Schönfeldt, Mario; Diehl, Oliver; Gassmann, Jürgen

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Recycling of NdFeB magnets in Germany

Commissioned study

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Editor:
German Mineral Resources Agency (DERA) at the
Federal Institute for Geosciences and Natural Resources (BGR)
Wilhelmstrasse 25–30
13593 Berlin
Germany

Authors:
Mario Schönfeldt, Oliver Diehl, Jürgen Gassmann

Address:
Fraunhofer Research Institution for Materials Recycling and Resource Strategies IWKS
Aschaffenburger Strasse 121
63457 Hanau
Germany

Contact at DERA:
Marius Kern (marius.kern@bgr.de)
Britta Bookhagen (britta.bookhagen@bgr.de)

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The Federal Institute for Geosciences and Natural Resources is the central geoscientific authority providing advice to the German Federal Government in all geo-relevant questions. It is subordinate to the Federal Ministry for Economic Affairs and Climate Action (BMWK).

Recycling of NdFeB magnets in Germany

Commissioned by the German Mineral Resources Agency
at the Federal Institute for Geosciences and Natural
Resources, Berlin

Fraunhofer
IWKS

Preface

Permanent magnets, especially Neodymium-iron-boron (NdFeB) magnets, are an indispensable component of many modern technologies crucial for energy and mobility transition. Due to their exceptional importance for the European economy, the European Union’s Critical Raw Materials Act (CRMA) also covers the recycling of NdFeB magnets. The demand for elements for these permanent magnets will continue to increase in Europe in the years ahead due to their use in a wide range of applications. Recycling will therefore also play an increasingly important role in Europe.

The German Mineral Resources Agency (DERA) is monitoring primary raw materials and recycled raw materials based on the German government's raw materials strategies from 2010 and 2020 and the measures agreed therein to increase the security of supply for German industry.

This study by the Fraunhofer Research Institution for Materials Recycling and Resource Strategies IWKS is part of DERA’s raw materials monitoring programme and was commissioned by DERA. It provides a comprehensive insight into the current status of NdFeB magnet recycling in Germany, the most important type of permanent magnets. The study centres on the technical processes involved in recycling at the end of a magnet’s life cycle.

The contents of the study help to better comprehend the challenges and opportunities arising during development of recycling processes for NdFeB magnets and to identify possible solutions for sustainable, efficient usage. If NdFeB magnets can be recycled efficiently in the future, this would be a crucial and urgently needed step towards diversifying the supply of rare earths for Germany and the European Union.

Dr. Peter Buchholz,
Head of DERA

German Mineral Resources Agency (DERA) at the
Federal Institute for Geosciences and Natural Resources (BGR)

Table of contents

List of figures

List of tables

List of abbreviations

Abbreviation	Meaning
AbfRRL	Waste Framework Directive
AVV	Waste Catalogue Ordinance
AlNiCo	Aluminium-nickel-cobalt
$(BH)_{max}$	Maximum energy density
Co	Cobalt
Dy	Dysprosium
EoL	End of Life
Gd	Gadolinium
HD	Hydrogen Decrepitation
HDD	Hard disk drive
HDDR	Hydrogenation Disproportionation Desorption and Recombination
kg/MW	Kilogram per megawatt
kJ/m^3	Kilojoule per cubic metre
KrWG	Circular Economy Act
MGOe	Mega-Gauss-Oersted
MRI	Magnetic resonance imaging
Nd	Neodymium
NdFeB	Neodymium-iron-boron
Pr	Praseodymium
RE	Rare earths
RE magnets	Rare earth magnets, used here to indicate rare earth permanent magnets made from NdFeB and SmCo
SSD	Solid state drive (hard drive)
SmCo	Samarium-cobalt
Tb	Terbium

Summary

Neodymium-iron-boron magnets (NdFeB) have the highest energy density among commercially available permanent magnet materials. This property makes them the most important type of magnet by far. NdFeB magnets are key components in different industrial applications, including electric motors, wind turbines and electronic devices.

Recycling processes for NdFeB magnets are categorised as short-loop recycling and long-loop recycling. Short-loop recycling has the advantage of consuming less energy compared to long-loop recycling and is particularly suitable for manufacturing recycled magnets. Although long-loop recycling may be more process-intensive, it allows rare earths to be recovered and can be applied to a wider range of waste flows containing magnets. Although direct reuse of magnets is admittedly the most sustainable option, this is not feasible in many cases.

The recycling potential of NdFeB magnets in Germany and the rest of Europe can be estimated by taking into account various sources such as electronic scrap, wind turbines and automotive applications, although the anticipated tonnages vary widely in some cases. Effective collection and return systems for NdFeB magnets need to be set up to increase recycling rates. There is currently no significant trade in end-of-life NdFeB magnets in Germany. NdFeB magnet recycling also entails logistical challenges. These include the heterogeneity of waste flows, varying life cycles of products containing magnets and the difficulty in automating disassembly of small components. The price of recycled magnets is closely linked to the price of primary magnets, which, in turn, is heavily dependent on the price of rare earth elements. This study presents an overview of companies and start-ups in Germany and beyond that are involved in magnet recycling.

1. Introduction

Due to their outstanding properties, rare earth permanent magnets (RE magnets) are used in numerous industrial applications such as electric motors, wind turbine generators and various electronic devices. Due to their limited availability and the environmental challenges of mining and extracting raw materials, sustainable recycling solutions are highly important.

The maximum energy density $(BH)_{max}$ is a key indicator of a permanent magnet material's strength. It is expressed in kJ/m³ (kilojoules per cubic metre) or MGOe (Mega-Gauss-Oersted). The maximum energy density of permanent magnets has changed considerably over time. About 100 years ago, magnets were not particularly powerful. For example, steel magnets had a maximum energy density of around just 8 kJ/m³. Ferrites (up to 24 kJ/m³) and Aluminium-nickel-cobalt magnets (AlNiCo; up to 80 kJ/m³) were developed in the middle of the last century. Great progress has been made since the 1960s with the development of RE magnets. Magnets based on Neodymium-iron-boron (NdFeB) in particular offer the highest values of all permanent magnet materials with a maximum energy density of around 445 kJ/m³ at room temperature (Figure 1). Consequently, they cannot be replaced without incurring losses in many applications where efficiency, weight reduction or small installation size are important.

In 2022, permanent magnets produced worldwide had a net value of 23 billion US dollars (Ormerod et al. 2023). NdFeB magnets accounted for 58 % of revenue generated and ferrite materials for 33 %, while polymer-bonded NdFeB magnets, which are embedded in a matrix made of materials such as epoxy resin (pressing method) or polyamide (injection moulding) totalled 6 %. Polymer-bonded NdFeB magnets offer several advantages over conventional sintered NdFeB magnets, including greater flexibility in terms of design and shape. However, they are generally not as magnetically strong and have a lower maximum operation temperature compared to sintered magnets (Ormerod & Constantinides 1997, Schäfer et al. 2023). AlNiCo or Samarium-cobalt (SmCo) magnets represent a very small market share of just 1 % each (Figure 2). Industrial recycling initiatives for permanent magnets are focussed on NdFeB magnets due to their widespread use, high materials costs and exceptional properties.

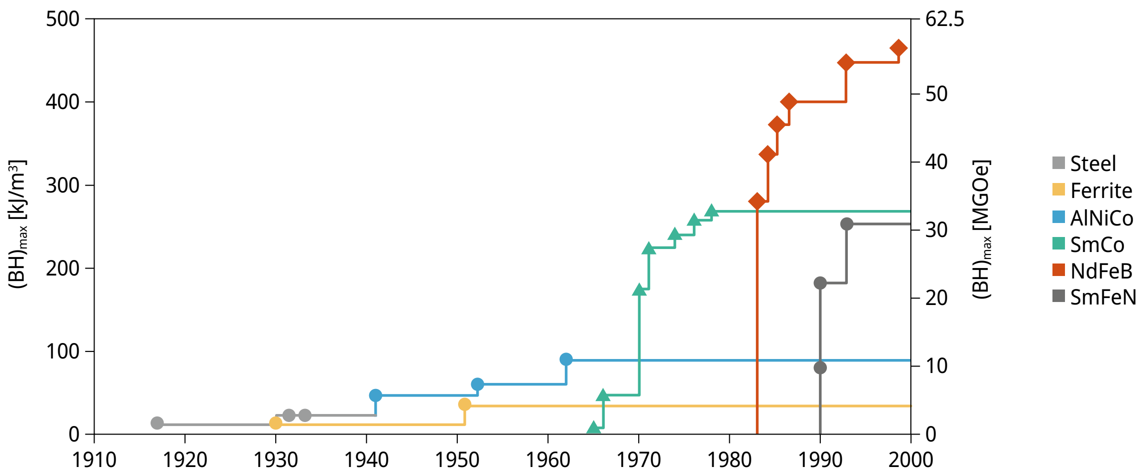

Fig. 1: Energy density $(BH)_{max}$ in kJ/m³ and MGOe for different permanent magnet materials and their historical development. Own graph based on Gutfleisch et al. (2011)

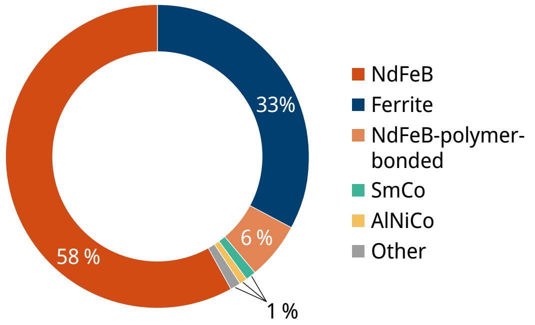

Fig. 2: Distribution by value for global permanent magnet production in 2022 (total value: 23 billion US dollars). Own graph based on Benecki et al. (2021) in Ormerod et al. (2023)

NdFeB magnets consist of 60 – 70 % iron, 30 – 32 % rare earths (mainly neodymium, praseodymium, dysprosium and terbium) and 1 % boron with added gadolinium, cobalt, copper, aluminium, gallium and niobium to improve magnetic and physical properties. Table 1 provides an overview of typical compositions of NdFeB magnets and the effect that the individual elements have.

In contrast, Sm_2Co_{17} magnets have a samarium content of around 25 – 28 % and consist of 45 – 50 % cobalt, 14 – 22 % iron, 3 – 12 % copper and 1 – 3 % zirconium. $SmCo_5$ magnets consist of 36 % samarium and 64 % cobalt.

RE magnets, especially NdFeB magnets, are used in numerous applications, ranging from smartphones to wind turbines. Due to their different sizes and required properties, the magnets they contain vary considerably in terms of their mass and chemical composition. The main areas of application are electric vehicles (24 %), consumer electronics (21 %), wind turbines (9 %), air conditioning (8 %), HDD hard drives (4 %), acoustic transducers (5 %) and robotics (1 %). 28 % is attributable to other applications (Roskill 2020). The magnets contained can be found in amounts ranging from a few

Tab. 1: Typical alloy components of NdFeB magnets and their effect (according to Yang et al. 2017, Kumari & Sahu 2023). The elemental formula for NdFeB magnets is simplified as $RE_2Fe_{14}B$ as this is the magnet's hard magnetic phase

Element	Content [weight %]	Effect
Fe	60 – 70	Formation of the hard magnetic $RE_2Fe_{14}B$ phase
Nd	20 – 30	
Pr	0,5 – 7	
B	0.3 – 1	
Dy	0.2 – 6	Improved temperature resistance, increase in coercive field strength
Tb	0.2 – 2	
Gd	0.1 – 3	Improved temperature coefficient
Co	0.4 – 3	Increase in the Curie temperature, improved corrosion behaviour
Cu	0.1 – 0.9	Improved sintering behaviour
Al	0.1 – 0.9	
Ga	0.1 – 0.3	Increase in coercive field strength and the alloy's hot formability
Nb	0.1 – 0.3	Grain refinement

grams in the case of the HDD hard drive to several tons in direct-drive offshore wind turbines (see Table 2).

This study aims to record the current state of NdFeB magnet recycling in Germany. It will examine the basic technical processes for recycling these RE magnets at their end of life (EoL) as well as the value creation and pricing in trading with them. The study also aspires to provide an approximate projection for future development up to 2030.

Tab. 2: Main areas of application and amount of NdFeB magnetic materials contained (Reimer et al. 2018). Direct-drive wind turbines are also known as gearless wind turbines. Hybrid turbines are wind turbines with a low-ratio gearbox without a failure-prone coupling (Marscheider-Weidemann et al. 2021)

Application	Mean magnetic mass
Wind power (direct-drive)	650 kg/MW
Wind power (hybrid)	160 kg/MW
MRI	2.5 t
Electric vehicle	2.5 kg
Hybrid vehicle	1.5 kg
E-bike	270 g
HDD	6 g

2. Recycling und reuse

2.1 Basics of recycling and explanation of common methods

Research activities examining recycling of high-performance RE magnets were intensified worldwide in the wake of the rare earths crisis in 2011. The different recycling processes can now be divided into two groups: short-loop recycling (also known as functional recycling or direct recycling) and long-loop recycling (also known as elemental recycling or indirect recycling). The methods that the two groups use (Figure 3) differ in terms of their processes, the associated plant technology required, the necessary chemicals and their end product (Gauß et al. 2015, Schönfeldt et al. 2018). Not all magnets or magnet-containing material flows can be recycled using any method. The reuse of EoL magnets in new applications is an even more sustainable solution than recycling. The advantages and disadvantages of each method and its associated processes and materials are described in more detail below.

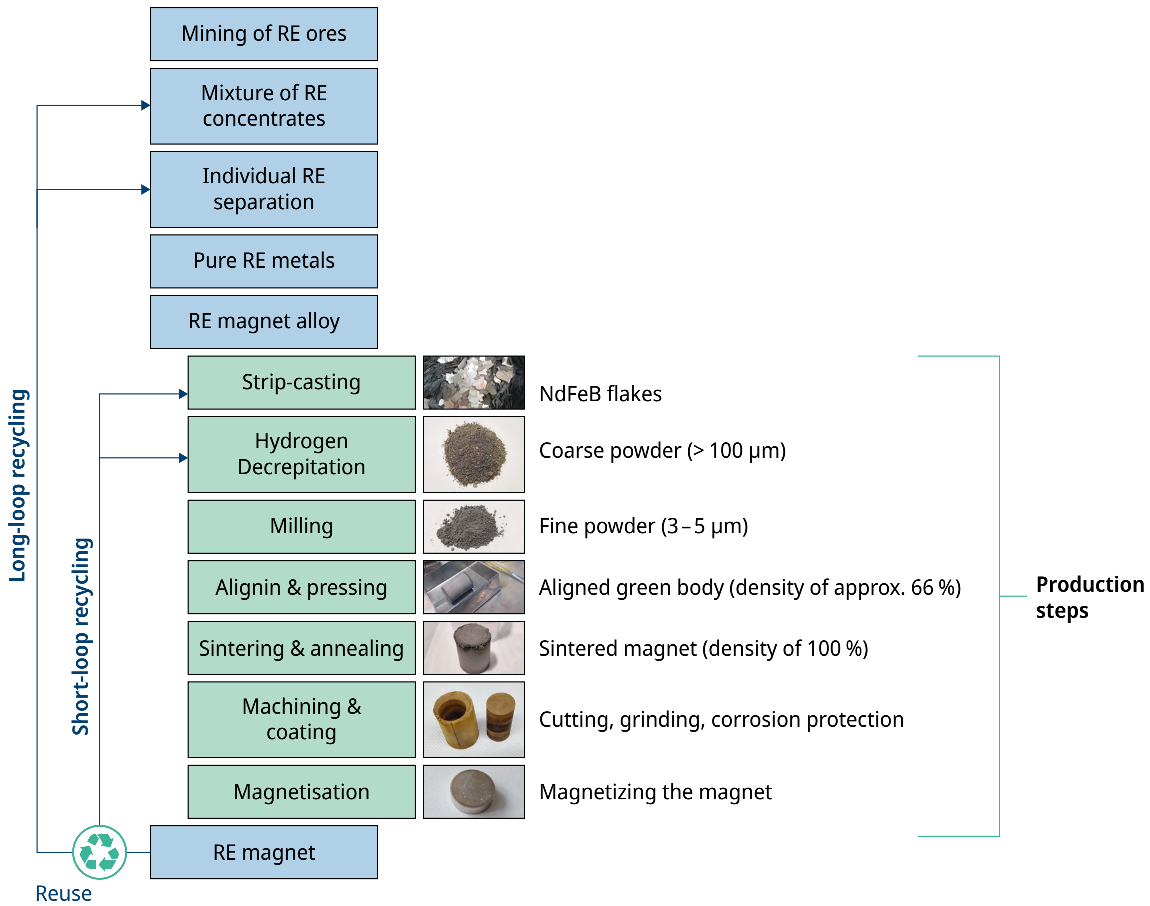

Fig. 3: Value creation, production steps and different recycling methods in NdFeB sintered magnet production. Own graph, partly based on Gauß & Gutfleisch (2016). Given the high oxygen affinity of rare earths, the process steps from strip-casting through sintering and annealing are conducted in an inert gas atmosphere or vacuum

Reuse

When reused, magnets are not destroyed and then recycled; instead, they are merely demagnetised, cleaned and possibly cut into a new shape or geometry. In the case of direct reuse, magnets can be used and magnetised in new applications once a new corrosion protection layer has been applied. The prerequisite for such reuse involves collecting a sufficiently large quantity of used magnets and identifying appropriate new applications with acceptable requirements for the magnet properties.

Short-loop recycling

The defining feature for all methods classified as short-loop recycling is the aim of producing recycled magnetic materials from used magnets or production waste. In contrast to reused magnets, used magnets are processed and their physical properties are changed so that they can then be used in similar production processes for their original purpose or for another one. The entire magnetic alloy is used with the chemical composition only slightly altered by including additives. The resulting magnetic properties are therefore dependent on the microstructure and chemical composition of the used magnets to some extent. The methods and process steps used in short-loop magnet recycling remain similar to the processes used in primary production (see Figure 3), thereby making it easier to integrate these methods into existing production lines. These methods can be applied to clean, non-oxidised magnetic material flows, but are not suitable for shredded materials due to the impurities they contain. Sintered magnets or hot-deformed magnets are suitable source materials for short-loop recycling. Polymer-bonded magnets, on the other hand, are not suitable for this method. This is because it is difficult to separate the plastic from the magnetic material. This is not effectively possible with moulded polymer-bonded magnets (epoxy resin) yet. Small quantities of injection-moulded, polymer-bonded magnets are sometimes remelted and recycled directly during production. Nevertheless, both types of magnets generally need to be recycled using long-loop recycling or wet chemical processes.

Short-loop recycling methods include (1) Hydrogen Decrepitation (HD), (2) the HDDR method (Hydrogenation Disproportionation Desorption and Recombination), (3) remelting and (4) the melt-spinning method (Yang et al. 2017).

During **Hydrogen Decrepitation** of used magnets, RE permanent magnets are decrepitated into a coarse powder in a hydrogen atmosphere. This process is similar to strip-cast flake or alloy decrepitation during primary production (McGuiness & Harris 1988). A small percentage of rare earths such as hydride is usually added to the coarse powder to compensate for impurities. This is followed by combined milling to sintering fineness (around 3 – 5 µm), powder particle alignment in an external magnetic field, pressing to form a green body, and sintering and annealing to form a fully dense sintered magnet. All these process steps are very similar to those used to produce primary magnets (Jin et al. 2016, Jin et al. 2018), meaning this recycling method can be easily integrated into primary production. The decrepitation of the used magnet when exposed to hydrogen is based on a reaction between the RE-rich phases and the H_2 gas. The microstructure of an NdFeB magnet consists of the ferromagnetic $RE_2Fe_{14}B$ phase, which is surrounded by RE-rich intragranular and grain boundary phases. These RE-rich phases react with the hydrogen diffusing into the magnetic material to form a rare earth hydride. The resulting volume expansion leads to cracks along the grain boundaries and ultimately to decrepitation of the magnet into a coarse powder (see Figure 4). As only the RE magnet reacts with the hydrogen, this method can also be used to separate magnetic scrap from steel or copper scrap (Walton et al. 2015). If magnets are glued or embedded, they are usually dismantled from the remaining material, decoated, cleaned and processed into a coarse powder before hydrogen decrepitation.

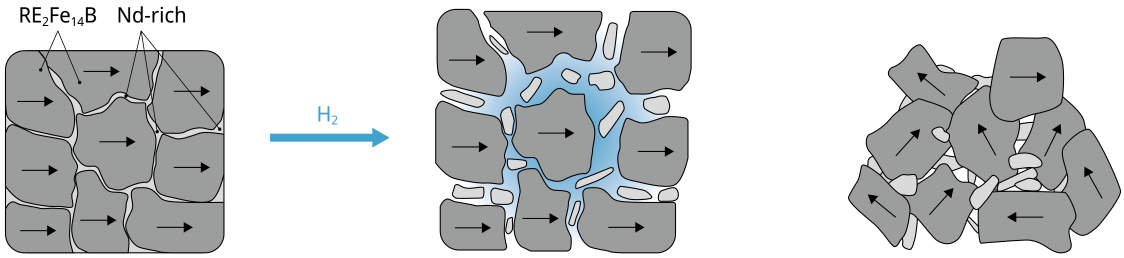

Fig. 4: Schematic diagram showing how hydrogen decrepitation works. Own graphic based on Gauß et al. (2015)

In the **HDDR method**, the used magnet is also processed in a hydrogen atmosphere. However, this method differs from pure hydrogen decrepitation (HD) due to different process pressures and higher temperatures between 750 and 950 °C (Habibzadeh et al. 2023). The magnetic powder's resulting microstructure is also significantly finer compared to the HD process and features polycrystalline grains with multiple magnetic moments (see Fig. 5). These powders are therefore used to produce isotropic (unaligned) or anisotropic (aligned) polymer-bonded magnets through injection moulding or cold pressing.

EoL magnets or production waste are melted by induction during **remelting**. This method is already used in industry to manufacture sintered magnets. Strip-cast flakes produced in this way can be further processed into sintered magnets using the subsequent primary processes. Selective slag management can reduce the oxygen content in the magnetic material from 0.2 – 0.5 % to below 0.1 %, although material losses of up to 30 % must be expected (Yang et al. 2017).

The **melt-spinning** method is used to remelt sintered magnets into nanocrystalline or amorphous ribbons that can be ground into powders and processed into polymer-bonded magnets. The magnets are melted by induction here in a similar way to the strip-casting method using a strip caster. The liquid melt is then cooled by a rotating metal wheel. In the case of

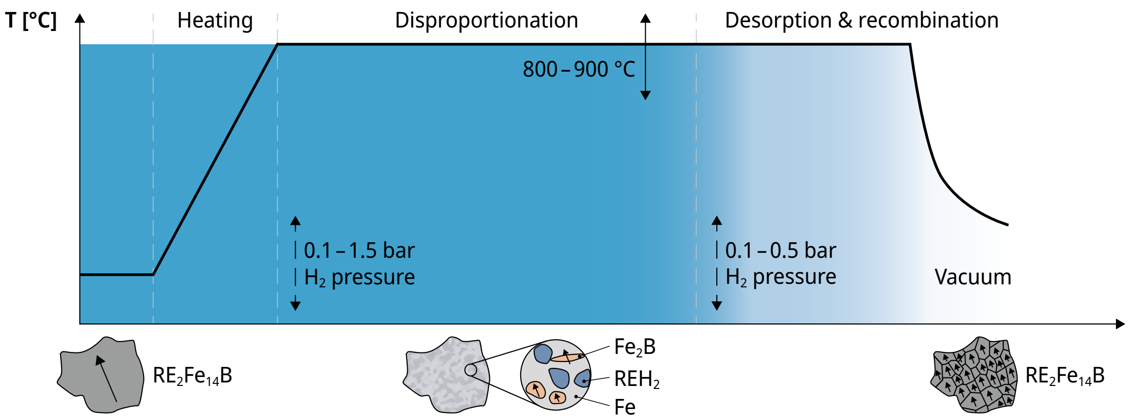

Fig. 5: Process diagram showing the HDDR method and resulting polycrystalline microstructure. Own diagram based on Gauß et al. (2015). During disproportionation, the $RE_2Fe_{14}B$ phase is broken down and reassembled (recombination) after desorption (outgassing of H_2). This transforms the microstructure from monocrystalline grains into a finer polycrystalline microstructure

the melt-spinning method, however, the metal wheel's rotational speed is many times higher, which has an effect on the melt's cooling rate. Due to the higher cooling rate, a nanocrystalline microstructure can be created, which benefits the magnets' coercive field strength. Due to slag formation, higher material losses may also be expected here compared to hydrogen-based processes.

Long-loop recycling

The purpose of long-loop recycling is not to manufacture recycled magnets directly, but rather produce rare earth elements or rare earth oxides as intermediate products, which can then be used to manufacture permanent magnets. In contrast to short-loop recycling methods, long-loop methods are better suited to smaller applications and material flows with different magnetic grades (a "grade" refers to a magnet class within the NdFeB alloy family; see Figure 9), magnetic properties and to shredded material flows. However, a degree of pre-sorting, separation and concentration is also required here to ensure cost-effective recycling. Long-loop recycling methods include: (1) hydrometallurgical methods and (2) pyrometallurgical processes. In both methods, electrochemical processes can be used for better separation and sorting of rare earths. In addition to sintered magnets and hot-deformed magnets, polymer-bonded magnets can also be used for long-loop recycling (hydrometallurgical methods).

During **hydrometallurgical** recycling, RE magnets are chemically leached (Figure 6). The magnets are dissolved in hydrochloric acid (HCl) or sulphuric acid (H_2SO_4) before being separated into the individual rare earths (e. g. Nd, Pr, Dy, Tb) using solvent extraction, ion exchange or ionic liquids. Once impurities have been removed, the individual rare earths are converted into RE fluorides or RE oxides. One disadvantage of these method are the high temperatures often required to increase selectivity of RE elements with

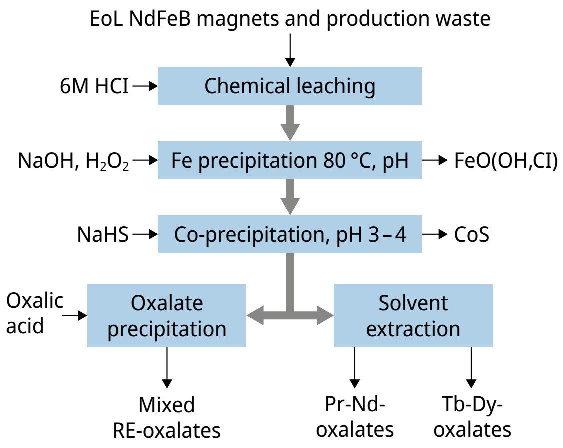

Fig. 6: Example of a hydrometallurgical recycling process for NdFeB magnets. Own chart based on ELWERT et al. (2017)

regard to iron (Fe) and other transition metals plus the high cost of the extraction agents.

Pyrometallurgical methods seek to convert rare earths into a phase that allows them to be separated from the rest of the material selectively. In contrast to hydrometallurgical methods, there must be sufficiently high RE concentrations present in the material flow. However, this approach uses lower quantities of water and acids, although it does require higher temperatures. The RE metals contained can be produced using molten salt electrolysis or metallothermic reduction.

Subsequent RE extraction can be performed by roasting, liquid metal extraction, molten salt extraction, liquid slag extraction or electrochemical processes. However, further hydrometallurgical processes such as chemical leaching are necessary after extracting rare earths from the remaining material (YANG et al. 2017). Figure 7 shows an example of a pyrometallurgical recycling method.

Figure 8 provides an overview of the different recycling methods and their processes. An overview of the advantages and disadvantages of the different recycling methods can be found in Table 3.

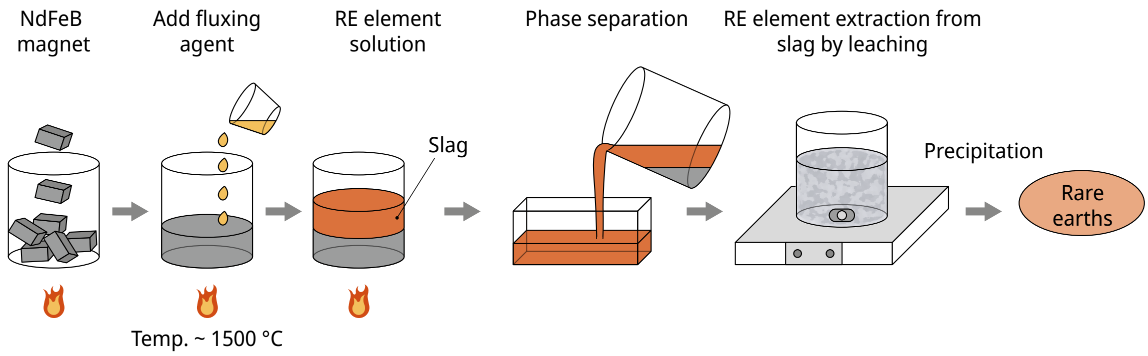

Fig. 7: Example of a pyrometallurgical recycling process for NdFeB magnets. Own illustration based on KUMARI & SAHU (2023)

Tab. 3: Overview of the advantages and disadvantages of reuse and recycling processes according to BINNEMANS et al. (2013) and JIN et al. (2020)

Reuse and recycling method	Advantages	Disadvantages
Reuse	– Most economical method, low energy consumption – Low chemical consumption – No waste production	– Only suitable for large, easily accessible magnets (wind turbines, large motors) – Material flows still low currently – Requirements of used magnet and new application must be compatible
Short-loop recycling	– Lower energy consumption than long-loop recycling methods – (Low or) no production of waste – Similar processes to those in primary production and can thus be integrated – Greater sustainability can be achieved than with long-loop recycling methods	– Removal and sorting processes necessary – Magnetic properties depend on the quality of the magnets used (oxidation) – Remanence reduced by 2 to 10 % by adding rare earths – Not applicable for shredded or inhomogeneous material flows
Long-loop recycling	– Contamination and impurities are less critical – Greater flexibility in terms of composition and properties – Theoretically best magnetic properties achievable – Can be used for shredded material flows or small applications – Can be used for all magnet compositions (also oxidized magnets to a certain extent)	– More process steps and larger amounts of energy (0.7 to 1.0 kg CO_2-equivalent more), water and chemicals are required compared to short-loop recycling, although less than for producing magnets from primary material

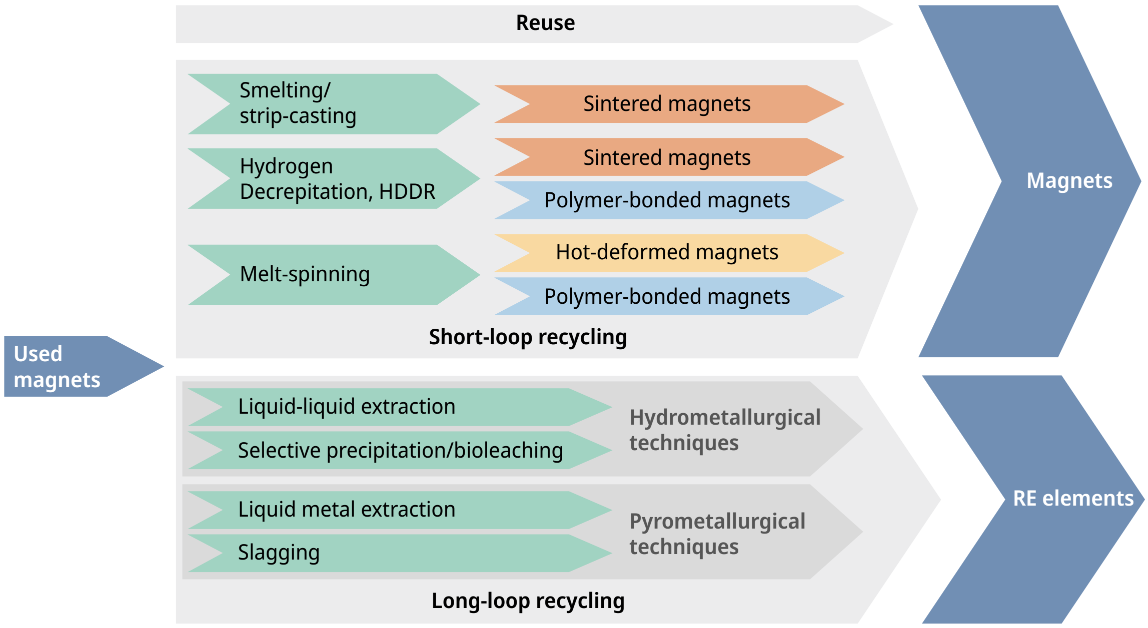

Fig. 8: Possible recycling techniques for used magnets or production waste with the technologies used. Own chart based on Gauß et al. (2015)

The most suitable method must be selected depending on the available material or waste material flow, costs and the desired properties of the reused or recycled magnets. Although the best magnetic properties can be achieved with long-loop recycling processes (equivalent to production from primary raw materials), costs are relatively high and these methods are process-, water- and energy-intensive. In contrast, using short-loop recycling methods means magnets can be produced at a reasonable cost; however, magnetic properties are dependent upon the characteristics of the EoL magnets.

Even though some recycling technologies have already been available for a number of years, industrial magnet recycling is still in the development process in Germany and the rest of Europe. One reason for this situation is that Chinese primary magnets are still very low-priced to some extent. Furthermore, consistent used magnet material flows are required to ensure reproducible properties. There are still challenges to be overcome here, particularly when it comes to collecting and removing used magnets and the automated and, consequently, cost-effective sorting of smaller applications and components. The widely varying lifespans of 2 – 3 years in consumer electronics and up to 20 – 30 years for wind turbines also have an impact on the availability of material flows containing rare earths. Moreover, impurities and mixtures of different magnetic materials (Ferrites, AlNiCo, SmCo, NdFeB) and different magnetic grades means that efficient removal and sorting processes need to be developed (Yue et al. 2019). However, the key challenge for industrial magnet recycling remains a stable, predictable supply of used magnets in sufficient quantities.

One possible solution for generating unmixed material flows would be the labelling of components and material flows to ensure better sorting and more effective recycling. Such labelling could consist of digital product passports, barcodes, QR codes or radio frequency identification (RFID) technology among other things (CUTEC Institute 2016). In addition to the magnet type, such labelling could encode other process-relevant parameters such as the type of corrosion protection layer, the proportion of heavy rare earths, the magnet grade and the magnet producer (Burkhardt et al. 2020).

2.2 Recycling potentials

The recycling potential of different material flows has been analysed in a number of scientific studies in recent years. Table 4 provides an overview of some of these studies. Due to varying assumptions and calculation methods, the authors arrive at results that differ markedly from each other to a certain extent. The quantities available for recycling are affected by factors such as the return rate, which can vary depending on the material flow and application. In the case of traction motors (28 – 36 %) and wind turbines (10 – 18 %), a relatively high return rate can be assumed whereas it may be significantly lower for e-bikes, industrial motors or HDD hard drives (1 % each) (Reimer et al. 2018). Other studies assume a future collection rate of 60 % for HDD hard drives or 90 % in the case of traction motors or wind turbines (Schulze & Buchert 2016). The actual EoL recycling rate for the rare earths Nd, Pr, Dy and Tb was less than 1 % in 2019. Reasons for the low recycling rates include the absence of collecting and return systems and a lack of financial incentives. In the case of shredded material fractions, the magnetic materials are lost in the iron fraction or are melted during steel or electronic scrap recycling and are subsequently found in the slag. Only when the first wind turbines are dismantled are the magnets they contain collected and then exported to Asia for reuse and recycling, which means they are no longer available for a German or European recycling or reuse activity (UBA 2019).

Technological developments such as replacing magnetic hard disc drives (HDDs), which have been in use for decades, with faster, magnet-free solid state drives (SSDs) have a direct impact on the future composition and volume of magnetic material flows. It is expected that 85 % of HDD hard drives will be replaced with SSD hard drives by 2032 (Peeters et al. 2018).

When it comes to wind turbine generators, rare earths and permanent magnets made using them are mainly featured in offshore turbines

Tab. 4: Recycling potentials of selected RE magnet material flows with a projection for future development

Study	Material flow	Region	Period	Quantity
Elwert et al. (2018)	NdFeB general	Europe	2015	150 t (of which 60 – 70 t are production waste)
			2016 – 2040	10,300 t – 183,000 t
Reimer et al. (2018)	NdFeB general	Europe	2018 – 2040	25,700 t – 233,000 t
UBA (2019)	NdFeB general	Germany	2015	800 t
			2030	1,700 t
			2040	4,800 t
GWEC (2023)	NdFeB wind power	World	2027	15,000 t
Schulze & Buchert (2016)	NdFeB general	World	2020	15,000 t – 22,000 t
			2030	27,000 t – 52,000 t
	Production waste for long-loop recycling	World	2020	28,000 t – 45,000 t
			2030	60,000 t – 158,000 t
IEA (2022)	RE elements (Nd, Pr, Dy, Tb)	World	2030	11,000 t
			2040	12,000 t

(up to 650 kg NdFeB magnets/MW, depending on the turbine type). Offshore turbines with a total capacity of 980 MW were installed in Germany in 2022. Wind energy in Germany is expected to expand to over 15 GW by 2030. The Global Offshore Wind Alliance (GOWA), an association of fourteen member states, including Germany, intends to increase global offshore wind capacity from at least 380 GW in 2030 to 2,000 GW in 2050 (GWEC 2022; GWEC 2023). The International Energy Agency anticipates a tripling of installed wind energy capacity and a 25-fold increase in electric vehicles by 2040 (IEA 2022). 77.6 GW of new wind turbines were installed worldwide in 2022 (of which 8.8 GW are offshore and 68.8 GW onshore). An average annual global growth rate of 15 % is expected until 2027 (GWEC 2022; GWEC 2023).

Elwert et al. (2018) states that the following trends and developments can be expected up to 2030:

1. Electronic products: decrease in theoretical recycling potential due to HDDs containing NdFeB being replaced by magnet-free SSDs
2. Electric vehicle sector: slight increase expected until 2030 and stronger increase after 2030
3. Industrial motors: constant increase
4. Wind power: systems will not be recycled until 2030 due to their long service life and the late market launch of NdFeB generators
5. MRI: decrease in recycling potential due to NdFeB devices being replaced with electromagnet-based equipment

It can be concluded that the theoretical recycling potential will remain largely constant until 2025, particularly with regard to waste from electronic products, electric vehicles and industrial motors. However, projections reveal that a significant increase in waste volumes from the electric vehicle sector is expected from 2025 (Elwert et al. 2018). Furthermore, it is anticipated that generators from wind turbines will be increasingly available for recycling from 2030 onwards. The increasing availability of EoL NdFeB magnets might potentially boost recycling, but it is questionable whether the general financial conditions are attractive enough for this.

3. Value creation and trade

3.1 Study of trade

In contrast to other scrap materials, such as steel or copper scrap, no relevant trade in EoL NdFeB magnets has been observed in Germany. It is known that there are bilateral agreements on magnet trading between recycling companies and recyclers of EoL NdFeB magnets, but the quantities involved are very low. The lack of widespread trade is attributable to a combination of technological, logistical and legal requirements, which together make the magnet recycling business model financially unattractive and impede suitable market and price formation. Before exploring these causes more closely, it is helpful to take a look at the recycling products that may emerge. Table 5 shows the product groups that might appear, depending on the different recycling processes.

Tab. 5: Possible product groups in the magnet recycling sector

Product group	Category	Classification hazardous substance	Comment
Magnetic components/systems	Waste	No hazardous substance	
Used magnet (residue)	Waste	 Possibly magnetised; apart from that no hazardous substance	
Flakes/coarse powder (after rapid solidification)	Intermediate product (alloy)		Sales market available since primary product is also offered in this form
Coarse powder (after hydrogen decrepitation)	Intermediate product (alloy)		
Pressed coarse powder	Intermediate product (alloy)		
Fine powder (after milling)	Intermediate product (alloy)		Not traded due to the potential risk
Recycled RE oxides	Intermediate product (oxide)	No hazardous substance	Few potential customers since reduction to elements is a complex process
Recycled RE elements	Intermediate product (element)	No hazardous substance (in bulk form)	Complex process, but end products are versatile in their use
Recycled magnets	Product	No hazardous substance	

3.2 Logistical challenges

The current prices for primary magnets are rather low from a purely financial perspective and are not sufficient to boost recycling as an immediately financially attractive alternative. This could be due in part to government measures taken by the leading global market supplier, China. A common characteristic of the recycling methods presented in the report is that the EoL magnetic material must have a certain level of purity, depending on the method used. This leads to technical and logistical challenges when separating and sorting EoL magnetic material in view of the different uses of permanent magnets in general and NdFeB magnets in particular. Separation and sorting are essential for a successful, cost-effective process and are shaped by the factors specified below.

Heterogeneous material flows

Different waste flows with varying NdFeB magnet contents are proving to be a major logistical challenge. NdFeB magnets are contained in a wide variety of electrical components. As many sources of NdFeB magnets as possible must be used to exploit a financially relevant quantity of EoL magnet material. The result, however, is a highly variable waste flow with a wide variety of components, magnet shapes and magnet proportions. This is at odds with current technological methods, which require specialisation in particular types of magnets. Heterogeneous material flows should be avoided, especially in short-loop recycling processes, so that reproducible properties can be achieved.

Different life cycles

In addition to the issues with waste flows, the magnets contained in products have different life cycles, depending on the product in question. Incoming waste flows therefore not only contain different magnets but also magnets from a wide variety of manufacturing periods, ranging from consumer goods that are only a few years old to applications spanning several decades. As all products and the components they contain have changed over time, the variety in waste flows increases by another time factor. Technological progress also plays a role in the use of EoL magnets with different life cycles. Due to constant optimisation of magnet composition and microstructure, older magnets, for example, differ from newer magnets due to their higher rare earth content. This is particularly true for extremely critical heavy rare earths such as dysprosium and terbium.

No automated disassembly processes for small products

Components have become smaller and lighter over the years, both in the consumer goods sector and in motor technology. While automated disassembly processes are certainly conceivable for larger components (motors, hard drive magnets), these become more challenging with increasing miniaturisation. Apart from the actual size, the design also plays a role: the way in which different components are joined to each other in tiny spaces (bonded, interlocked, encased) poses an additional challenge for single-type separation. This along with the wide range of variants means that there are no cost-effective automated disassembly processes for such small products. Shredded material flows can only be used for long-loop recycling processes.

Separation of different magnet types

In addition to the separation of magnets and non-magnetic material, there are further distinctions between different types of magnets that need to be considered. It is particularly important to avoid mixing the four magnetic materials used (Ferrites, AlNiCo, SmCo, NdFeB) during the recycling process as they are fundamentally different materials. It is known from primary production, that even the slightest cross-contamination between NdFeB and SmCo leads to extreme deterioration of the macroscopic magnetic properties and, consequently, renders the material unusable.

There are also further differences in chemical composition, properties and application within each individual material type. Figure 9 shows an overview of the different NdFeB magnet classes. The diversification of this material is largely due to the application temperature, because it can only be used in applications above 80 °C if alloyed with heavy rare earth elements (Dy, Tb). As a result, the variants (magnet grades) are classified according to different application temperatures (N, M, H, SH, UH, EH, AH, VH). The higher the temperature is, the higher the proportion of heavy rare earths are and the lower the energy density $(BH)_{max}$ is. Optimised processes in magnet production, including oxygen reduction, grain boundary diffusion and grain refinement, have successfully reduced the required proportion of heavy rare earths (from up to 10 weight % to < 4 weight %) and also to increase $(BH)_{max}$ across all magnet grades.

For magnet recycling, this means that there is a wide variance in alloys in NdFeB magnets, contingent on the specific application and the time of manufacture or the production techniques used. From the perspective of criticality and raw material costs, magnets with the highest proportions of heavy rare earths are likely to be of particular interest. This requires relevant knowledge of the materials – ideally their composition or, as a minimum, their magnet class or target application.

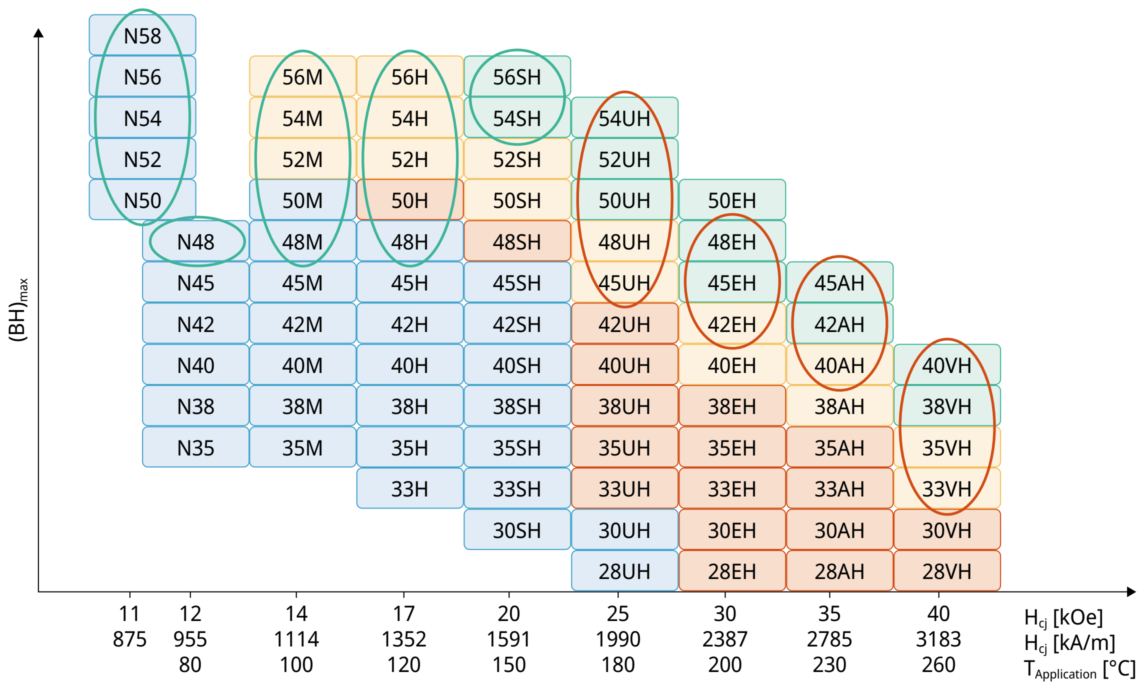

Fig. 9: Commercially available NdFeB magnet grades with details of typical magnetic parameters and operating temperatures. Own graph based on Furgeri (2020), on the basis of the Chinese standard GB/T 13560-2017 (2018). The colour coding represents the technical development of NdFeB magnets with the aim of achieving increasingly better or higher coercive field strengths and thus developing applications with higher temperatures, such as traction motors

3.3 Legal requirements

In the European Union, general handling of waste and recycling material is regulated by *the Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives*, known as the *Waste Framework Directive* (AbfRRL 2008), and its latest amendment *Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste* (AbfRRL 2018). This directive was adopted in Germany in 2012 with *the introduction of the Circular Economy Act* (KrWG 2012). The 2018 amending directive is essentially adopted by *Article 1 of the Act Implementing the European Union Waste Framework Directive (Amendment to the Circular Economy Act)* (KrWG 2020). The directives amended in addition to the AbfRRL are already partly implemented in separate articles of the *Act Implementing the Waste Framework Directive of the European Union* and partly in separate legislative and regulatory procedures (AbfRRL 2008).

From a legal point of view, EoL products in which RE magnets are embedded are waste from the moment they are discarded (Section 3 KrWG): "Waste (within the meaning of this Act) refers to any substance or object which the holder discards, intends to discard or is required to discard."). Once a product is legally classified as waste, it can no longer be freely traded as an ordinary commodity and must be traded as waste only. This imposes special requirements and documentation obligations on all potential traders.

For a substance to no longer be considered waste but a (recycled) commodity instead, the end of waste status must be requested and the authorities must approve this status. Paragraph 5 of the Circular Economy Act regulates whether the categorisation of a substance as waste can be terminated and specifies the conditions under which it can be terminated: the waste status of a substance or object terminates when it has undergone recycling or another recovery method and meets criteria so that

1. it is typically used for specific purposes
2. there is a market for it or a demand for it
3. it fulfils all technical requirements applicable to its intended purpose and meets all legal provisions and applicable standards for products, and
4. its overall use does not cause harmful effects to humans or the environment.

Proof of the end of waste status needs to be provided on all four levels. While the first three criteria can be fulfilled by definition, by a market evaluation or based on existing DIN/ISO standards, the last criterion focuses on evaluating the emissions released during the recycling process based on the Federal Immission Control Act (BImSchG 2023). The public compatibility of the recycling method can be demonstrated by means such as a life cycle assessment (LCA) compared to the primary process or landfill. However, a generally stable, homogeneous supply chain for EoL material is also a prerequisite for proof.

One way to increase the quantities of EoL magnets collected is through the Waste Catalogue Ordinance (AVV). As of today, EoL NdFeB magnets do not form a separate material flow and therefore do not need to be collected separately. This means that magnets do not need to be detached and separated. As a result, they often end up being mixed in with the steel scrap fraction. A separate waste code for magnets could serve as an incentive for companies to collect EoL magnets separately.

4. Prices

Although there is no publicly accessible market for EoL magnets and pricing is therefore based on bilateral agreements (see Section 3), a long-term view over a number of years reveals a clear influencing factor for this pricing. The price trend for EoL magnets obviously follows the price trend for primary magnets, which, in turn, reflects the trend in raw material prices. As with primary magnets, the rare-earth content in EoL magnets and their price development must therefore be regarded as a key factor in pricing. Due to the higher raw material costs, heavy rare earths (dysprosium, terbium) play a particularly important role in this context. Figure 10 shows the price development of light and heavy rare earths over the past 20 years, exemplified by neodymium and dysprosium. The price spike in 2011 was caused by export restrictions imposed by China, the world's largest producer. There were fears that a supply shortage could arise outside of China.

Figure 11 shows how the prices for EoL magnets have evolved in comparison to the raw materials for primary magnets over the same period as demonstrated by a typical magnet alloy. Although the costs for primary and recycled raw materials are at significantly different levels, the trend in terms of percentage price development is the same in both cases.

Future price developments for EoL magnets are likely to be aligned with the primary price of the alloy used with the content of rare earth elements being a significant influencing factor.

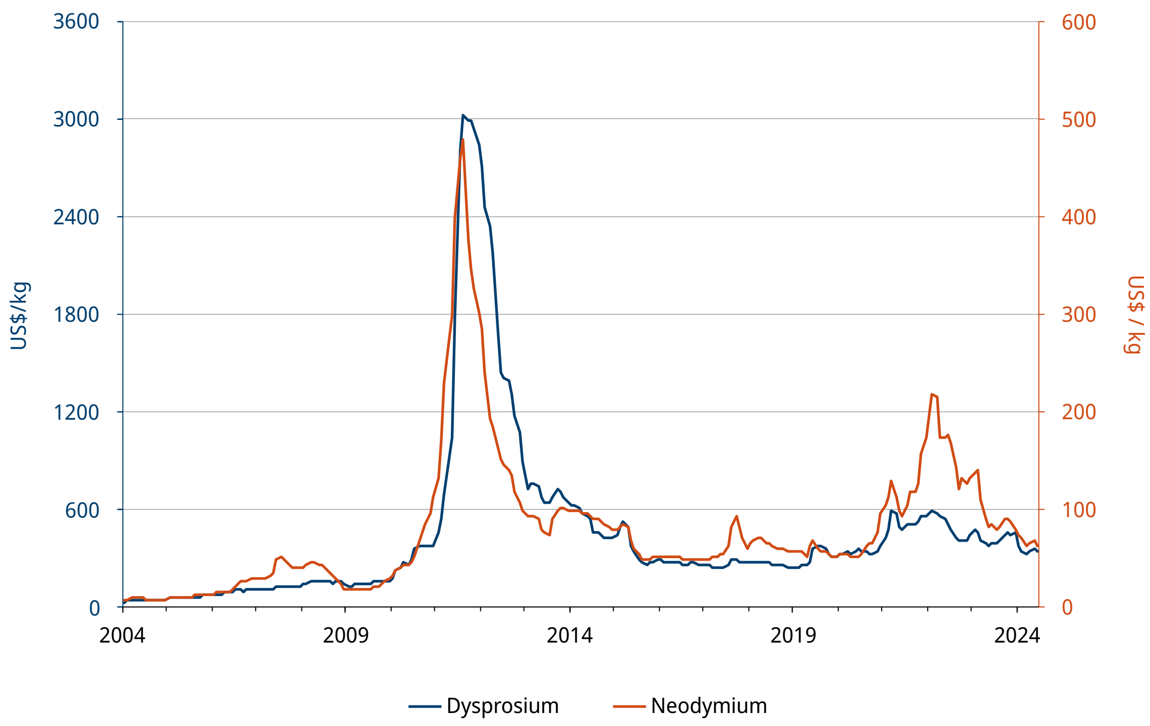

Fig. 10: Price development of the elements neodymium (Nd) and dysprosium (Dy) with a purity of 99 % since January 2004 (BGR 2024)

Fig. 11: Comparison of raw material costs for producing an example NdFeB magnet from primary material and recycled raw materials in the years 2017 and 2022. Own graph based on SCHÖNFELDT et al. (2023)

5. Implementation of recycling processes

The following section outlines notable NdFeB magnet recycling projects in Germany. A number of European and North American projects that have achieved international renown are also listed. Despite careful, systematic research, this list may be incomplete, particularly with regards to the European and international market. The study primarily provides an initial overview of this complex subject area and introduces the most common processes and the most important players.

A wide range of activities and cooperation between different stakeholders are required to ensure magnet recycling is financially sound in its implementation. First of all, research needs to focus on developing recycling methods that could be implemented under financially viable conditions. The aims of these scientifically researched recycling methods are to: a) produce highly pure rare earth oxides or elements, b) produce intermediate products for magnet production or c) produce recycled magnets. Sufficient recycling material must be available to ensure the recycling process itself can be set up on a financially viable basis. The logistics for collecting relatively unmixed material flows has not been established for NdFeB magnetic materials yet, so a system will need to be set up in the future. This will also include removing magnets which are usually embedded in components such as motors, generators, loudspeakers, medical devices or electronic components at the end of their life cycle. A further challenge to overcome is the fact that permanent magnets remain magnetised at the end of their service life, making them more difficult to handle during sorting, for example. Despite these obstacles, a magnet recycling industry has recently emerged in Germany, Europe and worldwide, driven by the demand for rare earths and the advantages for sustainability in using recyclates. This sector includes collectors, recyclers and magnet manufacturers.

The categories where the analysed market participants are described include: *company, location, industry, year of foundation, production period, source, activity, product, capacity and info*. Most of the companies in the magnet recycling sector are start-ups that have emerged from projects or scientific institutes in various forms over the last ten years. A variety of technologies for recycling magnets are being developed on the market and will be implemented on an industrial scale in the near future. The US-based company Noveon Magnetics Inc is already marketing a recycled magnet called EcoFlux in the US. This is not yet the case in Europe as the companies have not yet reached the required production capacity or are still at the development stage. Legal requirements such as the EU Critical Raw Materials Act will also provide the legislative framework for implementing the recycling of critical raw materials, including rare earths, in the future (CRMA 2023). This encourages the alternative use of critical materials, which can be achieved through national raw material deposits, national raw materials reprocessing and recycling (use of at least 25 % of critical elements from recycling).

The last section looks at university and non-academic research institutes working in the field of magnet recycling, focusing on institutes that have their headquarters in Germany. The activities examined include work on disassembly of components as well as the short-loop and long-loop recycling of magnets.

5.1 Industrial implementation

The Heraeus Group is a leading global technology and family firm based in Hanau, Germany. In addition to precious metals processing, the company also specialises in technology metals. **Heraeus REMLOY GmbH** operates within the Heraeus Group as a start-up for recycling magnetic materials containing rare earths. The rapid solidification technique is used for recycling, converting a molten metal into solid bodies (flakes) on a water-cooled metal wheel at solidification speeds of more than 1000 °C per second. After processing, the flakes are offered for magnet production, as Heraeus does not manufacture magnets itself. In principle, Heraeus REMLOY products are suitable for manufacturing polymer-bonded or hot-deformed magnets.

Tab. 6: Information about Heraeus REMLOY GmbH

Category	Description
Company	Heraeus REMLOY GmbH
Location	Bitterfeld-Wolfen, Germany
Industrial sector	Processor, recycler
Founded	2021
Production period	from 2024 onwards
Source	https://www.heraeus.com/de/landingspages/hrm/home_hrm/hrm_home.html
Activity	– Purchase of EoL magnets – Recycling of EoL magnets using the rapid solidification technique (melt-spinning)
Product	– Recycled NdFeB magnetic powder for producing permanent magnets – Powder for producing isotropic polymer-bonded magnets – Powder for producing anisotropic hot-deformed magnets (goal for the future)
Capacity	600 t per year in expansion stage 1, 1200 t per year in expansion stage 2

HyProMag GmbH is a technology start-up based in Germany that works closely with England-based HyProMag Limited. Both use a technology patented by the University of Birmingham as a recycling method (HPMS or Hydrogen Processing of Magnetic Scrap). HPMS refers to a technology for recycling NdFeB magnets using hydrogen decrepitation, which allows pulverisation of magnets and separation of non-magnetic material simultaneously. The two companies intend to jointly establish recycling activities in Germany, England and the US. At the same time, parent company Maginito Limited recently put into operation a pilot plant for long-loop recycling of NdFeB magnets in cooperation with Mkango Rare Earths UK Limited.

Tab. 7: Information about HyProMag GmbH

Category	Description
Company	HyProMag GmbH
Location	Pforzheim, Germany
Industrial sector	Processor, recycler, magnet manufacturer
Founded	2021 as a GmbH company in Germany and 2018 as a limited company in Birmingham England
Production period	Q1 2025
Source	https://www.hypromag.de/Start.html https://mkango.ca/ https://direct.argusmedia.com/newsandanalysis/article/2590758
Activity	– Purchase of EoL magnets – Recycling of EoL magnets using hydrogen decrepitation
Product	– Recycled magnetic powder – Production of sintered magnets – Production of polymer-bonded magnets
Capacity	The plant in Tyseley (UK) will initially produce 25 – 30 t of NdFeB magnets per year and plans to increase its capacity to between 100 to 330 t per year. A plant with similar capacities is currently at the planning stage in Germany.
Info	Collaboration with HyProMag Ltd. in England, utilizing the HPMS technology patented by the University of Birmingham (HPMS: Hydrogen Processing of Magnetic Scrap)

RockLink GmbH is a global trading and recycling company specialising in compounds and metals such as rare earths, nickel, cobalt, lithium and tungsten. It has developed a return box for small quantities of RE magnets (Magcycle). The collected EoL magnets are converted into powders and oxidised, which are then chemically separated in Asia and processed into RE metals.

Tab. 8: Information about RockLink GmbH

Category	Description
Company	RockLink GmbH
Location	Düsseldorf, Germany
Industrial sector	Trader, sorter, processor, recycler
Founded	Magnet collection since around 2004
Production period	In operation
Source	https://www.rocklink.de/
Activity	– Purchase of EoL magnets: NdFeB (sintered and polymer-bonded), SmCo, AlNiCo – All magnets are purchased in the form of scrap, dust, slag and grinding sludge – Conversion of EoL magnets into oxides and metals (carried out in Asia)
Product	– RE metals (produced in Asia; no magnet production)
Capacity	unknown
Info	Take-back system for used magnets in “Magcycle” magnet box for small quantities since 2018 (https://www.magnetrecycling.de/)

Lars Walch GmbH & Co. KG is a small family-run enterprise dedicated to metals recycling. In addition to purchasing precious metals, it also trades in RE magnetic materials. It removes used magnets from applications such as electronic scrap, wind turbines and medical devices and provides them for recycling.

Tab. 9: Information about Lars Walch GmbH & Co. KG

Category	Description
Company	Lars Walch GmbH & Co. KG
Location	Baudenbach, Germany
Industrial sector	Trader, sorter
Founded	1996
Production period	In operation
Source	https://walch-recycling.de/
Activity	– Purchase of EoL magnets and components
Product	– Sorted EoL magnets for recycling
Capacity	unknown

Carester is a French start-up which recycles rare earths. During recycling, magnets are oxidised and dissolved using a wet chemical method. The individual RE elements are then separated using a liquid-liquid extraction process so that high-purity rare earth oxides can be supplied to the market for further processing in metal production. In principle, the processes developed are also suitable for reprocessing rare earths from primary mining.

Tab. 10: Information about Carester

Category	Description
Company	Carester
Location	Lyon, France
Industrial sector	Processor, recycler
Founded	2019
Production period	Start of construction: Q3 2024 Pilot plant put into operation: Q1 2026
Source	https://www.carester.fr/en
Activity	– Collection of EoL magnets – Wet-chemical recycling of EoL magnets – Separation of RE oxides
Product	– Processed RE oxides (elements) – NdPr, Nd, Pr (as a mixture and separate elements)
Capacity	Recycling of 2,000 t of EoL RE magnets in 2027

MagREEsource is a French spin-off from the CNRS (Centre national de la recherche scientifique) which recycles magnetic materials using hydrogen decrepitation technology. In the future, it intends to supply recycling powders for both sintered and polymer-bonded magnets. In addition to these conventional applications, it also proposes to produce and distribute recycling powders for additive manufacturing.

Tab. 11: Information about MagREEsource

Category	Description
Company	MagREEsource
Location	Grenoble, France
Industrial sector	Processor, recycler, magnet manufacturer
Founded	2020
Production period	from 2025 onwards Acquisition of a 1000 m^3 plant in 2023
Source	https://www.magreesource.org/
Activity	– Collection of EoL magnets – Recycling of EoL magnets using hydrogen decrepitation
Product	– Recycled powders for manufacturing isotropic and anisotropic magnets – Recycled powders for additive manufacturing – Production of recycled magnets
Capacity	Recycling of 500 t of EoL RE magnets per year

Noveon Magnetics was founded in the US in 2012 as Urban Mining Company which recycles magnetic materials. The technology it uses is a patented magnet-to-magnet recycling process combined with a grain boundary process. Noveon is currently the only company actively marketing a recycled magnet, distributed under the name EcoFlux.

Tab. 12: Information about Noveon Magnetics

Category	Description
Company	Noveon Magnetics Inc.
Location	San Marcos, USA
Industrial sector	Processor, recycler, magnet manufacturer
Founded	2022 (from 2012 to 2022 as Urban Mining Company)
Production period	In operation
Source	https://noveon.co/
Activity	– Collection of EoL magnets – Recycling of EoL magnets using hydrogen decrepitation
Product	– Production of recycled sintered magnets distributed under the name EcoFlux
Capacity	2000 t per year
Info	Patented magnet-to-magnet recycling (M2M®) method and grain boundary engineering (GBE®) process

REEcycle was founded as a magnet recycling spin-off from the University of Houston. Its process is based on various steps consisting of chemical decoating of used magnets, mechanical shredding, chemical dissolution and filtration. The product offered for the market is an RE mix solution with around 87 % neodymium and 6 % praseodymium.

Tab. 13: Information about REEcycle

Category	Description
Company	REEcycle (REEGENERATE PTY Ltd.)
Location	Houston, USA
Industrial sector	Processor, recycler
Founded	2012
Production period	On a pilot scale since 2020
Source	https://www.reecycleinc.com/
Activity	– Collection of EoL magnets (electronics recycling; also others in the future) – Coating removal, magnet crushing, dissolving magnets in acids – Recycling of EoL magnets using hydrogen decrepitation
Product	– RE oxide mixture in solution (REEcycle does not undertake rare earth separation or metallization)
Capacity	unknown
Info	Patented process

Cyclic Materials is a Canada-based RE recycling start-up that also operates in the US. It uses a chemical recycling process after which separated RE oxides can be offered on the market. It is currently operating a pilot plant. There are plans to scale up the technology in Canada and the US over several stages, increasing capacity by up to 3000 t of separated rare earth oxide per year.

Tab. 14: Information about Cyclic Materials

Category	Description
Company	Cyclic Materials Inc.
Location	Toronto, Canada
Industrial sector	Processor, recycler
Founded	2022
Production period	600 t per year in 2026, 3000 t per year in 2030
Source	https://www.cyclicmaterials.earth/
Activity	– Collection of EoL magnets – Coating removal, magnet crushing, dissolving magnets in acids – Precipitation of rare earths as mixed oxides
Product	– RE oxide mixture
Capacity	Currently 10 t per year

Geomega Resource Inc. is a Canadian company specializing in rare earth element separation. Its technology can be used for primary mining or RE recycling. In the case of recycling, used magnets are chemically dissolved and then separated using a patented electrophoretic separation process. The products offered are separated rare earth oxides.

Tab. 15: Information about Geomega Resource Inc

Category	Description
Company	Geomega Resource Inc.
Location	Boucherville, Canada
Industrial sector	Processor, recycler
Founded	2009
Production period	Unknown
Source	https://geomega.ca/
Activity	– Technological background in mining processes – Dissolving EoL magnets in acids and separating rare earths using electrophoresis
Product	– Separated RE oxides
Capacity	1.5 t per day on a pilot scale, expandable to more than 1000 t per year

In addition to the magnet recycling companies described in detail here, there are other internationally active companies that wish to expand their business in the rare earths sector. French company **Solvay** is planning to install an RE hub to chemically reprocess rare earths for magnet production (Solvay 2024). **GKN Powder Metallurgy** and **Neo Performance Materials** are expanding their product portfolio by setting up production of RE-based permanent magnets in Europe (GKN Powder Metallurgy 2024; neo materials 2020). Utilization of rare earths from EoL applications and recyclates is also being considered in all three cases, but this is not the main focus of the initiatives.

5.2 Research institutes

In Germany, various university and non-university research institutes are conducting research into the recycling of magnetic materials. Some of the works on this topic are listed below.

Fraunhofer-Gesellschaft: several institutes are working on the subject of magnet recycling under the patronage of the Fraunhofer-Gesellschaft. Fraunhofer initiated this activity through the funding of the internal Fraunhofer lead project "Criticality of rare earths" in 2014 among other things. For this project, seven institutes worked together on various questions in the field of rare earths, which included not only recycling but also the search for alternative magnetic materials or new manufacturing processes. The Fraunhofer Research Institution for Materials Recycling and Resource Strategies **IWKS** has been working on the subject of magnetic materials since its foundation in Alzenau in 2012 and in Hanau in 2013. During this time, it has set up a production line to manufacture and recycle permanent magnets on a pilot plant scale (50 kg). Here, the research mainly focuses on short-loop recycling methods using melting processes and powder metallurgy. This research has been conducted as part of various public funded projects (FhG-LP-KSE, EU-EREAN, BMBF-RECVAL-HPM, BMBF-Supply-PBM, BMWK-Recycle-TEAM, FhG-RecyPer, Hessen-FunMag, Hessen-ZDR-EMIL) and appeared in scientific publications (Diehl et al. 2018, Schönfeldt et al. 2023). In addition to short-loop methods, Fraunhofer IWKS is also researching processes for long-loop recycling on a laboratory scale (Auerbach et al. 2019). The Fraunhofer Institute for Manufacturing Technology and Advanced Materials **IFAM** is working on hydrometallurgy-based RE recycling methods. The Fraunhofer Institute for Interfacial Engineering and Biotechnology **IGB** is conducting research into the electrophoretic separation of RE elements.

Technical University of Darmstadt: the Division of Functional Materials (Prof. Oliver Gutfleisch) in the Department of Materials Science is developing methods for recycling magnetic materials using hydrogen-based techniques. These techniques can be used to produce anisotropic sintered magnets or anisotropic polymer-bonded magnets (using the HDDR process). The methods have been used in several public funded projects (EU-EREAN, BMBF-RECVAL-HPM, BMWK-Recycle-TEAM, EU-MAGELLAN), leading to a close cooperation between TU Darmstadt and Fraunhofer IWKS. The results from these projects have been published in the following scientific publications among others: (Gutfleisch et al. 2013, Lixandru et al. 2017, Yang et al. 2017, Diehl et al. 2018, Benke et al. 2020, Schönfeldt et al. 2023).

Pforzheim University: at Pforzheim University, magnet recycling is being researched at the Institute for Strategic Technology and Precious Metals (STI) under the direction of Prof. Carlo Burkhardt. Research involves working on magnet recycling using the hydrogen decrepitation method to manufacture sintered magnets. The technology is being further developed to provide automated separation of magnetic powder from non-magnetic material. Work is being undertaken in cooperation with the University of Birmingham and is being commercially exploited in the start-up HyProMag. The following public funded projects are working on the recycling, dismantling and nomenclature of products containing magnets (EU-SUSMAGPRO, EU-REEsilience, EU-ReProMag, BMBF-MaXycle). The results from these projects have been published in the following scientific publications among others: Burkhardt et al. (2020), Burkhardt et al. (2023), Mishra et al. (2023).

RWTH Aachen University: the Institute IME Process Metallurgy and Metal Recycling and Chair of RWTH Aachen University, headed by Prof Bernd Friedrich, conducts research into pyrometallurgical and hydrometallurgical recycling processes for alloys, such as magnetic materials containing rare earths. Findings from its research have been published in the following scientific publications: Kruse et al. (2015), Kaya et al. (2021), Emil-Kaya et al. (2022).

Clausthal University of Technology: at Clausthal University of Technology, research was undertaken on pyrometallurgical recycling of magnets from electric motors under the leadership of Prof. Tobias Elwert (until 2018) as part of the public funded SemaRec project. Findings on the project's recycling approaches have been published in the following scientific publications: Elwert et al. (2017), Reimer et al. (2018).

Technical University Bergakademie Freiberg: at the TU Freiberg, Prof. Martin Bertau led the public funded MagnetoRec project, which centered on the chemical recycling of rare earths using solid-state chlorination. The project's findings appeared in the following publications: Lorenz & Bertau (2018), Lorenz & Bertau (2019).

The FAU (Friedrich-Alexander-Universität Erlangen-Nürnberg) has been working on dismantling of electric motors to remove permanent magnets as part of the EU REEPRODUCE project. **The Max Planck Institute for Sustainable Materials in Düsseldorf**, the **Leibnitz Institute for Solid State and Materials Research in Dresden** and **Aalen University** are also conducting research into permanent magnets. This research analyses the criticality of rare earths by replacing them with elements classified as non-critical.

6. Conclusion

To sum up, the selection of an appropriate recycling method depends on costs, material flows and the desired properties due to the variety of different material flows and applications containing magnets. Compared to long-loop methods, short-loop recycling methods are characterised by their lower energy input while long-loop methods can recycle a larger number of material flows and achieve better magnetic properties. Both types of methods offer decisive advantages and disadvantages, which is why they have been adopted for industrial use. Companies and start-ups offer both recycling method types on a national and international level. Universities and research institutes are working on further development and optimisation of both methods. Cooperation between industry and research will play a central role in developing sustainable recycling solutions.

Two established magnet recycling companies and additional start-ups will further expand short-loop recycling in Germany over the next few years. German-based magnet manufacturers will also need to replace some of their primary raw materials with recycled raw materials when the European Union's plans (Critical Raw Materials Act and Ecodesign Directive) are implemented. To increase the recycling potential of different material flows and the return rates of RE magnets, more effective collection and take-back systems need to be set up, involving all stakeholders in research and throughout the value chain. A separate waste code for EoL magnets (NdFeB) in accordance with the German Waste Catalogue Ordinance (AVV) could increase recycling rates and financial incentives and political regulations could promote the use of recycled raw materials. This would categorise RE magnets as a higher-value material, which would provide an incentive for companies to collect them separately. Overcoming the technical, logistical and legal challenges of trading will also be crucial to building and establishing a robust recycling industry.

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German Mineral Resources Agency (DERA) at the
Federal Institute for Geosciences and Natural Resources (BGR)
Wilhelmstrasse 25–30
13593 Berlin
Germany

dera@bgr.de