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Recycling potential of neodymium: the case of computer hard disk drives

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2.1 Introduction

In this chapter we will explore the question of how much neodymium realistically is available for recycling. First we review the literature on production statistics of neodymium (Section 2.1.1) and its main applications and its potential for recycling (Section 2.1.2). This is followed by a short overview of the technical options for recycling (Section 2.1.3). From this review we conclude that recycling of computer hard disk drives (HDDs) is currently the most feasible pathway towards large-scale recycling of neodymium. In the Results section we present a dynamic model of the recycling potential of neodymium from HDDs. Compared to existing literature we add empirical data on collection rates, using historical HDD shipment figures and up-to-date forecasts for both desktop and enterprise markets in order to improve modeling accuracy. Finally, we will reflect on the potential of recycling to contribute to the neodymium market, and what could realistically be done to close the HDD neodymium material loop.

2.1.1 Statistics on Neodymium primary production and application

Unfortunately, literature sources are rather nebulous on the subject of neodymium production and usage statistics. Zepf¹ shows that almost all literature sources ultimately depend on a single source of information, the China Rare Earth Information Centre. Nevertheless, he estimates that the total neodymium production in 2007 was 21,141 tons. In that same year NdFeB magnet production was estimated to be around 70,000 tons, implying that 18,500 tons (88%), of total neodymium production was used for magnets. Figure 2 shows the breakdown of other neodymium applications.¹ Note that these numbers carry an uncertainty of roughly 40% when compared to different literature sources and market analysis reports.

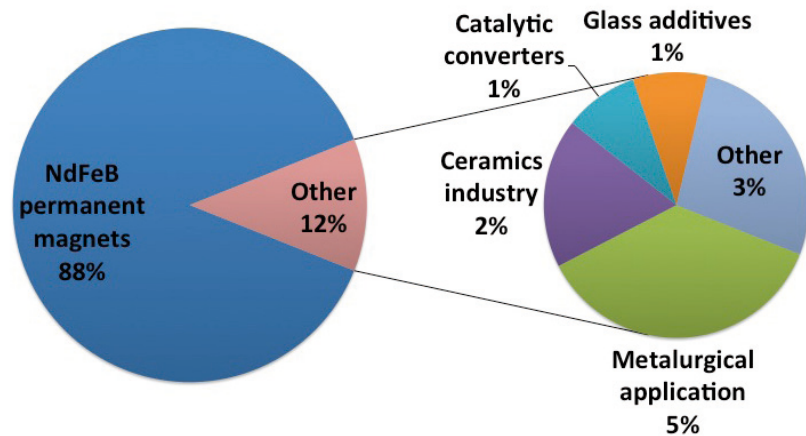


Figure 2 Neodymium use statistics.^{1,2} Note that these figures contain significant uncertainty.

Within the application of neodymium in magnets, data quality is again of concern. HDDs are often cited as the biggest application (30% in 2008),^{3,4} although Zepf¹ arrives at no more than 8% in 2010, a conclusion which is supported by our research presented later in this paper. Other NdFeB applications are noted in Table 1.

Table 1 NdFeB permanent magnet usage statistics.

Application	% range	Comment
Hard Disk Drive	8-35%	Most likely ~ 8% ¹
Wind turbines	0-15%	Most likely ~ 3.6% ¹
Automotive	15-25%	
Electrical motors	25%	Various industrial and consumer products
Optical	5%	
Acoustic	5%	
MRI	5%	
Others	0-37%	Calculated from the sum of other applications

The picture is complicated by reports from market analysis companies that during 2010-2012 NdFeB use fell by 50%, from 80 kton to 40 kton, reportedly because the rising price of rare earths caused many large consumers of NdFeB to switch to alternative technologies without permanent magnets.^{5,6} Looking at 2012 – just after the height of the rare earth scarcity crisis – they peg the worldwide NdFeB production capacity somewhere between 80 kton and 120 kton, implying a large overproduction capacity.^{6,7} This is corroborated by reports in the media that the main producer of neodymium halted production at its main facility for many months in the period 2011-2013.^{8,9}

From a recycling point of view we can see that due to the small volume and varied and/or diffuse nature of the non-permanent magnet applications of neodymium, recycling from sources other than permanent magnets would not make a significant impact on the neodymium supply. In the next section we will review the literature on recycling potential of NdFeB magnets.

2.1.2 Recycling potential

Du and Graedel³ estimate that in 2007 62,600 tons of neodymium and an additional 15,700 tons of praseodymium (Pr) were in stock in society. These in-use stock figures include magnets in many different applications, ranging from household appliances to wind turbines. Data quality issues aside (the authors write that these figures should only be seen as a first indication), these numbers are difficult to correlate directly to recycling because of the varying recycling potential of these different applications. Nevertheless Binnemans et al.¹⁰ attempt to do so by extrapolating the in-stock values given in Du and Graedel¹¹ with estimated growth numbers for the various applications of permanent magnets. They use two scenarios for collection rates, 30% and 60%, and assume a recycling process efficiency rate of 55%. This results in a first, very rough, estimate of 3300 – 6600 tons of Nd+Pr recycling potential from magnets in the year 2020.

Rademaker et al.¹² look at recycling potential from NdFeB magnets in more detail, but for a more limited set of applications. They provide a forecast for recycling potential from wind turbines, automotive and HDDs through 2030.

The very large quantity of magnets used in direct-drive wind turbines¹³ would appear to be a prime target for recycling. However, because of the estimated 20-year lifetime of wind turbines these magnets will not be available for recycling in the foreseeable future. Rademaker et al.¹² estimate that it should be possible to recycle neodymium from wind turbines in small amounts from 2023 onwards. This could increase to 1 kton of Neodymium from wind turbines by 2030, which would notionally cover 10% of the neodymium demand for wind turbines at that time. However, these calculations are made using direct-drive wind turbine projections from before the rare earth scarcity crisis. It has been reported that large Chinese wind turbine producers have reduced their reliance on direct-drive wind turbines.⁶ Therefore these figures could be a significant overestimation of the real future recycling potential in the projected time-span. However, lower demand from wind turbines also implies a lower neodymium demand, meaning that the potential for closing the neodymium loop might be less affected.

The same problems of recent NdFeB usage reduction exist with the estimations given for recycling from automotive applications. Additionally, while the total volume of NdFeB going towards the automotive industry is quite significant, this is not easily recyclable.

A car can contain between sixty and two hundred magnets in anything from seatbelts to the A/C system and different types of magnets are used for the same application depending on the car model.¹⁴ Therefore, automotive is a very difficult sector to start recycling permanent magnets without large and sustained support from the car manufacturers themselves.

Besides the current applications of NdFeB magnets in the automotive industry, there is of course also the promise of large-scale electrical transportation. Zepf¹ estimates that in 2010 ~1% of total NdFeB production was used for hybrid and full electric cars. Although this figure is expected to increase, the large-scale use of NdFeB in electric cars is still an uncertain proposition. For example, the American Energy Department invested \$22 million in research aimed at reducing rare earth use in this sector¹⁵ and it has been reported that future models of the iconic Toyota Prius could be built without NdFeB magnets.¹⁶

Rademaker et al.¹² also provide a first look at the recycling potential of neodymium from HDDs used in PCs. They find that until 2025 HDDs remain the largest source of recycled neodymium. At its peak, in 2015, the HDD industry could source 64% of its NdFeB requirement (11% of total NdFeB demand) from EoL HDDs. This figure then steadily decreases to being able to supply 36% of HDD demand in 2030.

HDDs present a relatively easy path to recycling. Technically recycling is relatively easy, because the magnets are always found in the same place, and are often easily removable once the HDD is opened. The supply of magnetic material should be relatively stable over time because HDDs have been in production for decades and the amount of magnet per HDD has not decreased significantly in the recent past.¹ This leads us to conclude that realistically, HDDs are the only significant and consistent source of recyclable NdFeB at this moment.

We note that the magnets used in HDDs usually don't contain dysprosium, which is another critical rare earth element used to increase the operating temperature of NdFeB magnets. As such, it is used in applications such as electric motors and wind turbines. With respect to the analysis presented in this paper, dysprosium in NdFeB magnets can alter the economic viability of recycling, due to its high price relative to neodymium. Other considerations remain similar.

2.1.3 Short overview of recycling process technologies

In paragraph 2.3 we concluded that at this moment the recycling of HDDs presents the clearest route towards recycling neodymium. In this section we will briefly discuss the technical options most suited for HDD recycling. Unless indicated otherwise we base ourselves on the excellent in depth discussion of rare earth recycling found in Binnemans et al.¹⁰

The first challenge is to remove the magnet from the HDD. This can be done manually. However, the costs are relatively high as an average worker can only disassemble up to 12 HDDs per hour. Hitachi has presented a machine where up to 100 HDDs per hour shake, rattle and roll in a drum until they fall apart, allowing workers to manually remove the magnets.¹⁰

Another approach is to utilize the fact that the magnets are always found in the same corner, and use a shear to cut the section with the magnet from the HDD. Although the magnets will not be completely liberated, most of the volume of the HDD can be removed this way.¹⁰

After separating the magnets from the HDDs, there are three traditional processing routes that could be used for recycling: hydrometallurgical, pyrometallurgical and gas-phase extraction. The hydrometallurgical route is equivalent to the primary production process described in section 2.1. Although this process is well understood, it has the significant disadvantage of requiring the metallic neodymium in the magnet to be converted into a chloride, and then back into its metallic form. This necessitates large energy expenditure, chemical usage and causes significant wastewater production. Although gas-phase extraction, where the extraction process is done while the neodymium is vaporised, was developed to overcome some of the more problematic aspects of hydrometallurgy, it similarly converts metallic neodymium to a chloride.¹⁰

Pyrometallurgical routes are an interesting alternative. Most elegant would be direct melting, where the magnet is melted and directly reprocessed into NdFeB flakes, so it can be further used in the traditional NdFeB production process. Although the nickel coating of the HDD magnets is reported to initially not have any negative effects on magnet performance, repeated recycling would lead to a high nickel content, which not only would degrade magnetic performance but also constitute a waste of the nickel fraction. Various other pyrometallurgical routes are discussed in detail in Binnemans et al. All have in common that they require large amounts of energy for the melting of the material.

We see hydrogen decrepitation as the most promising process for HDD recycling.^{10,17} The magnets are immersed in hydrogen gas, which causes them to disintegrate into small particles. Because the nickel coating does not react to hydrogen in the same manner, it can be removed through sieving. The powder can be directly reprocessed into new magnets because the particle size in the powder is almost equivalent to the particle size after jet-milling in primary magnet production. Recycling process efficiency rates of 95% have been reported.¹⁰

Additionally, hydrogen decrepitation works very well with the mechanical sectioning of HDDs, because the hydrogen will cause the magnetic material to turn to powder while not affecting the rest of the HDD. The powder can then be removed from the HDD case with rigorous shaking, with a reported 95% recovery rate. This eliminates the costly manual disassembly step.¹⁰

2.2 Method

In order to estimate the amount of neodymium available for recycling from HDDs, we constructed a dynamic model, using Vensim software (see supporting information for the model, its underlying datasets and additional information). The life cycle of HDDs was modelled with four main stages: production, in-society stock, End-of-Life (EoL) and recycling (see Figure 3).

2.2.1 Production

In the first stage of the model, the production of HDDs in a given year, we distinguish between two HDD formats: 2.5" HDDs containing relatively small NdFeB magnets, and 3.5" HDDs containing relatively large magnets. We also differentiate on the basis of application (see Figure 4). The time

period 2000-2012 is based on historical production data while 2013-2017 is based on production forecasts by market analysis companies.

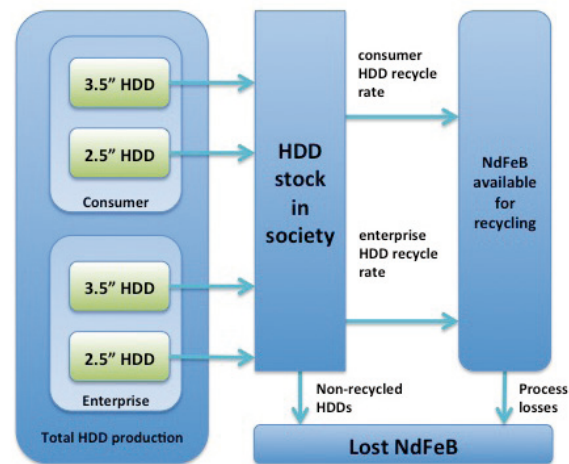


Figure 3 main model elements.

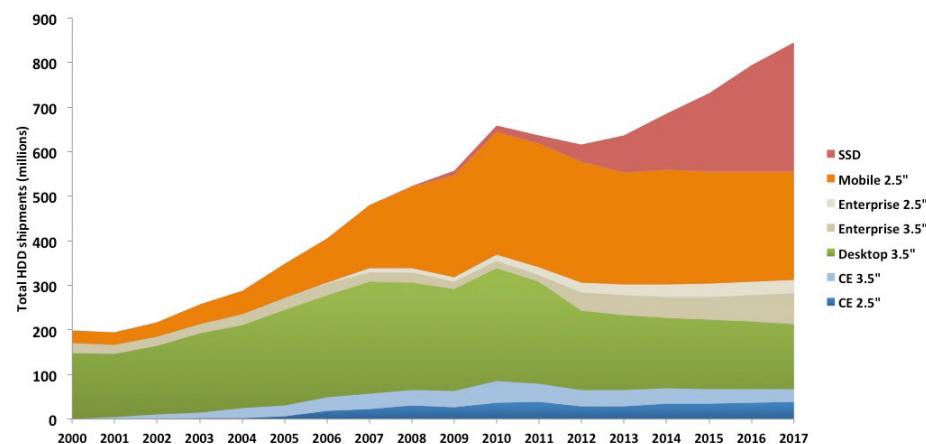


Figure 4 HDD production. Mobile 2.5" drives are used in laptops. Enterprise drives are used in servers or PCs in a business context. Desktop 3.5" are predominantly used in personal computers. Consumer electronics (CE), such as game consoles and digital video recorders, also frequently contain HDDs. For reference, we also include production statistics on solid-state drives (SSD) that do not contain magnets (see supporting information for data and references).

To arrive at the total amount of magnetic material used for HDD production in a given year, the HDD production figure is multiplied with the average NdFeB content of a HDD in that year. Zepf¹ has disassembled a large number of HDDs from the period 1990-2006 in order to measure the

change in NdFeB content of HDDs over time. For 2.5" HDDs there was no measured decrease and we assume 2.5 grams of NdFeB per unit. For 3.5" HDDs we assume that the average weight in 1990 was 17.87 grams, reducing each year by 0.35 grams. Additionally, we disassembled another 10 HDDs produced during 2007-2010. This allowed us to verify that there has been no significant departure from the trend line in more recent years.

2.2.2 In-society stock

The newly produced HDDs flow into the in-society stock, where they reside until the end of their lifespan. For consumer applications the Dutch WEEE collection agency reports an average lifetime of desktop PCs (with 3.5" HDDs) of ten years and six years for portables (2.5" HDDs).¹⁸ In the absence of global data, we assume these numbers to be representative for the rest of the world. For enterprise applications we assumed a six-year lifetime for both 2.5" and 3.5" HDDs, based on information disclosures from large consumers of HDDs in an enterprise setting.^{19,20}

2.2.3 End-of-Life

When the HDDs in the societal stock reach their EoL they can either be collected separately or discarded. This process is different for enterprise and consumer applications. In the Netherlands, personal computers and those consumer electronics most likely to contain HDDs are usually collected at municipal waste collection stations, their ultimate destination being general WEEE processing. On the other hand, HDDs used in enterprise applications are often collected and processed separately for reasons of secure data destruction.

In order to obtain empirically derived collection rates we set up a large-scale experiment at a WEEE-processing company, where three container lots with in total 27 tons of WEEE were sorted by means of hand picking. We found a potential 35% collection rate for HDDs from consumer applications. This experiment is discussed in detail in the supporting information. We assume that this 35% collection rate for consumer applications can be generally applied. We have not been able to conduct experiments for enterprise collection rates, because often they are already collected separately for secure destruction. Based on interviews with industry experts we assume a 90% collection rate.

2.2.4 Recycling

After collection the HDDs the magnets contained within them must still be recycled. In our model this process is represented by the recycling process efficiency coefficient. We assume that the recycling technology of choice is hydrogen decrepitation. In this process roughly 5% is lost when liberating the magnetic powder from the HDD encasing (see section 2.1.3); another 5% is lost due to the recycling process itself. We therefore assume the recycling process efficiency to be 90%.

Multiplying the number of HDDs that are EoL by the collection rate and the recycling process efficiency yields the total amount of NdFeB recyclable in a given year. We note here that the model runs until 2023 because data is available up to 2017, and the shortest HDD lifespan is assumed to be six years. Table 2 contains an overview of all the key assumptions in the model.

Table 2 key model assumption.

Assumption	Value	Source
NdFeB content of 2.5" HDDs	2.5 gram	1
NdFeB content of 3.5" HDDs	17.87-0.35*t gram (t=0@1990)	1
Lifetime of consumer HDDs	2.5" = 6 years 3.5" = 10 years	18
Lifetime of enterprise HDDs	Both sizes = 6 years	19,20
Collection efficiency consumer HDDs	35%	Experimental data
Collection efficiency enterprise HDDs	90%	Interviews with industry experts
Recycling process efficiency	90%	10
HDD production statistics	2000-2012 historical data, 2013-2017 forecasts	TRENDFOCUS INC.

2.2.5 Scenarios

In our baseline scenario the assumed collection rates and recycling process efficiency are relatively high. In order to test the influence of these assumptions in the model we constructed three alternative scenarios (Table 3).

In scenario A we explore what would happen if the collection rates were lower: 25% consumer collection rate (rather than 35%) and a 50% enterprise collection rate (instead of 90%). Note that reducing collection rates has the same effect as reducing recycling process efficiency would have.

The recent turmoil in the rare earth market could give HDD producers incentive to reduce their reliance on NdFeB magnets. Scenario B explores what would happen if the average NdFeB content of HDDs were reduced faster than suggested by the historical trend. We assume that the downward trend in HDD magnet content decreases twice as fast after 2012.

Finally, scenario C explores what would happen if both collection efficiency and NdFeB content were reduced.

The three scenarios are summarized in Table 3

Table 3 Scenario variations.

Scenario	Parameter
A Lower collection efficiency	25% consumer recycling rate/50% enterprise recycling rate
B Improved material efficiency in HDD	Doubling of downward trend in average NdFeB HDD content
C Lower collection efficiency and improved material efficiency in HDD	Combination of A + B

2.3 Results: NdFeB magnet recycling potential from HDDs in the coming decade

The goal of this research was to ascertain the potential of neodymium recovery from computer hard disk drives (HDDs). In Figure 5 we present the results of our dynamic model, showing how the potential for recycling NdFeB magnets from HDDs changes over time. The results are divided into enterprise and consumer applications. For both applications we show the recycling potential from 2.5" and 3.5" HDDs.

Figure 2 also shows NdFeB demand for the production of HDDs, for all applications combined. Because of data constraints, this NdFeB-demand line ends in 2017. Since the shortest lifetime in our model is six years, the recycling potential forecasts ends in 2023.

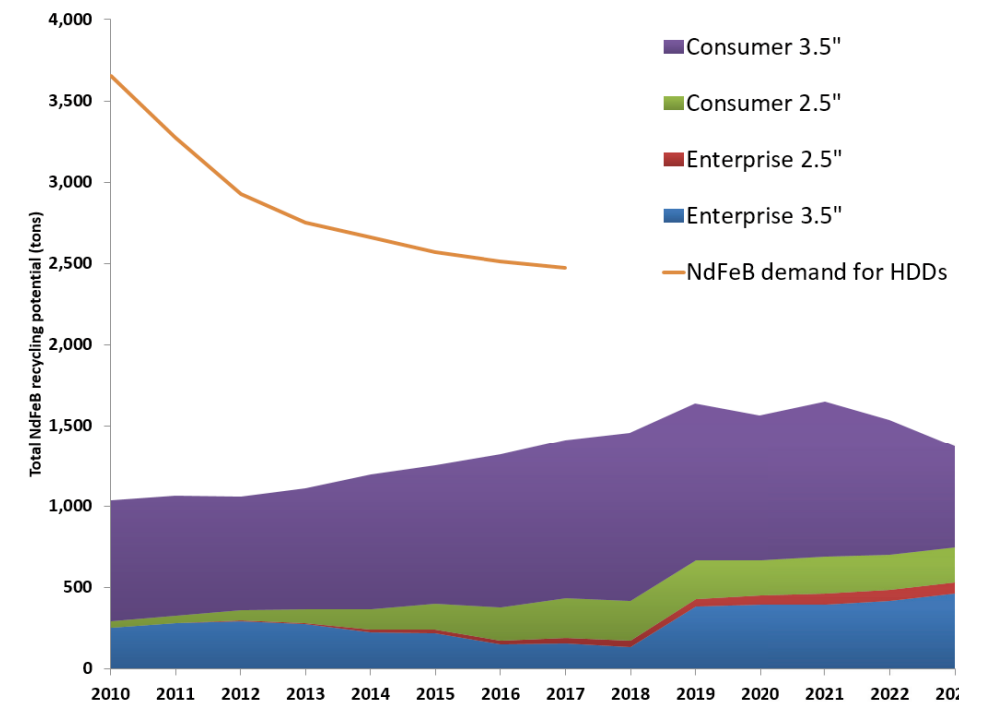


Figure 5 total NdFeB recycling potential (tons) from different HDD types/applications and NdFeB demand for the production of HDDs.

Our results indicate that in 2010, 28% of NdFeB demand for HDDs could have been provided by magnetic material from recycled HDDs. Because of decreasing NdFeB demand and increasing NdFeB available for recycling this increases to 57% in 2017. Based on the trend seen in Figure 5, it would be reasonable to assume that this number increase through 2023, after which the reducing quantity of NdFeB available for recycling will cause the loop-closing potential to decrease.

It is also of interest to put these results in the context of the wider Neodymium market. Our model

shows that between 1.0 and 1.6 kton NdFeB can be recycled. Considering that the total NdFeB consumption in 2012 was roughly 40 kton and that this is projected to climb to 80 ktons in the near future,⁶ our results imply that recycling from HDDs can supply in the NdFeB market with 1-3% of total demand.

In 2018 there is a sharp increase in NdFeB recycled from 3.5" enterprise HDDs. This is caused by the underlying dataset, where a methodological change in 2012 caused so-called 'nearline HDDs' (which are optimized for low-cost high storage capacity) to be added to the enterprise segment, at the expense of the 3.5" consumer segment.

The relatively sharp drop at the beginning of the NdFeB-demand line results from the chosen timespan, which coincides with major floods in Thailand. These caused a number of HDD factories to close, resulting in significantly lower HDD production. Subsequent reductions in HDD production results mostly from a shrinking market for 3.5" consumer HDDs, combined with a lower NdFeB content per 3.5" HDD.

Scenario analysis

In order to test the main assumptions in our model we constructed three scenarios. The results of these are shown in Figure 6. As expected, reducing the collection rate (scenario A and C) has a large impact on the results. On the other hand, varying the amount of magnetic material found in HDDs is less influential, although the effect would increase with time. Note that in scenario C lower collection rates also lessen the total impact of decreasing the NdFeB content of HDDs.

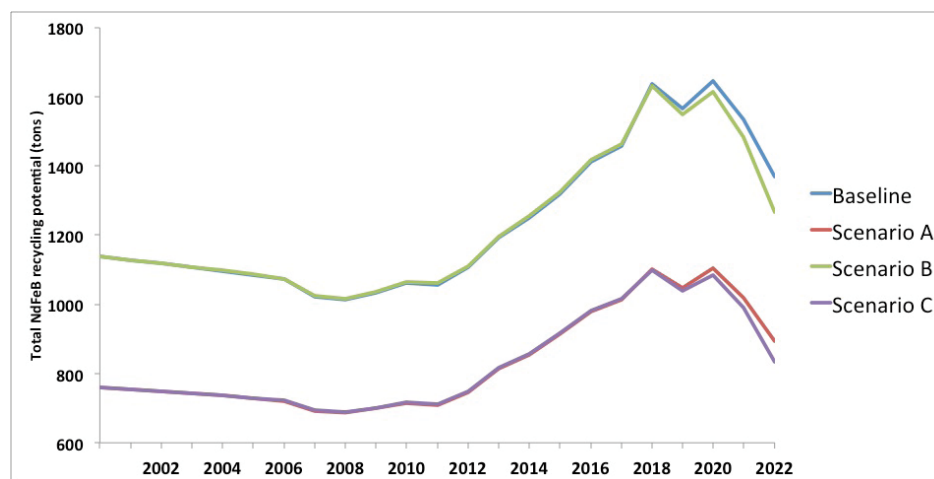


Figure 6 comparison of the baseline scenario with the three recycling scenarios described in Table 3.

2.4 Discussion

In this chapter we investigated the recycling potential of neodymium. Through literature analysis we concluded that of all current neodymium applications, NdFeB magnets are by far the most

dominant. Furthermore, in most non-magnet applications neodymium is dispersed to such a degree that setting up a closed loop recycling system would be very difficult.

However, even when restricting ourselves to NdFeB magnets, we find that its usage is spread among an enormous range of applications. Wind energy and e-mobility are often seen as significant potential recycling sources because they contain a high volume of magnets. However, literature shows that because of long lifetimes and price sensitivity these magnets will probably not be available for recycling in large volumes in the next two decades.

As we can see from the tumultuous developments in the neodymium market in the past few years, making predictions on neodymium recycling two decades away is a too long time-horizon for forecasting. Therefore we believe that in the foreseeable future the only realistic source of recycled magnets is from computer hard disk drives (HDDs).

We looked in more detail at recycling from HDDs, using a combination of experimental data and dynamic modelling. Within the application of NdFeB magnets for HDDs the potential for loop closing is significant, up to 57% in 2017. However, compared to the total NdFeB production capacity, the recovery potential from HDDs is relatively small (in the 1-3% range).

In practice there are some obstacles to recycling NdFeB from HDDs.

First, the costs are currently prohibitive. The going rate for 1 kg of EoL magnets in Japan is 10-12€ (although the price can vary according to the dysprosium content, personal communication Toshiyuki Kanazawa, Kanazawa Shokai, 02-05-2014). Although this is an order of magnitude more than the recycling value of shredded HDDs (± 1.2 €/kg, personal communication Ramon Bongers, Van Gansewinke Groep, 02-09-2013), the low weight of the magnet makes that the added value of recovery does not exceed the added processing costs. Likewise, although disassembly of HDDs yields a clean printed circuit board (PCB) fraction, containing a host of precious metals, the PCB is usually already mechanically sorted from shredded HDDs. Therefore this makes little difference to the final financial calculation.

Second, for enterprise applications we assumed that HDDs collected for secure destruction are available for recycling, since they are already collected separately. However in practice, contractual agreements sometimes stipulate that HDDs must be shredded immediately upon arrival at the waste management company. This makes it more difficult for companies to experiment with recycling. Finally, without high-temperature demagnetization, shipping and handling large volumes of NdFeB magnets can be difficult, because of their very high magnetic strength.

In the longer term there are a number of wild cards to consider. Although it is not forecasted that SSDs will significantly reduce the usage of HDDs, a technological breakthrough could cause the price of SSDs to drop significantly, which in turn would drive replacement of HDDs by SSDs. Manufacturers could also choose to drastically reduce the amount of NdFeB contained in HDDs, or change HDD design so that the magnets are less easily recycled. For instance, recently HDDs have

become available that are filled with helium, in order to reduce friction with the spinning platters. These are welded shut to prevent the helium from escaping. Presumably this also makes it more difficult to recover the magnets (personal communication Thomas Coughlin, Coughlin Associates, 20 - 11- 2013).

We suggest that it could be possible to design a HDD so that a true closed loop should be possible. Considering that the aluminium casing and the placing of the magnet is almost identical in every HDD we imagine it should be possible to standardise these two components and use a simple standardised method to remove the other components from the casing.

Moving beyond the subject of how much NdFeB we can recycle, we would like to address the question of what problems recycling would alleviate. The discussion is often framed in terms of security of supply: for western countries it is not desirable to be dependent on China for virtually the entire supply of rare earths. Since most of the basic processing facilities that are needed to produce neodymium magnets are to be found in either China or Japan, measures to reduce dependence should focus not only on the recovery of NdFeB from waste, but also on the production facilities to reprocess the EoL magnets into new material.

In terms of resource scarcity, we think that in the near future, recycling neodymium will be able to contribute very little because of the distributed nature of the applications. The fact that the whereabouts of a critical metal such as neodymium can only be traced for such a small fraction of the total use, leading to a diminutive recycling potential, should give pause for thought. We suggest that if neodymium is to be used sustainably, a concerted effort must be made to categorize the applications in which it is possible to create a closed-loop and only use Neodymium for these applications. The potential of recycling can be increased significantly if neodymium can be traced from mine to material, product and finally to waste. Therefore we are now working on combining global input output data with data on product composition in order to increase our knowledge on the whereabouts of different elements (<http://fp7desire.eu/>).

Finally, as other authors have done before us,¹ we would like to highlight data quality issues. During our literature research we found many inconsistencies and data of uncertain origin. We have tried to provide a quantitative model on the basis of the available data, but given the degree of cross-referencing in the current literature, more accurate results require new sources of primary data.

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Supporting Information Available

A description of the collection experiments and a short analysis of the environmental benefits of HDD recycling, the input and output of the dynamic model and the dynamic model itself. This material is available free of charge via the Internet at <http://pubs.acs.org/>.

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