics sector, Sekine et al. (2017) reports NdFeb magnet weights ranging from 0.56 kg to as high as 3.36 kg per unit (averaging 1.96 kg), a lifetime of 11.7 years and a 100 % adoption rate. With regard to industrial pumps and motors, consulted experts reported average NdFeB magnet weights of 35 g for the former and 175 g for the latter, while the reported NdFeB magnet adoption rates were 10 % for industrial pumps and 2 % for industrial motors. Based on the same consultations and on Habib et al. (2014b), we assumed a lifetime of 21 years for industrial pumps, and 17 years for industrial motors. While market data for industrial robots and pumps were retrieved from the Prodcom database (Eurostat, 2022a), the market evolution of industrial motors was built upon Elwert et al. (2018) who estimated the theoretical recycling potential of NdFeB magnets from this application.

Due to the general paucity of information regarding the EoL phase of industrial applications, collection and dismantling efficiency rates were retrieved from Shulze et al. (2016), who include them within the broad ‘other motors’ application category (80% collection rates, 40% disassembly efficiency rate). To define alternative scenarios’ rates, a 15% uncertainty was applied, leading to a 65 – 95% range for the collection rate and 25 – 55% for the dismantling efficiency rate.

6.2.9 Medical applications (MRI)

Magnetic resonance imaging (MRI) is a medical scanner that typically embodies significant quantities of magnets, usually between 700 and 3 000 kg (Shulze et al., 2016). Based on data from the literature, we assumed an average NdFeB magnet weight per scanner of 1 700 kg, a 10 lyear ifetime and a 10 % NdFeB magnet adoption rate (Ciacci et al., 2019; Habib et al., 2019b; Shulze et al., 2016).

Tables 3 and 4 below summarise all assumptions and variables used for this assessment.

Table 3. Assumptions based on project's evidence and literature

				Collection rate (%)		Disassembly efficiency rate (%)	
Application category	Application	Lifetime (years)	Magnet weight (kg or kg/MW)	Sc.1	Sc.2	Sc.1	Sc.2
Mobility applications	EVs	13	1,9	50	90	85	95
	Conventional vehicles	12	0,225	50	90	40	60
	Electric bicycles	6	0,27	50	90	75	90
	Electric scooters	6	0,27	50	90	75	90
	Electric motorbikes	6	0,27	50	90	75	90
Energy applications	Wind turbines (onshore)	25	160*	90	99	90	95
	Wind turbines (offshore)	30	650**	90	99	90	95
Consumer electronics	Desktop computers	8	0,013	60	85	60	90
	Laptop computers	6	0,005	60	85	60	90
	Smartphones	3	0,001	60	85	60	90
	Printers	5	0.015	60	85	60	90
	Digital cameras	6	0.005	60	85	60	90
	Electric shavers	4	0.001	60	85	60	90
Acoustic devices	Headphones & earphones	9	0,0017	60	85	60	90
	Microphones	9	0,0017	60	85	60	90
	Loudspeakers	9	0,026	60	85	60	90
Home appliances	Washing and drying machines	12	0,135	48	85	75	90
	Air conditioners	11	0,325	48	85	75	90
	Refrigerators	15	0,2	48	85	75	90
	Dishwashing machines	12	0,05	48	85	75	90
Industrial applications	Industrial robots	12	8,5	40	80	40	60
	Industrial pumps	22	0,35	40	80	40	60
	Industrial motors	13	0,175	40	80	40	60

Notes: *Hybrid drive; ** Direct drive.

Table 4. NdFeB magnet adoption rates based on project's evidence and literature, (%)

Application category	Application	2000 2005	2005 2010	2010 2015	2015 2020	2020 2025	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Mobility applications	EVs	93	93	93	93	93	93	93	93	93	93
	Conventional vehicles	25	25	38	50	75	75	75	75	75	75
	Electric bicycles	50	50	50	75	100	100	100	100	100	100
	Electric scooters	50	50	50	75	100	100	100	100	100	100
	Electric motorbikes	50	50	50	75	100	100	100	100	100	100
Consumer electronics	Desktop computers	100	100	100	100	100	100	100	100	100	100
	Laptop computers	100	100	100	79	58	36	14	10	10	10
	Smartphones	100	100	100	100	100	100	100	100	100	100
	Printers	100	100	100	100	100	100	100	100	100	100
	Digital cameras	100	100	100	100	100	100	100	100	100	100
	Electric shavers	100	100	100	100	100	100	100	100	100	100
Acoustic devices	Headphones & earphones	30	30	30	50	70	80	80	80	80	80
	Microphones	30	30	30	50	70	80	80	80	80	80
	Loudspeakers	15	15	15	20	25	30	35	40	40	40
Home appliances	Washing and drying machines	1	9	17	25	25	25	25	25	25	25
	Air conditioners	1	4	7	10	10	10	10	10	10	10
	Refrigerators	1	4	7	10	10	10	10	10	10	10
	Dishwashing machines	1	9	17	25	25	25	25	25	25	25
	Microwaves	30	30	30	30	30	30	30	30	30	30
	Vacuum cleaners	8	8	8	8	8	8	8	8	8	8
Industrial applications	Industrial robots	100	100	100	100	100	100	100	100	100	100
	Industrial pumps	10	10	10	10	10	10	10	10	10	10
	Industrial motors	2	2	2	2	2	2	2	2	2	2

6.3 Results and discussion

6.3.1 Demand

Figure 9 reports current (2020) and future NdFeB magnet demand for the assessed applications in the EU. As shown, the estimated magnet demand arising from such selected applications amounts to about 12 kt, and therefore represents roughly 68 % of the overall EU NdFeB magnet market[39]. Currently, demand seems to be fairly evenly distributed among the various applications, with the mobility product group accounting for about half of the total. In terms of specific contributions, conventional and electric vehicles are responsible for a considerable share of overall demand (19 % each). Significant magnets demand is also arising from onshore and offshore wind (6 % and 12 %, respectively), home appliances (18 %) and electric bicycles (10 %). Within the home appliances product group, washing and drying machines and refrigerators reported the most significant contribution to overall magnets demand (i.e., 5 % for the former and 4 % for the latter). With regard to consumer electronics and audio devices, they together account for about 10 % of overall demand.

Looking at the future evolution of demand, short term projections show an exponential increase in the years leading to 2030, when total demand is set to triple compared to 2020 levels (i.e., from 12 kt to about 36 kt). In this decade, we expect demand to grow at a compound annual growth rate (CAGR) of 11.3 %. In particular, demand growth will be largely driven by the boom of the EVs sector and, to a lower yet still significant extent, by new wind turbine installations. According to our assumptions, the European EVs market will in fact increase six-fold between 2020 and 2030, moving from 1.3 to 4 million units sold per year in 2025 and to over 8 million by 2030. Wind power generation – both onshore and offshore – is also expected to see a rapid acceleration, with offshore annual installations growing from the 2.9 GW in 2020 to almost 16 GW in 2030, and onshore increasing from 11.8 to 33.4 GW over the same period. The Wind turbine share of total demand will instead reach 33 % in that year (19 % for offshore, 14 % for onshore).

Looking further ahead to 2040 and beyond, demand for NdFeB magnets is projected to gradually decelerate and eventually stabilise. The 2030-2040 decade will still see a sustained, yet slightly slower demand growth, with an overall 42 % increase over the whole period (CAGR: 3.5 %). The EVs and wind power sectors will remain the major demand drivers, recording 38% and 76% growth respectively in magnet demand. Onshore wind in particular is expected to double its magnet demand (from 4.9 to 9.8 kt) due to both significant market expansion and the gradual phasing-out of NdFeB magnet-free sub technologies, as foreseen by Carrera et al. (2020). From 2040 to 2050, our estimates show a significant slowdown in demand, which will nonetheless grow by 12 % over the decade (CAGR: 1.2 %). Such growth will be almost entirely driven by onshore wind, as EV market demand will have stabilised by then. Overall, we estimate

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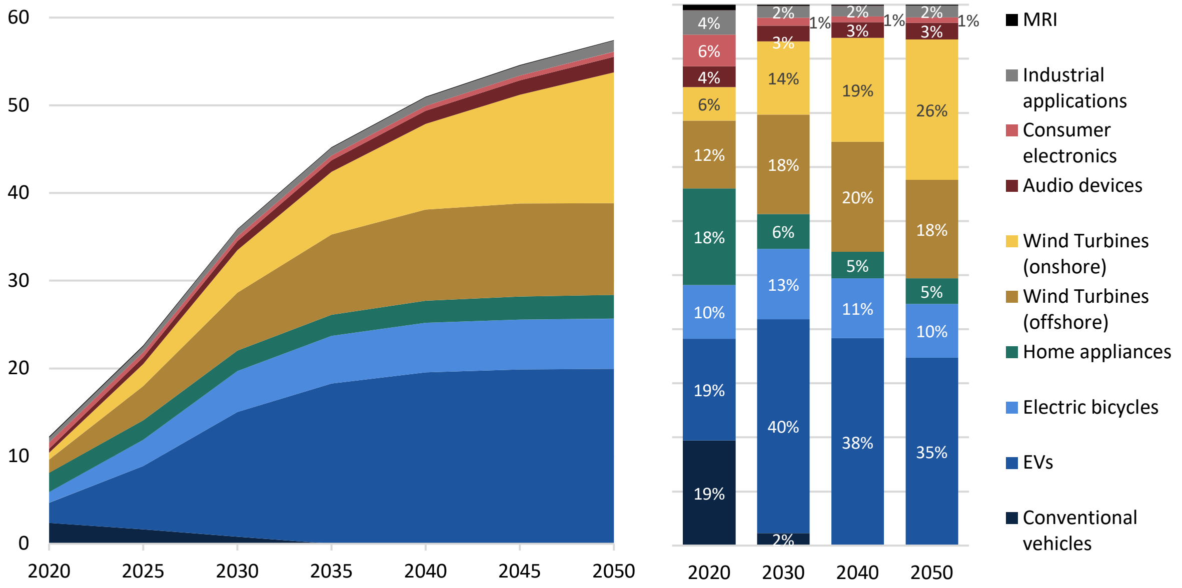
[39] As reported in Chapter 3, current EU NdFeB magnet demand is about 18 kt.

magnet demand from assessed applications to reach about 51 kt by 2040 and 58 kt in 2050. By 2050, wind turbines will represent the largest demand segment among those considered.

Figure 9. NdFeB magnet demand in the EU from selected applications, thousand tonnes (left) and shares (right)



Source: Own elaboration.

Notes: Demand from the mobility and energy product groups has been disaggregated by application for clarity; for the disaggregation of other product groups, please refer to the Appendix. Eectric scooters and motorcycles were excluded from the figure due to negligible volumes.

6.3.2 Theoretical recycling potential

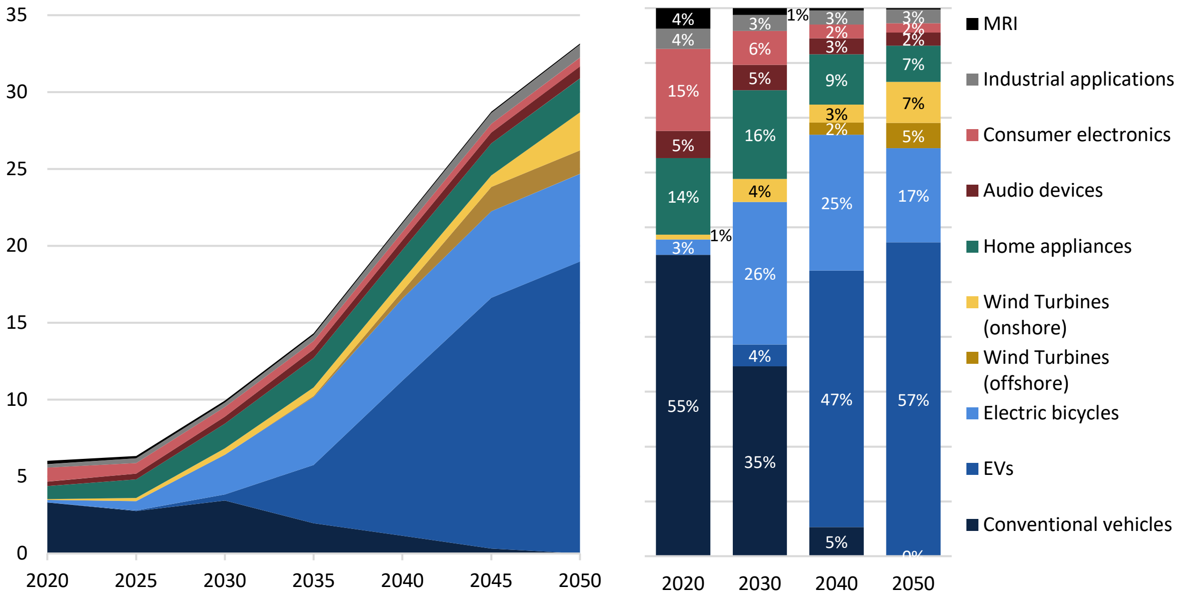
In order to assess the potential contribution that recycling can play in meeting the future surge in demand for NdFeB magnets described above, in this section we will estimate the 'theoretical recycling potential' (TRP), i.e. the overall amount of EoL NdFeB magnets available for recycling at a specific point in time. In the following section, based on this potential, and on the assumptions on the efficiency of the NdFeB magnet recycling chain outlined in the previous chapter, two scenarios on the future potential availability of the secondary supply of NdFeB magnets will be built.

Figure 10 shows the evolution of NdFeB magnet TRP for the assessed applications during the years 2020-2050. As shown, the majority of EoL magnets today come from the mobility sector, and in particular conventional vehicles (55 % of the total). Consumer electronics and audio devices also provide a significant contribution to EoL volumes, accounting together for about 20 % of the total (15 % and 5 %, respectively). Home appliances follow with 14 %. Overall, the TRP was 6 kt in 2020 – that is, roughly half of the total demand for NdFeB magnets in the same year.

The situation described above will likely persist in the years leading to 2030, with the only exception being the significant increase in EoL magnets being generated from electric bicycles. Based on the current and expected future trends of this market, we assume the number of electric bicycles reaching EoL to rapidly increase in the second half of the 2020s, to the point where they will represent the second largest waste stream in 2030 after conventional vehicles (26 % of the total TRP). By 2030, we expect the overall TRP to reach approximately 10 kt, i.e. 27 % of total magnet demand in the same year. In addition to conventional vehicles and electric bicycles, home appliances will represent the largest waste stream of NdFeB magnets in 2030, with about 1.6 kt.

Starting approximately in 2035, a significant number of EVs will start reaching the EoL stage, thereby making significant quantities of NdFeB magnets available for recycling. By 2040, we expect EoL magnets coming from EVs alone to reach about 10 kt per year, about thalf of the total TRP of the same year. From 2040 to 2050, following a similar trajectory to that observed in the years 2030-2040, the TRP will be steadily increasing, reaching over 33 kt in 2050. By then, EVs will account for roughly 57 % of all NdFeB magnet TRP, with the second largest waste stream being represented by electric bicycles (17 %).

Figure 10. NdFeB magnet theoretical recycling potential in the EU from selected applications, thousand tonnes (left) and shares (right)



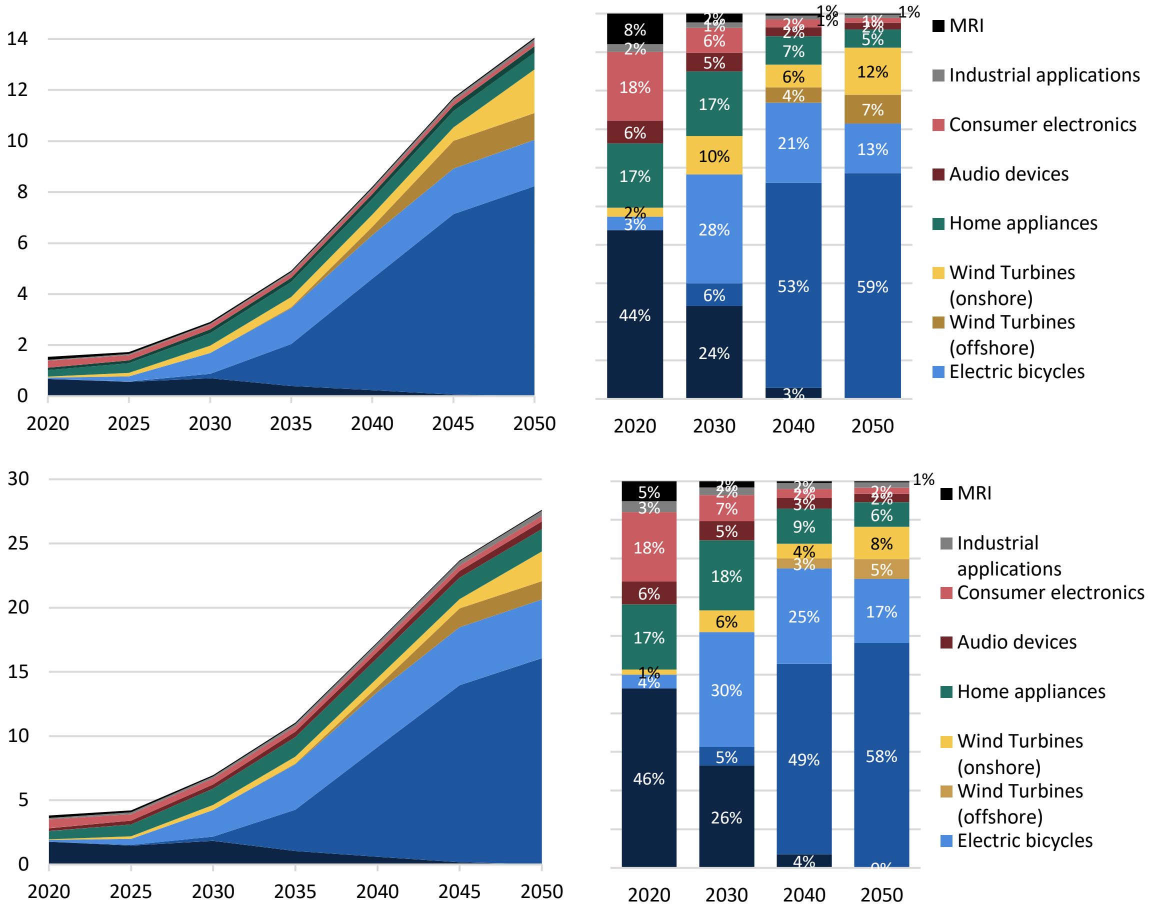
Source: own elaboration.
Notes: TRP from the mobility and energy product groups has been disaggregated by application for clarity; for the disaggregation of other product groups, please refer to the Appendix. Eectric scooters and motorcycles were excluded from the figure due to negligible volumes.

6.3.3 Secondary supply

Based on the above TRP estimates, the secondary supply presented below gives an indication of the amount of NdFeB material that could potentially re-enter the production cycle in the future, accounting for material losses occurring along the main stages of the recycling chain (collection, disassembly and physical recycling). As described in the methodology section, two different scenarios with varying levels of ambition have been built to reflect the uncertainties around these losses.

The evolution of the secondary supply of magnets broken down by application category is illustrated in Figure 11. Irrespective of the scenario considered, the secondary supply of NdFeB magnets is likely to follow a path similar to the TRP, with conventional vehicles, audio devices, consumer electronics and home appliances largely driving in the short term, and EVs and electric bicycles taking over from the early 2030s onwards. Notably, about 30 % of the short-term secondary supply of NdFeB magnets could be generated from home appliances, consumer electronics and audio devices alone. Due to their relatively long lifetime, wind turbines will likely play a marginal role in terms of secondary supply, reaching between 6 % and 10 % in 2030 and 13 %-19 % in 2050.

Figure 11. Potential NdFeB magnet secondary supply in the EU from selected applications in scenario 1 (above) and scenario 2 (below), thousand tonnes (left) and shares (right)

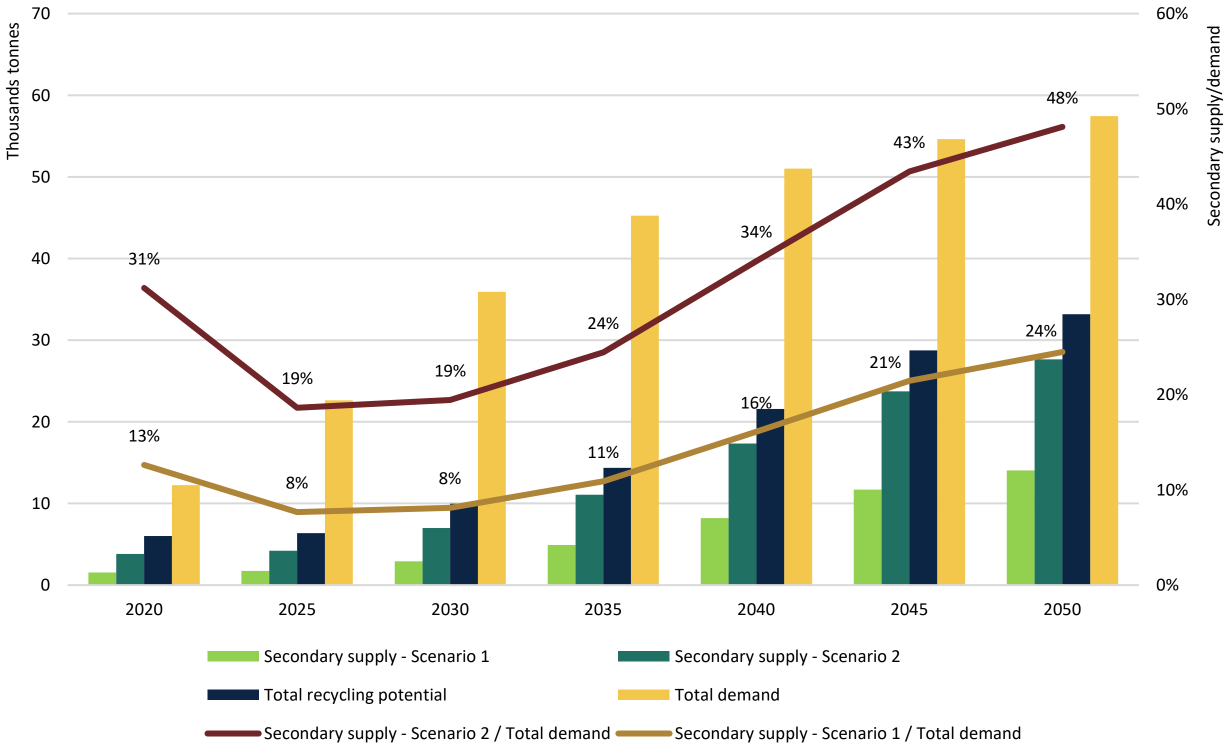


Source: own elaboration.

Notes: Secondary supply from the mobility and energy product groups has been disaggregated by application for clarity. Eectric scooters and motorcycles were excluded from the figure due to negligible volumes

Figure 12 shows the comparison between the aggregate NdFeB magnet demand and secondary supply over time. Based on our results, if a viable NdFeB magnet recycling chain were to be established for the assessed applications in the EU, we could reasonably expect it to contribute 8-19 % of overall NdFeB magnet demand in the short-medium term (2025-2030). As discussed above, conventional vehicles together with audio devices, consumer electronics and home appliances could cover an important part of this demand. Starting approximately in the second half of the 2030s, thanks to both a gradual slowdown in the demand for magnets and the increasing availability of EoL magnets – mostly from EVs and electric bicycles – recycling starts playing an ever-increasing role. In 2040, between 16 % and 34 % of the demand could be met by recycled material, while in 2050 the secondary supply-demand ratio could reach close to 50 % in the most optimistic scenario.

Figure 12. NdFeB magnet aggregate demand, TRP, secondary supply and secondary supply-demand ratio in the EU



Source: own elaboration.

7. CONCLUSIONS AND POLICY RECOMMENDATIONS

Securing access to rare earth elements for permanent magnet production is crucial if the EU is to sustain its green and digital transitions; however, booming global consumption, high import dependency and rising geopolitical instability are exposing the EU to potential supply risks. Recycling rare earth permanent magnets from end-of-life (EoL) products, if systematically implemented, could help mitigate such risks. However, as seen through the lenses of our qualitative analysis and interviews with experts in the field, although technologies for recovering and recycling magnets from EoL applications are already available there are several barriers in place – policy, economic, supply chains and technical – that hinder their wide scale adoption.

With regard to barriers stemming from the existing policy framework, a key recurring one raised by consulted experts refers to the lack of clear labelling or marking requirements on products providing information about magnets. As shown during implementation of the INSPIRES project, this complicates the work of dismantlers and recyclers who need to manually dismantle the devices to verify the presence, location and type of magnet. Insufficient public financial support for recycling processes, the lack of material-specific recycling targets and quotas to boost the development of secondary markets, and the lack of eco-design rules were other key policy-related barriers identified in the analysis. From an economic perspective, the major barriers include the high costs of extraction of magnets from disposed products, the low and/or volatile rare earth prices and the challenging competition with extra-EU magnets and with magnets produced via primary materials. Concerning the supply chain, a prime barrier relates to the absence of a whole supply chain for recovered magnets in Europe due to underdeveloped segments of the value chain such as refining and a magnet manufacturing segment. The lack of transparency and traceability for permanent magnets, possible uncertainties and scepticism about the performance of recycled magnet, a still undeveloped and uncoordinated collection system for EoL products and the current low (and uncertain future) volume of EoL magnets available for recycling also pose challenges to scaling up recycling operations in the EU. Finally, on the technology front, the challenging extraction of magnets from EoL products, some potential technical limitations of the HPMS recycling process (e.g. due to impurities and magnet oxidation) and a general lack of technical knowhow about magnet recycling in the EU compared to other world regions emerged as the most critical barriers.

Looking into the opportunities arising from building an effective magnet recycling chain in the EU, our analysis provides estimates about the future demand for magnets and the potential of recycling to cover such demand. Based on the quantitative assessment, we estimate that under different scenarios with varying levels of ambition recycling could cover between 8 % and 19 % of rare earth magnet material requirements in the short-medium term (i.e., until 2030). In this timeframe, the key product groups providing opportunities for the recycling of rare earth magnets are conventional vehicles, home appliances, consumer electronics and audio devices.

Moving beyond 2030, the share of future demand potentially covered through recycling increases, and in 2050 we estimate it could range between 24 % and 48 %. This dynamic is largely due to future market developments: with the upcoming expansion of relatively new markets such as electromobility and wind turbines, magnet demand will, in fact, significantly outstrip potential magnet secondary supply in the next 5 to 10 years. However, once a larger number of such applications start reaching EoL and demand begins to flatten – i.e. towards the second half of the 2030s – recycling will start to play an increasing role. In the longer term, an ever-increasing number of EoL magnets from disposed EVs, electric bicycles and wind turbines would provide important feedstocks of secondary sources of magnets.

Taking stock of the above, the following recommendations are proposed:

R1. Introduce labelling requirements to improve the transparency of EoL magnets. As shown in our analysis, different types of magnets can be found in disposed products, and magnets' material compositions – even within the same magnet type – can vary significantly. The recycling of magnets especially through the 'short loop' HPMS process, requires a detailed knowledge of EoL magnet types and composition, as well as of the potential presence and type of coatings used. However, the INSPIRES work showed that due to the limited availability of such information, companies currently need to manually disassemble the devices to analyse the magnet and determine whether they are fit for the recycling technology. This is a labour-intensive process that cannot be economically feasible in the absence of external financial support. Introducing transparency requirements (about, e.g. the type of magnet, the location in the product, chemical composition and the presence of coatings) in the form of a label or marking on products could therefore significantly improve the efficiency of the recycling process and provide additional incentives to extract the magnets from EoL devices. Information about magnets could be collected along the value chain through a digital product passport as is currently being planned for batteries in the context of the Battery Regulation.

R2. Develop recycling quotas and targets for magnets. Currently there are limited incentives for recovering magnets from EoL products, and markets for recycled magnets are underdeveloped. Establishing a quota on the level of recycled content in new magnets could provide a demand push and help boost the development of markets for secondary magnets. Such quotas could be accompanied by material-specific recovery targets to encourage recovery of rare earths from EoL applications and support circularity in the sector. The recycling quotas and recovery targets should be ambitious yet realistic, while the industry should be given a trajectory to develop suitable infrastructure and to scale up recycling processes for magnets.

R3. Provide financial support for the establishment of magnet recycling processes in the EU. As emerged during the consultations with experts, currently the recycling of permanent magnets is not financially sustainable outside of publicly funded projects such as INSPIRES. Specifically, the processes of disassembling EoL products and extracting the magnets entail high costs, thereby limiting the profitability of the overall recycling process. Moreover, recycled magnets cannot yet compete with magnets produced through virgin materials. Thus, providing financial support and incentives to recyclers could assist the commercialisation and scale-up of the recycling processes. For instance, this could take the form of investment support for new magnet recycling infrastructure, or tax incentives for products containing recycled magnets. Support should be stronger during the first kick-off period, and be gradually phased off once recycling capacity reaches a sufficient scale and market penetration of recycled magnets increases. In addition, public R&D funding along the whole permanent magnet value chain – from rare earth mining up to magnet production and recycling - should further increase to fill the gap in technical knowledge with extra-EU producers, notably China.

R.4 Establish eco-design requirements to facilitate the extraction of magnets. The difficulty in accessing rare earth magnets from EoL products has been highlighted during the consultations with experts as one of the major technical and economic hurdles for the recycling of magnets. This is because magnet-containing products are typically not designed to take into account further disassembly and recycling of their components. Introducing eco-design requirements for such products and components could therefore facilitate the extraction process, and improve the business case for magnet recycling. In the case of EVs, for instance, the dismantling of rotors to extract magnets – which are typically firmly embedded in them – was noted by experts as a significant obstacle that could be tackled by redesigning the rotors themselves.

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APPENDIX

Table A 1. Wind turbines average magnets' weight assumptions

	Offshore wind				**Onshore wind**			
	Direct-drive	Hybrid drive	Others	Avg magnet weight per installed MW	Direct-drive	Hybrid drive	Others	Avg magnet weight per installed MW
Magnets weight (kg/MW)	650	160	0		650	160	0	
1990	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
1995	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
2000	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
2005	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
2010	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
2015	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
2020	75 %	25 %	0 %	527,5	5 %	20 %	75 %	64,5
2025	68 %	20 %	13 %	470,8	10 %	25 %	65 %	105
2030	60 %	15 %	25 %	414	15 %	30 %	55 %	145,5
2035	59 %	14 %	27 %	405,9	17 %	33 %	51 %	159,3
2040	58 %	13 %	29 %	397,8	18 %	35 %	47 %	173
2045	57 %	12 %	32 %	385,7	19 %	38 %	44 %	183,5
2050	55 %	10 %	35 %	373,5	20 %	40 %	40 %	194

Source: Reimer et al. (2018); Carrara et al. (2020).

Figure A 1. Breakdown of NdFeB magnets demand for home appliances, audio devices, industrial applications and consumer electronics by application (thousand tonnes).

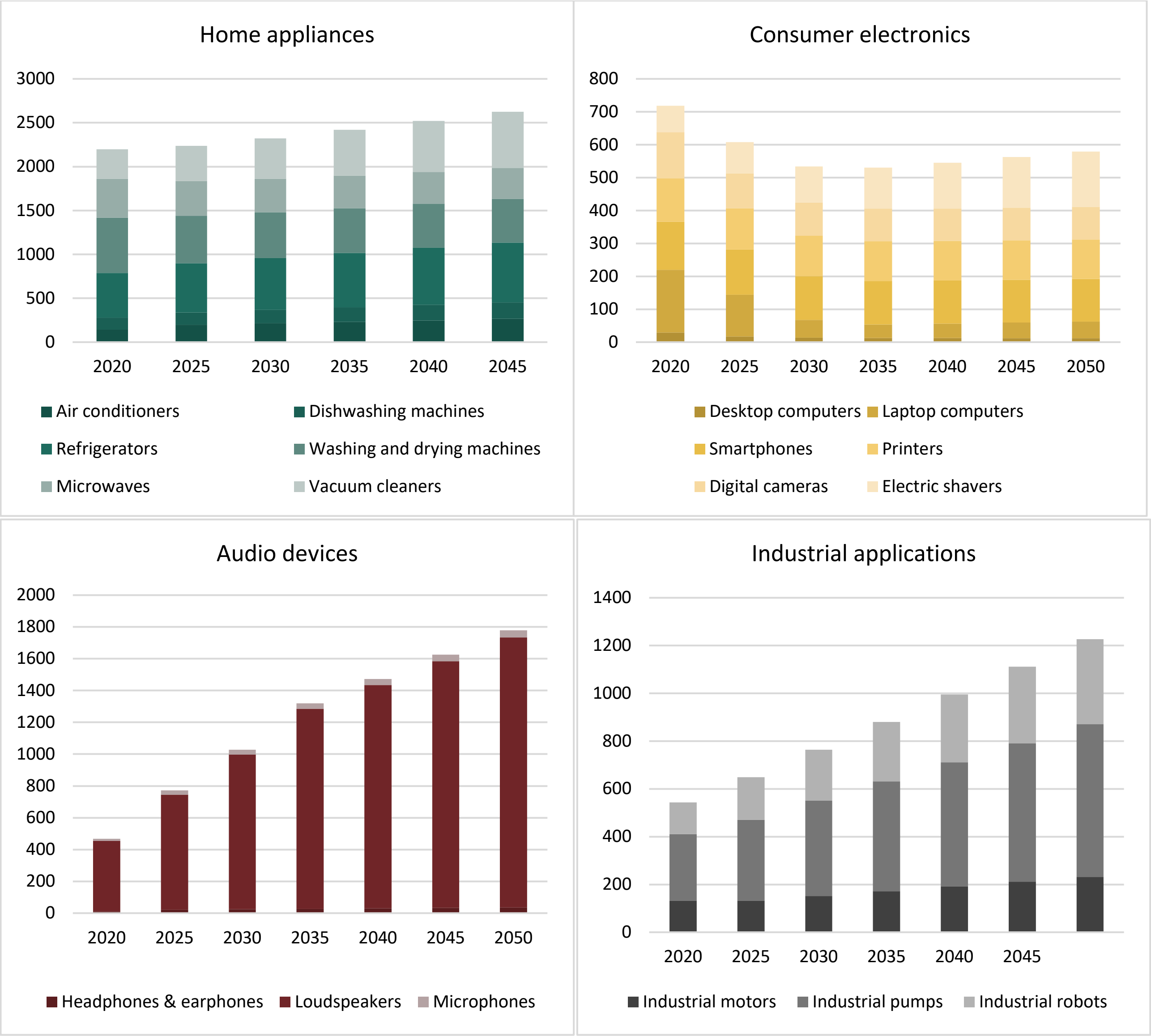


Figure A 2. Breakdown of NdFeB magnets theoretical recycling potential for home appliances, audio devices, industrial applications and consumer electronics by application (thousand tonnes

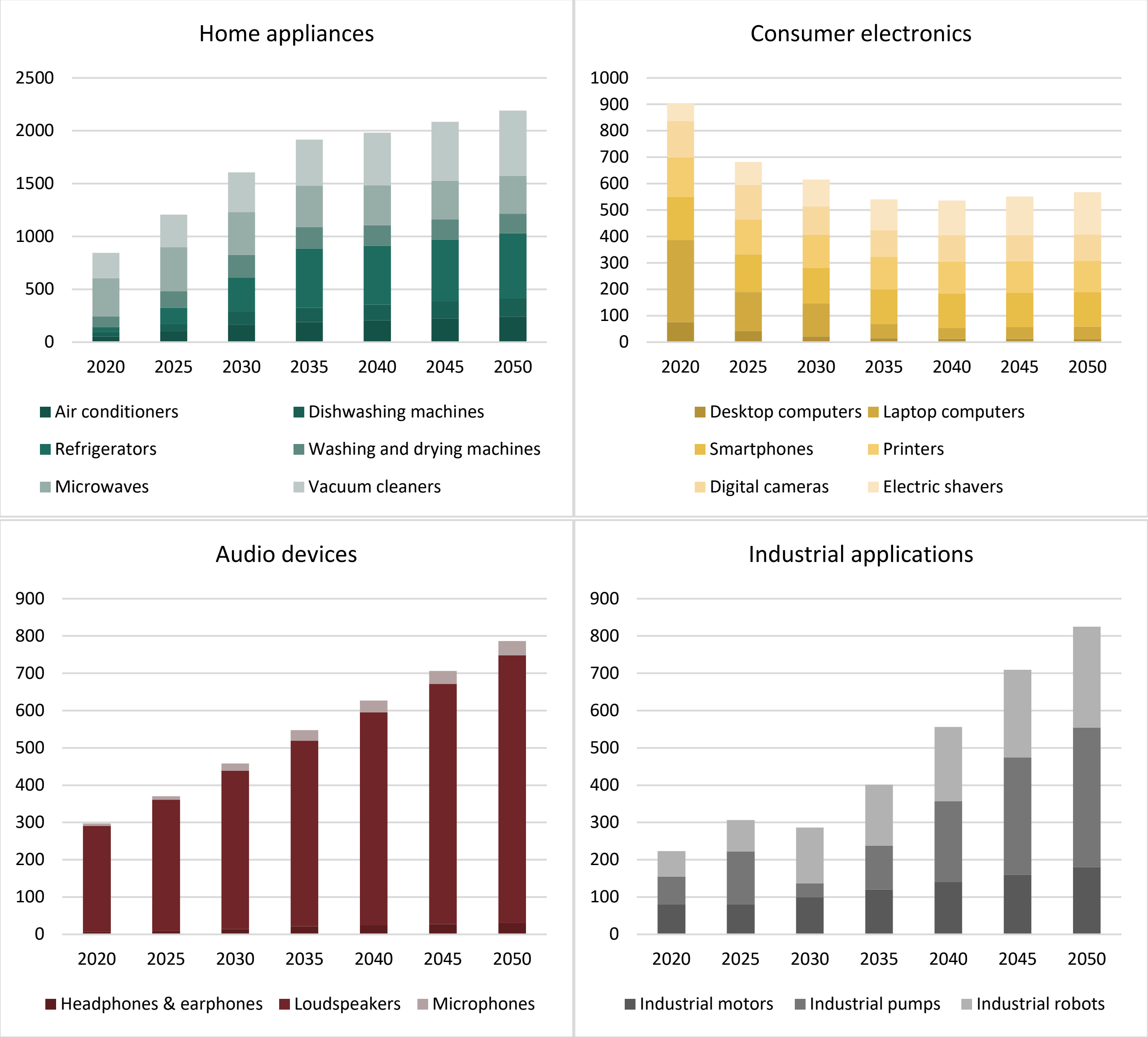
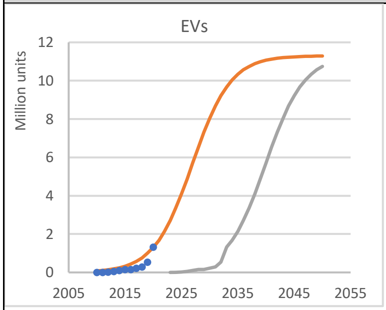
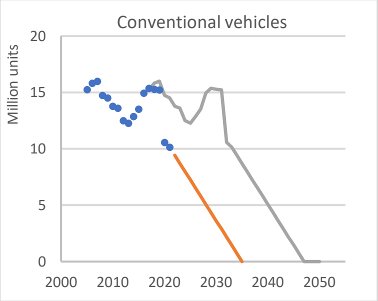


Figure A 3. Historical (blue dots) and estimated future (orange line) markets of assessed products, and EoL products (grey line)

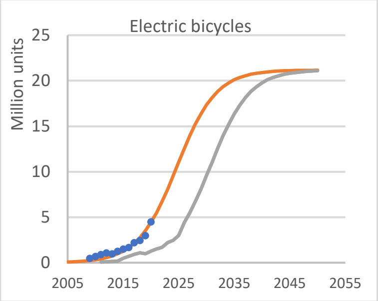
Mobility applications



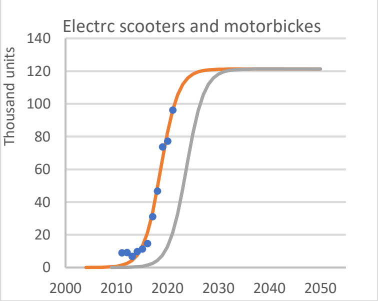
Source: EEA (2021), IEA (2022), Wood McKenzie (2020), BNEF (2022).



Source: ACEA (2022), EEA (2022).

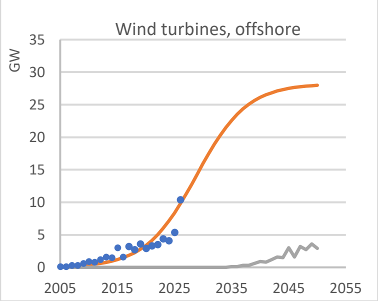


Source: ECF (2020), Statista (2022)

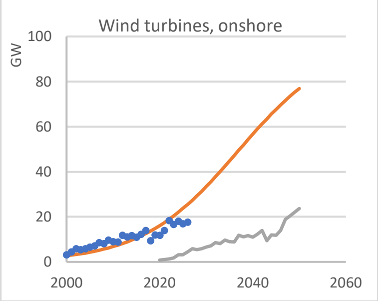


Source: ACEM (2022)

Energy applications

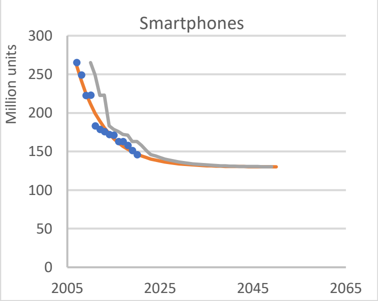


Source: WindEurope (2017;2022), Carrara et al. (2020), GWEC (2022).

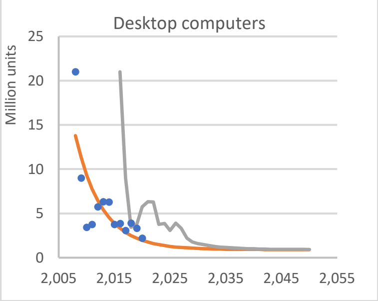


Source: EWEA (2012), WindEurope (2017;2022), Carrara et al. (2020).

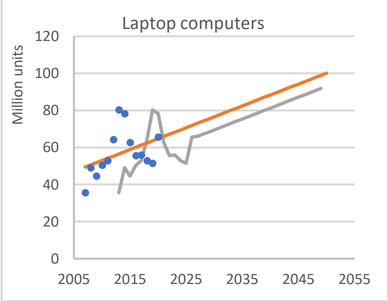
Consumer electronics



Source: Eurostat (2022a)



Source: Eurostat (2022a)



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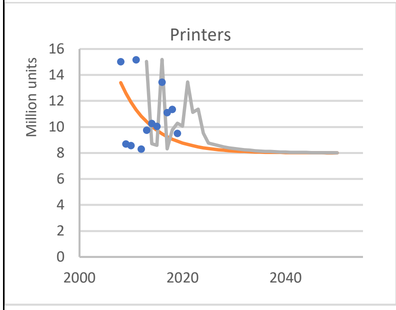

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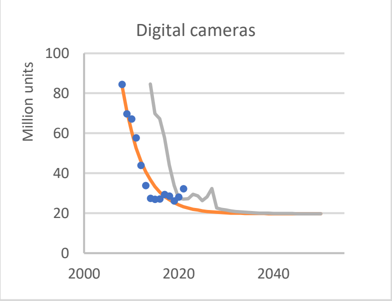

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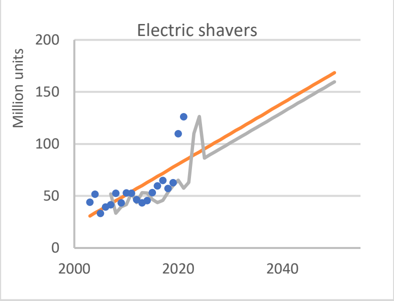
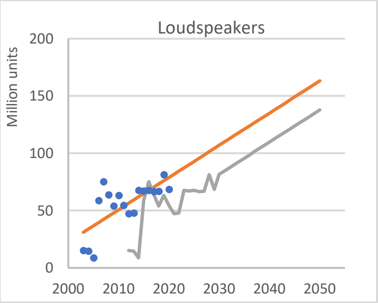


Source: Eurostat (2022a)

Acoustic devices



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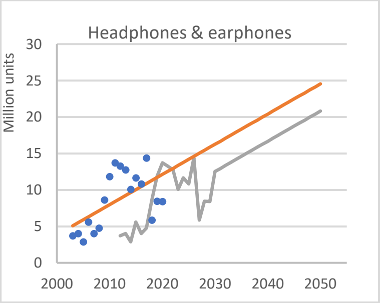

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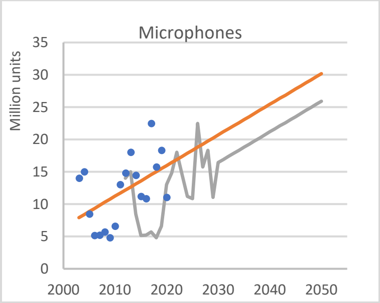

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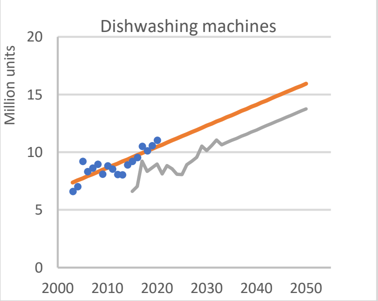
Home appliances



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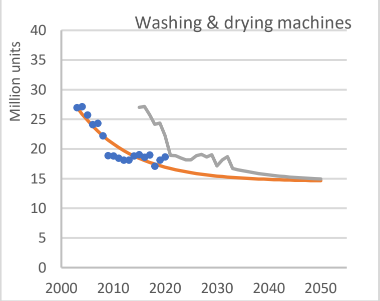

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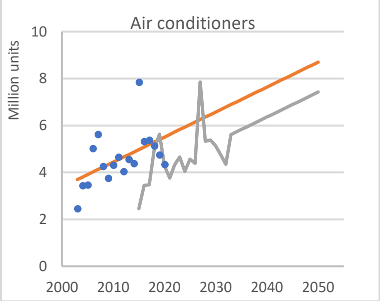

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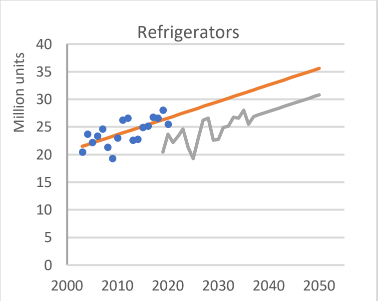

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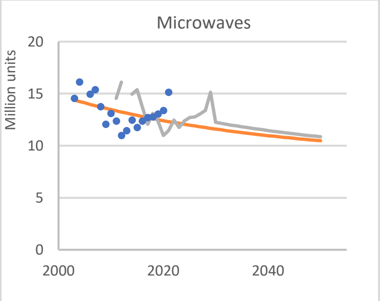

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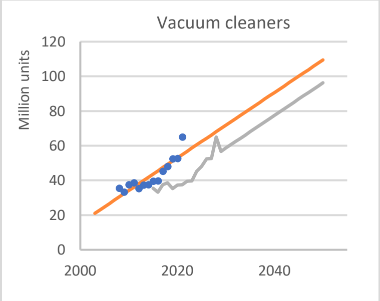
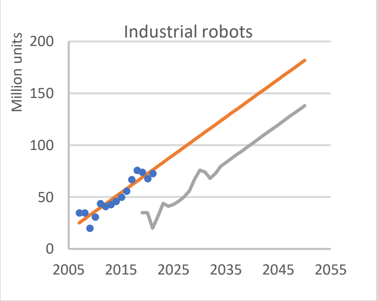
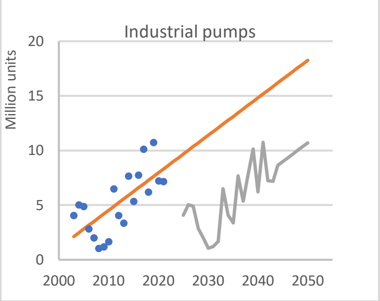


Source: Eurostat (2022a)

Industrial applications



Source: IFR (2021)



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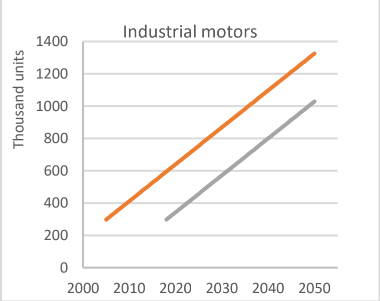

Source: Elwert et al. (2018)

About INSPIRES

Intelligent and Sustainable Processing of Innovative Rare-Earth Magnets

INSPIRES is a project co-funded by the EU that aims to recover and supply rare earths within the EU through radical innovations in the recycling of permanent magnets (PMs) focusing on one of the most readily available sources: home appliances. INSPIRES will optimise methods at industrial scale for sustainable extraction, recycling and use of recycled magnets in new motors. For more information about the project, see: https://www.inspires-magnet.eu/.

Supported by
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Connecting matters
Co-funded by the European Union

The consortium includes leading partners in the development of recycling strategies of PMs, real-life scrapping and waste logistics practitioners, electric motor and white good manufacturers, and sustainability (DTU) and circular economy experts (CEPS). Together the consortium covers the entire magnetic circular supply chain: home appliance recoverers and dismantlers (SUROVINA, ZEOS), NdFeB recyclers (HSPF, CSIC, CNR, JSI), recycled magnet producers (KOLEKTOR), motor developers (DOMEL), home appliance end users (GORENJE).

List of partners

CSIC
Consejo Superior de Investigaciones Científicas

DTU Technical University of Denmark

CEPS

gorenje

KOLEKTOR

HOCHSCHULE PFORZHEIM

ZEOS

Institut "Jožef Stefan" Ljubljana, Slovenija

surovina

DOMEL

CEPS
PLACE DU CONGRES 1
B-1000 BRUSSELS