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Recycling Decisions in 2020, 2030, and 2040—When Can Substantial NdFeB Extraction be Expected in the EU?

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Abstract: In recent years, China's dominant role in the rare earth market and the associated impacts have strengthened the interest in the recovery of rare earth elements (REE) from secondary resources. Therefore, numerous research activities have been initiated aiming at the recovery of REEs from different types of waste streams, which includes, inter alia, neodymium-iron-boron (NdFeB) magnets. Although several research projects have successfully been completed, most experts do not expect an industrial implementation in Europe within the next years. This article analyses the reasons for this situation, addressing the availability of sufficient amounts of NdFeB wastes, the technology readiness level of the developed processes in Europe, as well as the economic aspects. Based on these analyses, an estimation of a realistic timeframe for the industrial implementation of NdFeB recycling in Europe is deduced and critically discussed.

Keywords: NdFeB magnets; rare earth elements; recycling; recycling potential; neodymium; dysprosium

1. Introduction

Since the 1980s, China has become the dominant producer of rare earth elements (REE), reaching market shares of up to 97% in 2010. In 2017, China mined about 81% of the world production (approx. 130,000 t/year), and is the only country that operates the full production chain from ores to REE metals at the industrial scale. Despite its monopolistic position, the REE prices remained stable on relatively low levels before 2010 due to the uncontrolled and unregulated growth of the Chinese REE industry, which resulted in low production costs but caused tremendous environmental damage. Therefore, the security of the supply was not questioned and interest in alternative REE sources was generally low. This situation changed drastically when China introduced export restrictions and duties for REEs in 2010, leading to massive price increases around 2011 and serious concerns about the security of the supply outside China. Since then, prices for rare earth compounds and metals declined significantly due to excess supply. Furthermore, China abandoned the export restrictions and duties in 2015 after the World Trade Organization upheld a ruling in favor of the United States, the European Union, and Japan's claims that China violated trade rules. Nevertheless, there are still mid- and long-term supply risks, as China will presumably stay the dominant REE producer in the next decade [1–3].

In answer to China's policy, many projects regarding primary production, recycling, substitution, as well as associated topics, such as the material flow analysis of REEs, have been initiated in recent years [4–7]. Regarding primary production, 442 projects were listed in December 2012 [4]. However, less than five have reached industrial scale, the most notable being Lynas Corporation Ltd., which has mining operations in Australia and refining operations in Malaysia [1]. As there are no competitive REE deposits in Europe [4], the European Union (EU) focuses on the recovery of REEs from secondary resources and substitution. Although first research and development projects have already been completed, only very few entered, or will enter, industrial scale [5–7].

This article analyses the reasons for this development in the case of neodymium-iron-boron (NdFeB) magnets, which are the main application for the REEs neodymium (Nd) and dysprosium (Dy) and represent a major share of the REE market by volume (22%) as well as by value (37%) [8]. NdFeB magnets are currently the strongest permanent magnets and are used in various applications (see Figure 1). Due to the high number of applications and expected high growth rates, mainly driven by electromobility and wind turbines, NdFeB magnets presumably bear a high recycling potential [9,10].

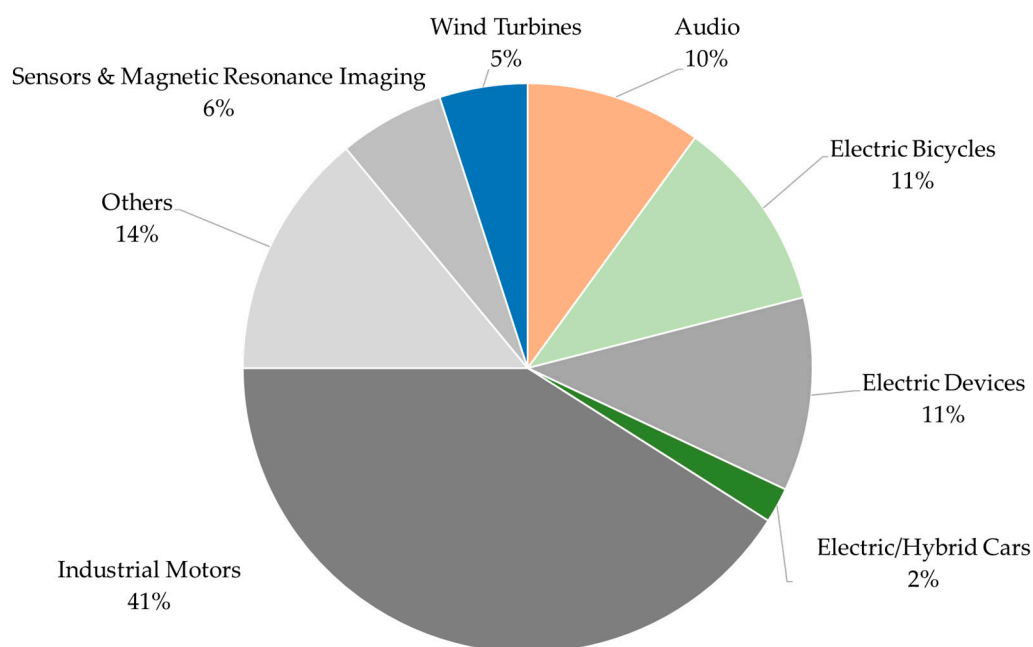


Figure 1. Shares of the different applications in the global neodymium-iron-boron (NdFeB) magnet market in the year 2012 [11].

After providing background knowledge about NdFeB magnets (Section 2), in this study, an attempt was made to enlighten this contradictory situation by using a holistic approach, starting with an estimation of the theoretical European recycling potential until 2040 (Section 3). Based on this, a more realistic scenario for the availability of NdFeB scrap is deduced, considering technological as well as economic aspects (Section 4). In Section 5, the implications are critically discussed.

2. NdFeB Magnets

Sintered NdFeB magnets are the strongest permanent magnets available today. Global production in 2014 was 112,000 t, of which about 88% were produced in China, followed by Japan. Europe and other regions have only minor market shares [12].

The excellent magnetic properties can be traced back to the strongly magnetic matrix phase $\text{Nd}_2\text{Fe}_{14}\text{B}$, featuring high saturation polarization and high magnetic anisotropy. Because of the low Curie temperature and low corrosion resistance of pure $\text{Nd}_2\text{Fe}_{14}\text{B}$, the properties are usually enhanced by alloying other REEs and cobalt. Typically, the alloys contain between 60–70 wt% iron (Fe), 28–35 wt%

REEs (Pr, Nd, Tb, and Dy), 1–2 wt% boron (B), and 0–4 wt% cobalt (Co). The benefit of adding Dy in place of Nd is that it improves coercivity and therefore temperature tolerance. At the highest end of possible operating temperatures (approx. 200 °C), NdFeB magnets contain up to 10 wt% Dy. Terbium (Tb) can perform in a similar function but is rarely used due to its high price. Praseodymium (Pr) can directly substitute Nd to some extent without a severe impact on the magnetic properties. Co is commonly added to improve the corrosion resistance. For further improvement of the corrosion resistance, the magnets are phosphated or coated with organic or metallic coatings [6].

The most important trend in research, development, and production of sintered NdFeB magnets aims at an increase in coercivity using less Dy for economic reasons, as well as minimization of the related remanence losses. The most promising approaches to achieve this target are a further reduction of the grain size and the grain boundary diffusion process. Though the first approach has not been industrially implemented so far, the grain boundary diffusion process was introduced industrially some years ago [13].

3. Theoretical Recycling Potential of NdFeB Magnets in the European Union until 2040

In this section, the theoretical recycling potential of NdFeB magnets from the main applications, being electric vehicles (propulsion motors), auxiliary motors in passenger cars (electric and with internal combustion engine), electric two-wheeled vehicles, industrial motors, wind turbines, magnetic resonance imaging (MRI), hard disk drives (HDD), and audio devices, will be estimated for the years 2018–2040. As the relative share of other applications (currently 14%) is supposed to decrease due to expected high growth rates of electromobility and wind power [10], they are excluded.

The theoretical recycling potential was defined as the total amount of NdFeB magnets from end-of-life applications excluding post-production wastes. Post-production wastes were not considered as their amount of approx. 60 t/year [14] was low in comparison to the potential from post-consumer wastes (see Section 3.4) and was not expected to increase in the EU. To establish a benchmark, in this section, it was assumed that there were no losses through export and that 100% of the products were recycled after their life cycle, with a technical recycling efficiency of 100%. In this way, the theoretical recycling potential of NdFeB magnets could be assessed. More realistic recycling rates were later assumed in Section 4 for a direct comparison. The period under review was chosen up to the year 2040 to take into account, on the one hand, the long life cycle of major applications and, on the other hand, to have an acceptable forecast accuracy. A possible substitution of NdFeB magnets was not considered as alternative technologies are often less efficient (e.g., permanent magnet-free propulsion motors for electric vehicles), and extreme price increases of NdFeB magnets, which would favor substitution, are unlikely. Furthermore, a replacement of NdFeB by new materials is not expected within the next years. Therefore, the introduction of a new magnet material would only significantly affect the market after our considered time horizon due to the long lifespan of most considered products. Regarding the magnet composition, a simplified REE composition of 32 wt% Nd and Dy, 67 wt% Fe, and 1 wt% B was assumed. As Pr and Tb are minor constituents and substitutes for the aforementioned elements, they were not considered.

The most important assumptions for the calculations for each application are explained in Section 3.1. In Section 3.2, the sales data estimation is presented. These results are used to calculate the return flows in Section 3.3.

3.1. Key Assumptions for the Considered Applications

In Table 1, assumptions for average magnet content, percentage of application containing NdFeB magnets, Nd/Dy ratio, average lifespan, and related standard deviation are summarized. Further details are given in the following.

Table 1. Literature based assumptions.

Application	Average Magnet Content		Nd/Dy [%] ³	μ_L ; σ_L [a] ⁴	Sales Data Sources
Electric Vehicles	2500 g	[15]	27/5	15; 3.75	[16–19]
Hybrid Electric Vehicles	1500 g	[15]	27/5	15; 3.75	[16–19]
Auxiliary Vehicle Motors	175 g	[9]	29/3	15; 3.75	[20]
Electric Bikes	270 g	[21]	29/3	5; 1.25	[22–24]
Industrial Motors ¹	-		28/4	-	[25,26]
Wind Turbines, Direct Drive ²	650 kg/MW	[11]	28/4	22; 5.50	[27–32]
Wind Turbines, Hybrid Drive ²	160 kg/MW	[11]	28/4	22; 5.50	[27–32]
Magnetic Resonance Imaging	2.5 t	[33]	31/1	12; 3.00	[11,34]
Hard Disk Drives	5.67 g	[21]	32/0	6; 1.50	[26,35,36]
Audio Devices ¹	-		32/0	-	[34]

¹ Available data was already given in tons of NdFeB. ² Only wind turbines with integrated NdFeB magnets were considered. ³ Adopted from [34]. ⁴ Adopted from [37].

The product segment of electric vehicles is grouped into hybrid electric vehicles (HEV) and electric vehicles (EV). HEVs include mild, full, and plug-in hybrid electric vehicles. Whereas HEVs are typically equipped with permanent magnet motors, due to the limited space, some car manufacturers prefer magnet-free motors for EVs despite lower power densities and efficiencies. As propulsion motors are operated at elevated temperatures, comparatively high average Dy contents were assumed [15]. At present, even higher Dy concentrations up to 10% are observed, but these concentrations are expected to decrease (see Section 2).

All passenger vehicles contain auxiliary motors, which are partly equipped with NdFeB magnets. The magnet content varies. For this study, an average magnet content of 175 g/vehicle was assumed based on [9].

In the market of electric two-wheeled vehicles, a distinction is made between pedelecs, electric bicycles (e-bikes), electric scooters, and electric motor bicycles. Pedelecs require pedalling to activate the motor. In contrast, e-bikes can drive solely electric without pedalling. It is important to note that the term e-bike is often synonymously used for pedelecs, e-bikes, and e-scooters in literature [38]. In this paper, only pedelecs and e-bikes were considered and summarized in the following under the term e-bikes. Electric scooters and electric motor bicycles represent niche markets in the EU and were therefore neglected. According to [39], since 2015 all electric bicycles are equipped with permanent magnet motors. In 2007, the share was 47.1%. For the calculations, a linear increase between 2007 and 2015 was assumed.

The main application of NdFeB magnets is in industrial motors (see Figure 1). They exist in a wide range of sizes and power classes, and are used, for example, in conveyers, pumps, and robots. The data and assumptions were mainly based on a study conducted in Germany by the Institute for Applied Ecology [25].

Currently, three types of wind turbines are produced: Traditional drive train, direct drive, and hybrid systems. Only the last two designs contain NdFeB magnets. Direct drive systems require less maintenance than the other systems as they operate without gears. Therefore, they are the preferred technology for the offshore sector [40]. In contrast to most other applications, a detailed database of installed on- and offshore wind turbines in Europe is available and enabled a direct assignment of the respective magnet content.

According to field strength, magnetic resonance imaging (MRI) devices can be classified into low-, mid-, and high-field systems. Only low-field systems contain NdFeB magnets, whereas the other systems use electromagnets. The global compound annual growth rate is estimated at 3% including the high-growth markets, India and China [41]. As this study focusses on the EU, a lower annual growth rate of 2% was assumed.

While e-bikes, electric vehicles, and wind turbines represent fast growing markets, the market share of hard disk drives (HDD) is declining [36]. They are continuously replaced by faster solid-state-drives

(SSD), which do not contain magnets. The HDDs are divided into 2.5'' and 3.5'' drives with global market shares of 40% and 60%, respectively [35].

3.2. Methodology for the Prediction of Sales Data

The general approach to predict the future sales in the different industrial branches is to extrapolate the sales trends from a combination of past sales data and available forecasts.

As an example, the prediction of future HDD sales is outlined. Figure 2 shows exemplarily our predicted sales data for HDDs for the EU market. The data was based on past sales and a prediction from a worldwide study published by Statista [36]. We assumed a proportional relationship between sales and gross domestic product (GDP) in a region, allowing the estimate of sales on the EU market from the global market. Utilizing annual GDP data [26], we derived the annual GDP_{EU}/GDP_{World} -ratio to receive the portion of HDD sales in the EU market. For example, in 2016 the EU accounted for approx. 21% of the global GDP, leading to the assumption that 90.4 million out of the 424.1 million HDDs were sold in this market. In Figure 2, the resulting sales data is depicted (blue diamonds).

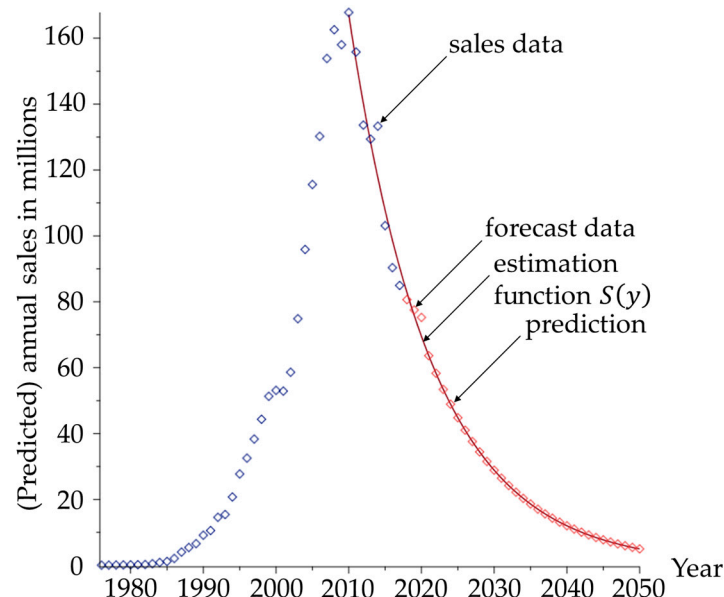


Figure 2. Sales data (blue diamonds), best-fit function (red curve), and forecast (red diamonds) for hard disk drives (HDDs).

It is clear that due to the technical advantages of SSDs over HDDs, the latter experienced a declining market share starting from around the year 2010. To capture this trend, we used a multinomial least-square fit with an exponential estimation function to predict the sales (S) in the year (y):

$$S(y) = e^{a+b \cdot y}, y > 2010 \quad (1)$$

It can be expected [42] that HDD sales will decline and slowly approach zero as customers switch to the new SSD technology. The function given in Formula (1) was therefore chosen for its asymptotical properties. It is well known that an exponential function of this type can be linearized to find the unknown parameters a and b by ordinary least squares. The best-fit parameters were $\hat{a} = 179.588$ (t -Test, $p < 0.000$) and $\hat{b} = -0.087$ (t -Test, $p < 0.000$), and resulted in an adjusted R-squared value of 0.9998. In Figure 2, the consequential estimation function (red curve) and the corresponding sales values (red diamonds) are depicted.

If the trend for other applications was not clearly asymptotical, polynomial estimation functions were more suitable for complex trends and were selected. A similar approach was used for other

applications in the case of incomplete sales data to close gaps via interpolation. Whenever forecasts on sales were available, the data points were incorporated into the predictions.

By applying this method, we were able to estimate annual sales for the time span until 2040, which was relevant to our return flow calculations. It should be noted that a possible increase in uncertainty for sales estimates in the distant future is unproblematic because the corresponding return flows will not be relevant for the considered time span.

3.3. Methodology for the Calculation of Return Flows

To illustrate the calculation of return flows, we utilized the following example. Sales data for the years 2015–2018 were considered: In the year 2015, sales amounted to 1000 units, in the year 2016, to 3000 and, after a year without sales, 5000 units were sold in the year 2018.

We assumed the lifetime to be normally distributed with mean $\mu_L = 5$ and standard deviation $\sigma_L = 1.25$. Therefore, the return year X_i of unit i was a normally distributed random variable $X_i \sim \mathcal{N}(y_{S,i} + 5, 1.25)$, where $y_{S,i}$ was the sales year of that unit i . In general, the probability density function was given by Formula (2):

$$f(y|y_{S,i} + \mu_L, \sigma_L) = \frac{1}{\sqrt{2\pi\sigma_L^2}} \cdot e^{-\frac{(y-y_{S,i}-\mu_L)^2}{2\sigma_L^2}} \quad (2)$$

The three distinct probability density functions for the units 1 to 1000 with sales year $y_{S,i} = 2015$, the units 1001 to 4000 with $y_{S,i} = 2016$, and the units 4001 to 9000 with $y_{S,i} = 2018$ are shown in Figure 3. As we can see from Figure 3, eventual inaccuracies, caused by a negative lifetime, have a probability close to 0%. With the expected lifetimes, considered in the real data set, being larger than $\mu_L = 5$, the probability was even lower than in this example.

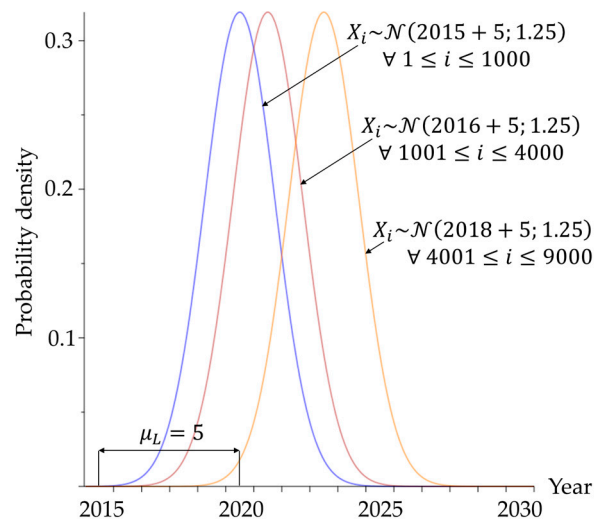


Figure 3. Probability density functions for the return year of units, which were sold in the years 2015, 2016, and 2018, respectively.

The expected returns $R(y_R)$ in a specific year y_R (i.e., returns between y_R and $y_R + 1$) were then given by Formula (3):

$$\mathbb{E}[R(y_R)] = \int_{y_R}^{y_R+1} \sum_i f(y|y_{S,i} + \mu_L, \sigma_L) dy \quad (3)$$

Following the example, we expect $R(2022) = 1929.38$ units to return in the year 2022. A simulation of the exemplary sales data can illustrate the result. In Figure 4, we see the absolute returns obtained from the above probability densities. The blue bars show the returns of the 1000

units that were produced in 2015, the red bars the returns of the 3000 units produced in 2016, and the orange bars the returns of the 5000 units that were produced in the year 2018. In 2022, the returns amounted to $83 + 704 + 1145$ units, which were produced in the years 2015, 2016, and 2018, respectively. The resulting 1932 units were close to the theoretical value 1929.38 and we could expect a convergence to the latter value when averaging multiple simulations.

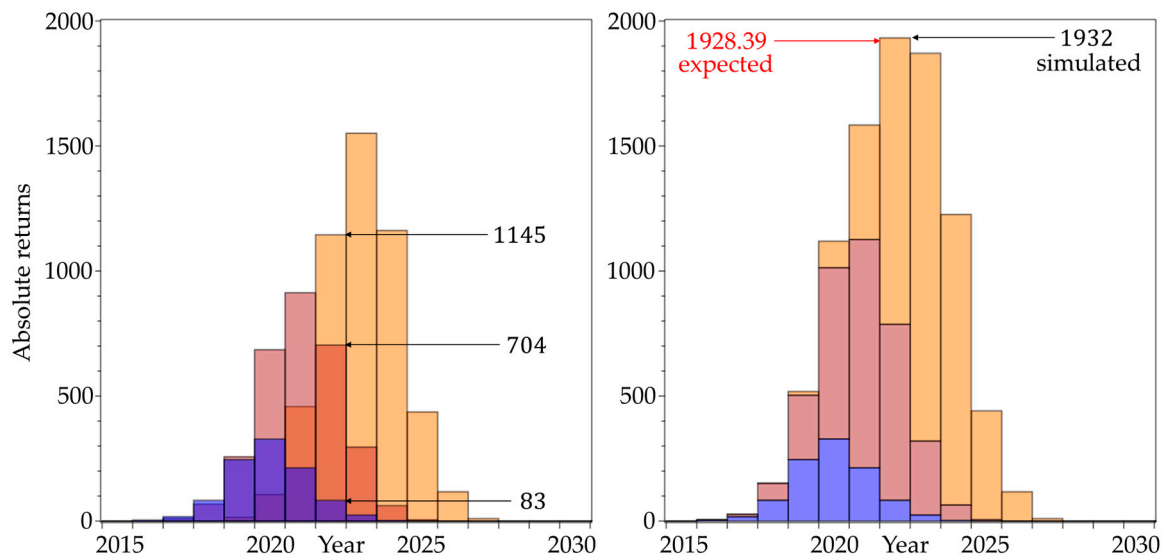


Figure 4. Simulated absolute return flows superimposed (left) and stacked (right). For the year 2022, the simulation (one run) provides a value of 1932 units. The exact expected return derived from the calculation for this given year was 1928.39 units.

This methodology was applied to the real sales data we derived in the previous section for all sources of NdFeB magnets. The usual timeframe of input data was 1995–2040 and the returns were calculated for the years 2018–2040.

3.4. Results

By applying this stochastic approach to the sales data from Section 3.2, we obtained the expected unit returns for the desired years. Both are shown in Figure 5. Depending on the average lifespan, the sales trends were only depicted for their relevant time spans. For example, in case of wind turbines, the average lifespan was $\mu_L = 22$ years. Consequently, only sales data until around 2025 will be impactful for the return flow estimates.

Considering the magnet content per unit (see Table 1), we obtained the resulting amounts of magnets per application in tons per year (Figure 6). It can be seen that the annual theoretical recycling potential increases only slightly in the next 10 years. In this first period, auxiliary vehicle motors, magnet resonance imaging, and electronic devices dominate. From 2028 on, a strong increase can be expected, which is mainly caused by the expected market penetration of (H)EVs and e-bikes. The share of wind turbines will increase from 2030, but remains comparatively low until 2040. The total theoretical recycling potential from 2016–2040 is about 233,000 t of NdFeB, corresponding to 66,600 t Nd and 7900 t Dy.

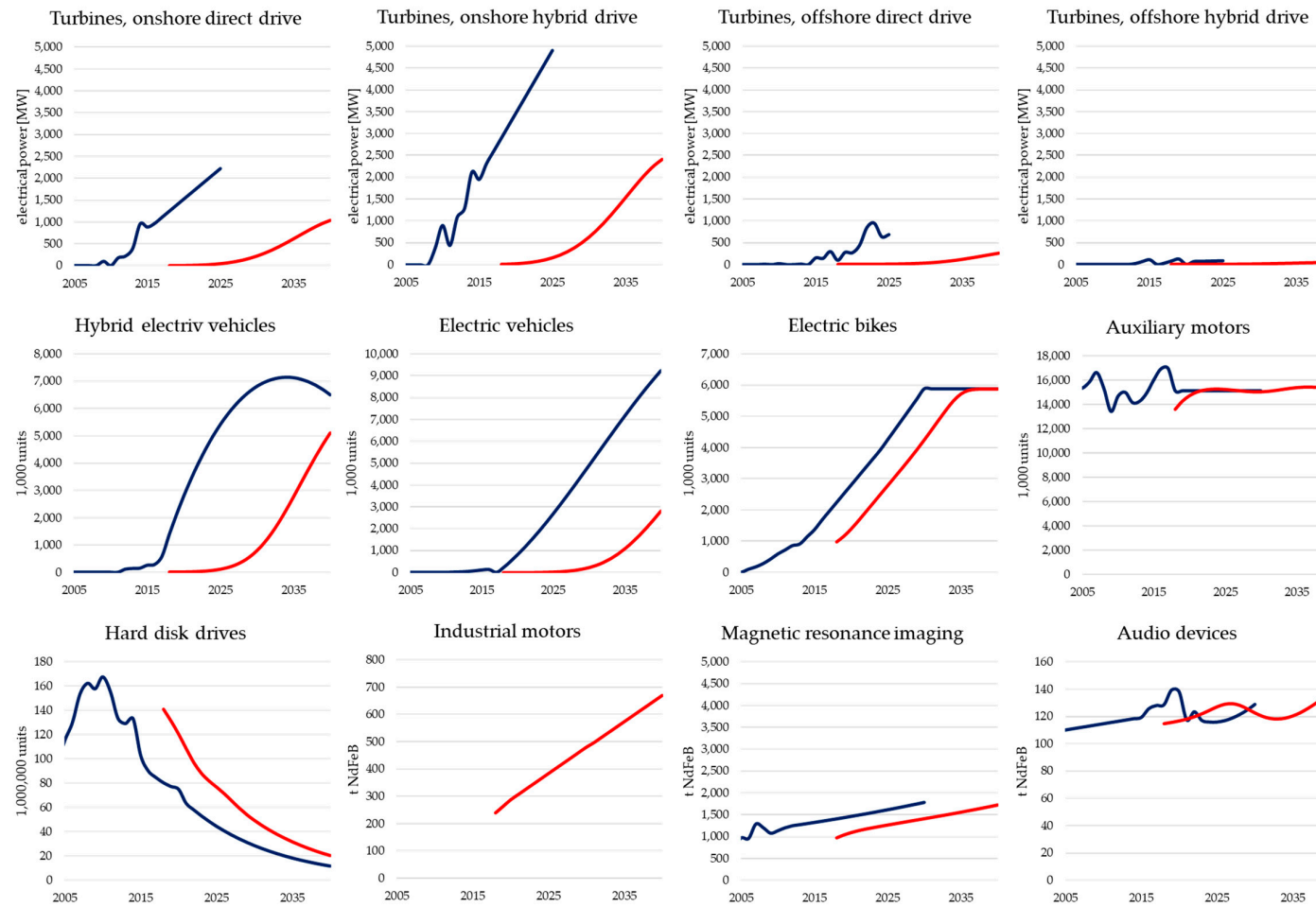


Figure 5. Sales (blue) and returns (red) by application. Y-axes units vary whilst x-axes depict year dates. The relevant range of sales trends is shorter, if the associated average lifespan is high (e.g., wind turbines).

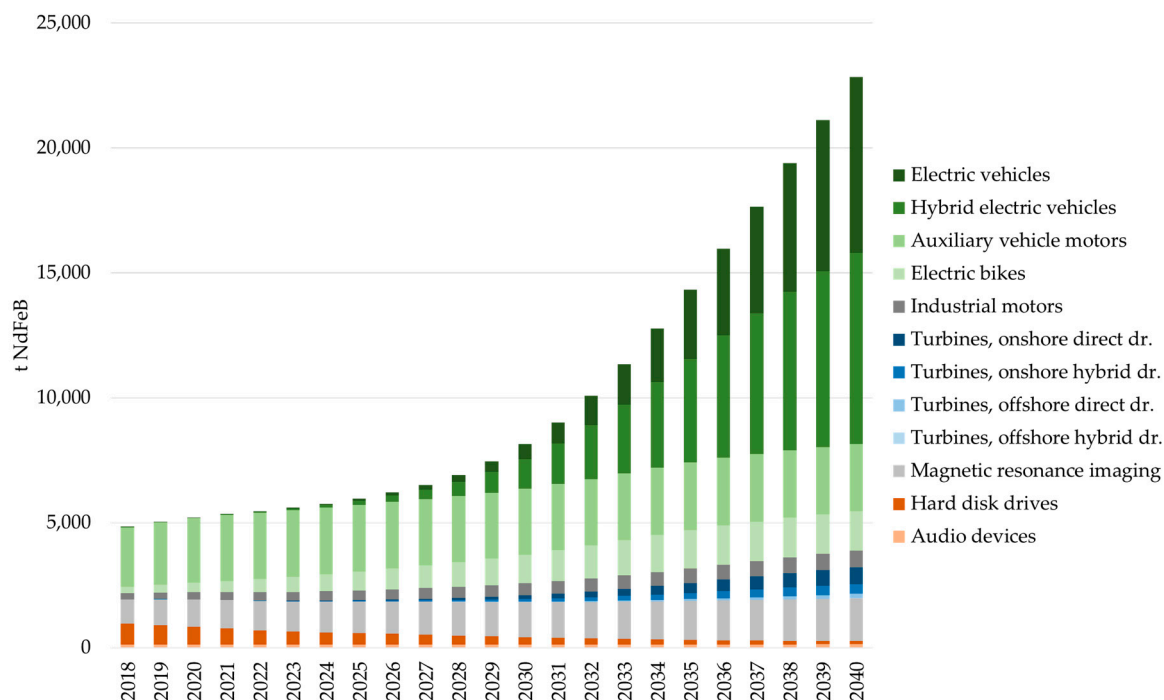


Figure 6. Potential return flows by application in tons of NdFeB.

4. Estimation of the Practical Recycling Potential in the European Union until 2040

The recycling chain of NdFeB magnets consists of the steps: Collection, magnet extraction, and recycling of the extracted magnets, and was recently reviewed by [8]. According to this review, currently, no recycling of NdFeB wastes takes place. However, our own market studies, in collaboration with scrap dealers and electronic scrap recycling companies, revealed that in today's industrial practice, collection of post-production wastes and limited extraction of NdFeB magnets from different applications takes place in the EU [14,43,44]. The magnet scraps are exported to China and Japan for metallurgical recycling. At present, approximately 150 t are exported annually, whereof about 40% originate from magnet production. Whereas the amount of production scrap has been relatively constant in recent years, increasing amounts of scrap from other applications, such as HDDs, MRI devices, and wind turbines, are observed [14,43].

The low traded amount of NdFeB wastes in comparison to the theoretical potential indicates that an extraction is not economic in most cases. The economic feasibility of the magnet extraction depends on the market prices for NdFeB scraps, which are strongly connected to the REE prices, and the extraction costs. The scrap prices fluctuated between 4 and 15 US\$/kg in the last years [43].

For the recycling of extracted magnets, different approaches are currently under development in Europe, which can be classified into direct reuse, reprocessing of the alloys, and raw material recovery, all bearing a series of advantages and disadvantages. At present, none of the approaches is developed beyond pilot scale [5,8,15].

Theoretically, a direct reuse of the magnets would be economically and environmentally the most favourable way of recycling, due to the low energy demand as well as consumption of auxiliary and operating materials. However, in practice, reuse cannot be expected due to progress of development regarding NdFeB magnets and applications, difficulties in the non-destructive extraction of the brittle magnets, and cleaning without compromising the dimensions [5,8,15].

Prerequisites for reprocessing of the alloy are that magnet scraps are of known and homogeneous composition and a thorough removal of any impurities, such as glue residues and coatings, is undertaken, as the magnetic properties deteriorate even at low impurity concentrations (ppm range). For the actual reprocessing of the magnetic alloys, several processes are under investigation, such as re-melting of the alloy, purely mechanical comminution, and comminution after hydrogen

decrepitation. All these options allow feeding of the cleaned magnet scrap into the established production chain for NdFeB magnets. The main drawback of these routes is that contamination with trace impurities cannot be prevented, which causes a deterioration of the magnetic properties. Therefore, reprocessing of alloys cannot be considered a practical way for the production of high-end magnets, a market segment in which European producers are active [5,8,15].

For raw material recovery, various approaches and processes have been developed in recent years, which can be classified into gas-phase extraction, pyrometallurgical methods, and hydrometallurgical methods. Despite disadvantages such as high consumption of chemicals and the production of wastewater, hydrometallurgical processes can be regarded as the most promising way. Reasons for this are their flexibility, with respect to the chemical composition of the wastes, impurity removal, and their ability to treat metallic and oxidized NdFeB wastes (e.g., grinding sludges from magnet production) [5,8,15].

Within the German research project “Recycling of components and strategic metals of electric drive motors”, a life cycle assessment (LCA) was conducted for reuse, reprocessing of the alloy by comminution after hydrogen decrepitation, and a hydrometallurgical process route. The LCA was carried out according to ISO 14040/44 based on small pilot-scale data and reviewed by an independent external expert. The LCA revealed that all these recycling options show clear environmental advantages in comparison to the primary production of neodymium and dysprosium [45].

4.1. Assumptions for the Practical Recycling Scenario

In the following, the assumptions for the realistic recycling scenario are explained for each application based on literature review, interviews with market participants, and our own investigations.

For electric motors, semi-automated extraction technologies for magnets from rotors were developed within a German research project, which can, in principal, be transferred to motors from other applications [15]. However, the scale-up to industrial scale will require at least several years. In case of electric motors, it was assumed that (partly) automated extraction technologies will be available from 2026 onwards at an industrial scale. Therefore, no recycling will take place before 2026 from electric motors. As a European-wide implementation of the extraction technology will require at least several years, a linearly increasing magnet extraction rate from 0% in 2025 to 50% in 2040 was assumed.

For (H)EVs a European recycling rate of 50% was adopted from [46] for all end-of-life vehicles. It was assumed that only traction motors will be extracted from vehicles and dismantled for specific treatment, whereas magnets from auxiliary motors will be lost in the shredding process. An economic assessment of the recycling of propulsion motors concluded that a magnet extraction is economically feasible [15].

For e-bikes, a significantly lower recycling rate of only 5% was estimated. Due to the lack of data on the market for second hand bikes, unknown disposal routes, and the young e-bike market, this rate is a noteworthy uncertainty factor in the calculations. From an economic point of view, magnet extraction is currently uneconomic considering German labour costs, but might be feasible in Eastern and Southern Europe [21].

In case of industrial motors, a recycling rate of 10% was assumed due to high export rate of second-hand motors to non-European countries [25]. Furthermore, the profitability strongly depends on the motor size. Therefore, only mid- and large-size motors were of interest.

In case of wind turbines, it was assumed that 90% of all wind turbines are recycled after their use in the EU, with a magnet extraction efficiency of 90% resulting in an overall rate of 81% from the theoretical potential. The high rates seem to be realistic as the owners are responsible for the dismantling of the turbines, reuse of the turbines in other wind parks after more than 20 years cannot be expected, and the high amounts of large magnets represent a significant monetary value.

Little information is available on the recycling of magnetic resonance imaging devices. As they occasionally appear on the scrap market [43], a recycling rate of 5% was assumed. Like industrial

motors, many second-hand devices are probably exported to developing countries. The extraction of magnets from MRI devices requires demagnetization of the magnets to remove them from the steel frame, but has economic potential due to the high amount of magnets (2–3 t) per unit.

For electronic products, it was assumed that only magnets from hard disk drives are extracted to a certain extent, which already takes place today in sheltered workshops and by prison inmates in Germany, due to the lower labor costs in comparison to the regular labor market [44]. An extraction using regular workers is uneconomic [21]. An extraction of magnets from audio devices was neglected, as they do not appear on the scrap market due to the prohibitive extraction costs [21]. The extraction rate for HDDs was estimated to be 2% of the theoretical potential in the EU. According to our market research, the current extraction rate in Germany is approx. 5%, but this rate cannot be projected to the EU due to the lower recycling standards, especially in Eastern and Southern Europe.

4.2. Possible Scenario for the Availability of NdFeB Scrap in the EU

Based on the theoretical recycling potential and the assumptions in Section 4.1, we obtained the return flows depicted in Figure 7. The general trend was comparable with Figure 6, but on a much lower level. The scenario predicted an annual recycling rate increase from 1% to 21% of the theoretical potential. The overall recycling potential from 2018–2040 was about 25,700 t of NdFeB (see Table 2), corresponding to 7100 t Nd and 1100 t Dy. In comparison to the global consumption of these elements for NdFeB magnets, the impact on the REE market will be low. According to [10], the global demand for Nd/Pr and Dy/Tb was 28,900 t and 2000 t, respectively, in 2013, and is expected to increase to an annual demand of 62,400 t Nd/Pr and 7200 t Dy/Tb until 2035.

The highest recycling potential will stem from mobility and wind turbines, which shows strong growth after 2028. Before 2028, the amounts do not exceed 250 t/year, 1,000 t will be reached around 2033, which is considered the minimum amount for an industrial recycling plant [47]. The predicted return flows in 2018 are in accordance with the information we received from interviews with scrap dealers, who estimated the market volume to be 60–80 t without production wastes from magnet producers.

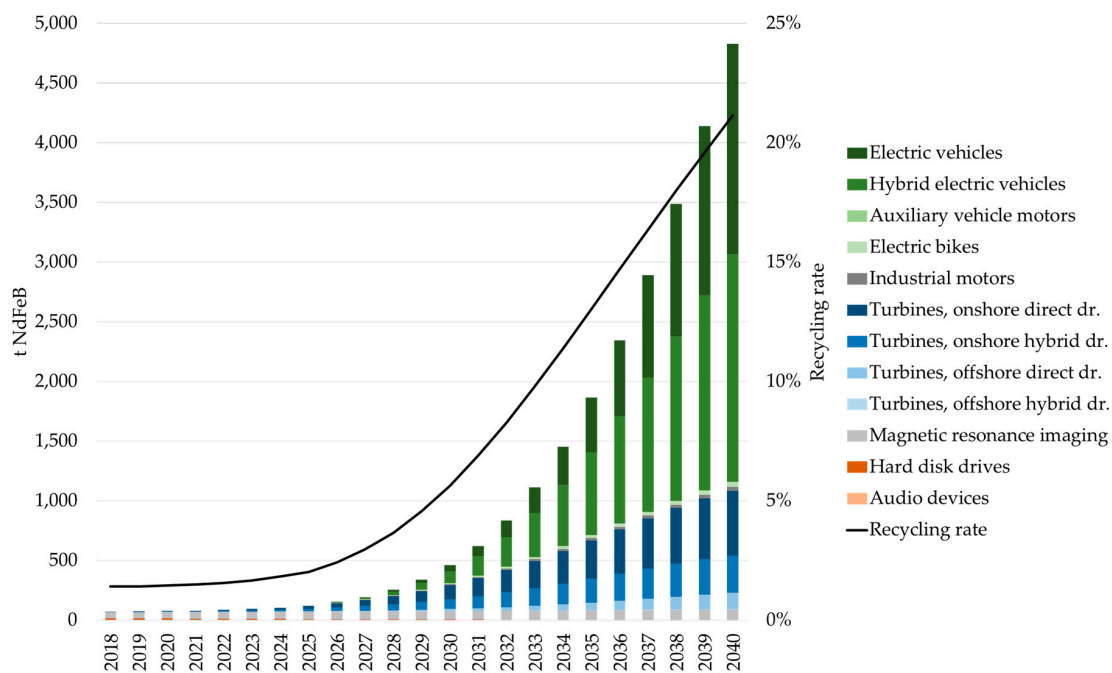


Figure 7. Estimation of the realistic return flows by application in tons of NdFeB and overall recycling rate.

Table 2. Comparison of the theoretical potential and realistic returns of NdFeB in tons accumulated from 2018 up to 2040.

Application	Theoretical Potential Returns [t NdFeB]	Estimated Realistic Returns [t NdFeB]	
Electric Vehicles	36,336	7097	(28%)
Hybrid Electric Vehicles	49,320	9140	(36%)
Auxiliary Vehicle Motors	60,861	0	(0%)
Electric Bikes	23,832	292	(1%)
Industrial Motors	10,575	232	(1%)
Wind Turbines, Direct Drive	5776	4678	(18%)
Wind Turbines, Hybrid Drive	3066	2483	(10%)
Magnetic Resonance Imaging	31,585	1579	(6%)
Hard Disk Drives	8704	174	(1%)
Audio Devices	2836	0	(0%)
Total	232,891	25,675	(100%)

5. Discussion and Conclusions

Since the REE crisis, a lot of research regarding the recycling of NdFeB magnets has been conducted and several companies have discussed the development of NdFeB magnet recycling as a business segment. Despite all these activities, industrial recycling of NdFeB wastes does not take place in the EU. Instead, collected scrap is exported to China and Japan for recycling. This is desirable from an environmental point of view [15], but does not reduce the import dependencies of European companies, a proclaimed objective of many political initiatives.

This study shows that the main reason for this situation is the insufficient amount of NdFeB scrap to feed an industrial plant. According to our appraisal, the necessary volumes above 1000 t/year cannot be expected before 2033. Furthermore, at present, the necessary recycling technology is not available at an industrial scale in Europe. However, considering the predicted slow increase of available NdFeB waste in the upcoming years, there is enough time to scale-up the developed approaches.

Although NdFeB magnet recycling is currently not a profitable business segment for recycling companies, our forecast shows that a strong increase of the available scrap amounts can be expected in the future. Therefore, companies should regularly review industrial trends and scrap market developments to enter the market at an optimal time.

Regarding future research and development, our study shows that an emphasis should be laid on an efficient extraction of NdFeB magnets from mobility applications and wind turbines. In comparison, most other applications are of minor importance for economic reasons, due to expected technological changes, and export to non-EU countries for second use.

Furthermore, a critical discussion regarding the funding of research and development in the field of metallurgical recycling of NdFeB magnets is necessary. Considering the small market share of European magnet producers (approx. 1%), the demand for neodymium and dysprosium metal, which are both primarily used for the production of NdFeB magnets, is low. Both metals are mainly imported to the EU in the form of magnets or magnet containing products. Therefore, the future markets for recycled neodymium and dysprosium are presumably in Asia.

However, a funding stop would inevitably lead to a major loss of metallurgical and material expertise in Europe, which has been (re)built in recent years, and to a further consolidation of Europe's dependency on Asia. Considering the importance of NdFeB magnets for the European automotive and other industries, this development bears major risks. However, to avert these risks a fundamental reorientation in the European raw material policy would be required.

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