Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling

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ABSTRACT: End-of-life recycling is promoted by OECD countries as a promising strategy in the current global supply crisis surrounding rare earth elements (REEs) so that dependence on China, the dominant supplier, can be decreased. So far the feasibility and potential yield of REE recycling has not been systematically evaluated. This paper estimates the annual waste flows of neodymium and dysprosium from permanent magnets, the main deployment of these critical REEs, during the 2011−2030 period. The estimates focus on three key permanent magnet waste flows: wind turbines, hybrid and electric vehicles, and hard disk drives (HDDs) in personal computers (PCs). This is a good indication of the end-of-life recycling of neodymium and dysprosium maximum potential yield. Results show that for some time to come, waste flows from permanent magnets will remain small relative to the rapidly growing global REE demand. Policymakers therefore need to be aware that during the next decade recycling is unlikely to substantially contribute to global REE supply security. In the long term, waste flows will increase sharply and will meet a substantial part of the total demand for these metals. Future REE recycling efforts should, therefore, focus on the development of recycling technology and infrastructure.

1. INTRODUCTION

The rare earth elements (REE) group consists of yttrium, the lanthanides series and, in some definitions, scandium. Their unusual magnetic and optical properties make them crucial to a variety of highly technological applications. Kingsnorth’s supply demand statistics indicate that “the supply and demand for individual REOs is not in balance” and that at least until 2020 it will remain so with shortages for neodymium (25%), dysprosium (23%), terbium (29%), and erbium (39%). Other REEs will be in excess.1 The imbalance is partly caused by relatively low occurrence of certain REEs in mineral deposits versus higher occurrence of other REEs. Furthermore, with an 86% share of production in 20122 and various announced export quotas1 China dominates the REE market. Fifty percent of the global REE reserves are in China.2 With current and forecast supply shortages, and the geopolitical situation resulting from limited Chinese exports, REEs have a high “supply risk”.3 This, along with their importance in various clean and high-tech applications, has led the EU and the U.S. to label certain REEs, such as neodymium and dysprosium, “critical” metals.3,4 Recycling is often cited as one of the ways of reducing REE criticality.

The focus in this article is on high-performance sintered NdFeB magnets that deliver high levels of magnetic strength in relatively compact sizes. NdFeB magnets were first implemented in the 1980s and have become essential in applications crucial to the transition to a low-carbon economy. In 2008, rare earth permanent magnets (REPMs) accounted for 21% of all REE use in terms of volume and 38% in terms of value5 and constitute the most important REE application with anticipated supply issues. At 10−15% per annum between 2010 and 2015, the highest expected growth rate of REE applications will be from NdFeBs.6

All NdFeB magnets contain neodymium (Nd). Sometimes terbium (Tb) is also added. Dysprosium (Dy) is introduced when it is necessary to increase the operating temperature.7 Praseodymium (Pr) is generally added to replace neodymium at a lower cost. These are all considered “critical metals”.4 REE supply risks negatively impact the development of certain NdFeB applications, such as direct-drive wind turbine generators and high performance electric motors in hybrid electric vehicles.8 At present NdFeB magnets cannot be substituted by other permanent magnets without some performance loss.9 NdFeB magnets contain high concentrations of rare earths (see Table 1) from the magnets themselves.

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Their recycling is potentially technically feasible if efficient physical dismantling and separation techniques, and metallurgical separation and refining methods, are available in the future. No commercial recycling exists for rare earths derived from end-of-life (EOL) NdFeB magnets\(^{10}\) nor for other rare earths derived from other EOL products.\(^{11}\) Industrial recycling only exists for REE recovery from manufacturing scrap and waste.\(^{12,13}\) This is mainly due to the relatively low prices of REEs in the past and the complex and dissipative use of REEs including the permanent REE magnet (REPM). There was simply no incentive in the past to develop industrial recycling technologies. Supply issues and in particular sharply rising prices for most REEs in recent years have created new REE recycling incentives, also economically.

Recycling can potentially reduce dependence on virgin production\(^{15}\) while altering the geographic distribution of REE supply. In 2007, the global in-use stocks of the rare earth elements Nd, Pr, Dy, and Tb in NdFeB magnets in computers, audio systems, wind turbines, automobiles, household appliances and MRI was estimated to be 97 Gg; four times the extraction level in that year.\(^{16}\) These in-use stocks indicate opportunities for recycling in general but do not specifically

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### Table 1. Key Assumptions in the Calculation of EOL REPMs Flows from Wind Turbines, Automotive Technology, and HDDs in PCs.\(^{a}\)

<table>
<thead>
<tr>
<th>assumption</th>
<th>wind turbines</th>
<th>automotive</th>
<th>HDDs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010: 10</td>
<td>2020: 22.5</td>
<td>2030: 30</td>
</tr>
<tr>
<td>percentage of sales or installed capacity that contains REPMs (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>mass of REPM (kg)</td>
<td>700</td>
<td>&lt;2008: 0.65–1.24</td>
<td>1.05</td>
</tr>
<tr>
<td>composition(^{b}) (%)</td>
<td>Nd: 29</td>
<td>Nd: 29</td>
<td>Nd: 29</td>
</tr>
<tr>
<td>lifetime(^{c}) (years)</td>
<td>regular: 20</td>
<td>Dy: 9</td>
<td>Dy: 9</td>
</tr>
<tr>
<td></td>
<td>repowering: 12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>incl. refurbishment: 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>collection rate (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

\(^{a}\)Refer to section B of the SI for more input data. \(^{b}\)The neodymium content in the composition of the magnets is the sum of Nd and Pr. \(^{c}\)HDDs: Including hibernation period.

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Figure 1. Calculation model for EOL potential of REO in REPMs in HDDs in PCs.
quantify that potential. In the current literature there are no estimates concerning future end-of-life (EOL) REE flows. Such quantification of future EOL flows is, however, the basis upon which the potential of a recycling strategy to reduce REE criticality can be assessed.

Du and Graedel estimated that in 2007 computer, wind turbine and automotive applications accounted for 66% of all NdFeB use. This represents the bulk of all NdFeB use. Over 80% of the REE content in NdFeB magnets in the above-mentioned applications is in the form of neodymium and dysprosium so considering these elements accounts for a substantial portion of NdFeB use. In terms of annual production data, in 2008 NdFeB magnets accounted for 76% of Nd use, 73% of Pr use, 100% of Dy use, and 11% of Tb use. In this article, we estimate the future annual EOL flows and in-use stocks of neodymium and dysprosium in NdFeB magnets in wind turbines, electric motors in hybrid and electric vehicles, and hard disk drives in PCs between 2011 and 2030.

By quantifying the recycling potential, the results of this research will contribute to recycling in order to reduce REE criticality. Not only the data, but also the general trends in recycling will influence strategies on REE criticality.

2. METHODOLOGY

The metal life cycle consists of four principal stages or processes: extraction, fabrication and manufacturing (F&M), use, and waste management and recycling (WM&R). These stages form the basis to material flows analysis (MFA). In this research, the inflow in finished products was taken as a starting point and transformed to forecast end-of-life flows that enter the WM&R stage. All forecasts were performed on two geographical scales: global and EU-27. This article mainly presents global results. Outcomes for the EU-27 are attached in the Supporting Information (SI) in sections C1 and C2. The forecast EOL flows are presented in terms of REO content (Nd2O3 and Dy2O3), which is a common form when trading rare earth elements as commodities. Here these oxides are simply referred to as neodymium (Nd) and dysprosium (Dy).

Figure 1 illustrates the EOL flow model predictions. Examples and data are given in brackets. The methodology is explained by discussing the forecast EOL hard disk drives (HDDs) from PCs. The calculation model for Wind turbines and Automotive motors is attached in the SI (Figure S1 and S2). The key assumptions are elucidated in Table 1 and section 2.3.

2.1. Inflow in Finished Products. The data on unit sales (automotive, HDDs in PCs) and newly installed capacity (wind turbines) comprised the main input and was based on industrial reports, sales forecasts and expert opinions.

A technological type distinction was made for automotive (plug-in hybrid electric vehicles and hybrid electric vehicles versus full electric vehicles) and HDDs (desktop versus portable). The data were then translated to neodymium and dysprosium content that enters the in-use stock.

In Figure 1, the inflow into finished products is based on a “baseline” sales forecast. To determine the composition of the forecast waste streams, the percentage of desktop and portable PCs in the total sales was extended to overall PC sales forecasts. EOL flows from portable and desktop PCs are calculated separately, because they have a different lifetime, rate of adoption of solid state drives (SSD), and REPM mass per unit product. The number of HDD-based desktops and portables (tablets excluded) is obtained by multiplying the forecast unit sales with the percentage of PCs that contain HDDs (C for desktops and D for portables). HDDs in other applications, such as data centers, are not included in this analysis. Multiplying the amount of HDD in desktops and portables by the REPMs mass per HDD (E for desktop, F for portable) results in the total amount of REPMs in the sold desktops and portables. Lastly, the inflow of neodymium and dysprosium into finished products is obtained by multiplying the total REPM mass by the composition (I) and converting the mass to the oxide equivalent: Nd2O3.

2.2. End Of Life Stage. The EOL flows in the WM&R stage were calculated on the basis of the flows into use and the lifetime of the applications. Export and reuse were also considered.

In Figure 1, the HDDs leave the in-use stock as EOL flows into the WM&R stage after a certain average lifetime (G). A part can be exported for reuse and informal recycling (H). The remainder (J) forms a waste stream of EOL desktops and portables. The maximum recycling potential is the share (K) that is collected for recycling from the waste stream of EOL flows. The collection rate is defined as the number of collected EOL HDDs from PCs, divided by the number of generated EOL flows from HDDs in PCs in that year.

2.3. Key Assumptions. Table 1 lists the key assumptions of this study. More input data can be found in the SI (section B).

Three scenarios were created, based on varying assumptions (SI section B4). The lower bound scenario assumed that growth would be slower both in applications (e.g., installed wind power) and REPMs in those applications (e.g., lower percentage of REPM-based turbine models). With the upper bound scenario, the opposite applied. Differences in collection rates were also accounted for. In this article the midrange scenario (i.e., baseline scenario) is presented. The lower-bound and upper-bound scenarios are attached in the SI (section B4 and C3).

The historic and forecast data of installed wind capacity were based on Global Wind Energy Council and European Wind Energy Association reports. The automotive forecast was mainly based on two reports: one by the global marketing information services company J.D. Power and one by the global management consulting firm McKinsey & Company. In all three cases, there is a degree of uncertainty about how the industry will develop. The development of wind energy is embedded in a complex interplay of policy making, technological development, the economic climate and global events that influence public opinion (e.g., the Fukushima disaster). Similar factors shape the development of hybrid and electric vehicles, the main difference being the role of consumers, since vehicles are typical consumer products. The PC market is characterized by rapid and unforeseen developments (e.g., the success of tablets and solid state drives), as is typical in much of consumer electronics.

Uncertainties in technological development were analyzed on the basis of research reports, news articles, and expert opinion. Some of the issues related to the use of REPM magnets in wind energy technology are: certain producers, notably the German Enercon, produce non-REPM-based direct drive generators without performance loss; REPM-based direct drive generators are viewed as a new technology, which brings risks to investors, engineers are reducing the need for dysprosium by using air-cooling; finally, current and forecast REE supply issues bring risks for the manufacturing and maintenance of REPM-based wind turbine generators thus creating oppor-
tunities for other technologies. In the automotive industry, there are no commercially available substitutes for REPM-based electric motors that do not have significant performance losses. Research into non-REPM-based induction motors has however been announced and some success has been claimed. In the HDD market, the influence of tablets on PC sales and the rate of implementation of the SSD in PCs are the main uncertainties. However, SSDs are expected to remain a more expensive storage medium. The impact of SSDs on HDD demand is, therefore, dependent on the future storage capacity requirements of PCs. On PC sales, a lower bound scenario was performed (section B4 and C3 of SI).

The exact composition of NdFeB magnets differs per application. There is no clear composition data uniformity. The low neodymium estimate is 20%. Estimates made by Shin Etsu, Great Western Minerals Group, Technology Metals Research and Avalon Rare Metals range from 28% to 31%. It should be noted that in most applications, the NdFeB magnet also contains certain amounts of praseodymium (Pr), a cost-effective neodymium replacement with no significant performance penalties. The extent to which praseodymium is added is strongly influenced by price-developments and differs per year and producer. In our calculations, the Nd figures are the sum of Nd and Pr as listed in Table 1. We assumed the neodymium content to be 29%. The dysprosium content in NdFeBs per application is presented in Table 1.

The collection rate is accounted for in the quantification of the recycling potential. For current rates, published statistics were our main source. For future collection rates we have taken the maximum feasible collection rate to obtain a maximum recycling potential. We have based our estimates on policy targets and educated guesses in line with the criteria influencing collection. One important criterion was the producer–user relationship, where a business-to-business relationship proved advantageous for collection rates. The collection rates of industrial goods tend to be higher in business-to-business relationships, because of stakeholder awareness, limited ownership changes, use location, and economic recycling incentives.

2.4. Metrics and Terminology. To gauge the significance of the forecast EOL quantities as a supply source they need to be related to new metal production. The recycling input rate provides such a gauge and also includes factors such as new scrap recycling not included in this research, while “potential recycling supply ratio” (PRSR) is used here as an indication of the old scrap recycling potential: dividing collected EOL quantities in year \( x \) by the inflow of metal for newly finished products in that same year \( x \):

\[
\text{potential recycling supply ratio (PRSR)} = \frac{\text{REO in collected EOL flows}}{\text{REO demand}}
\]

The PRSR defined here is the “static” potential recycling ratio. It compares the collected EOL products or scrap that is ready for recycling with the total production or demand for such metal in the same year. By contrast, a dynamic PRSR would compare the collected EOL products or scrap in a certain year to the total demand in the year of manufacturing of the EOL products. When there is more than one type of product and with very different life cycles — like a combination of REPM scrap from wind turbines, automotive motors and computer HDDs, it becomes impossible to use “dynamic” PRSR to quantify the total recycling ratio for a specific metal. When predicting the present and future potential recycling rate, “static” PRSR gives a better quantification of how important the recycled materials are compared to total demand at any time. Since it gives a more direct comparison for market demand than the inherent source of EOL products, static PRSR is used in this article to quantify the recycling potential.

“REO demand” is the term to indicate the REO content of newly finished product inflow. When REO content in collected EOL flows becomes input in finished products, there will be efficiency losses during the new metal production stage. Ideally, these losses are accounted for in the PRSR. However, due to an absence of accurate data on this process, these losses are not included. If they were included, either a lower amount of EOL flows would remain after new metal production, or a higher ‘REO demand’ would be needed as new metal production input. Either way, the actual ratio lowers proportional to the efficiency ratio of the new metal production process. This ratio is further lowered by losses in the preprocessing and end-processing of EOL products. These losses are not included as the practice of preprocessing and end-processing is still in an early stage of development and efficiencies of possible processes vary widely. When the EOL product collection rate increases, the PRSR increases proportionally.

When interpreting the data, it should be remembered that the PRSR will be lower, proportional to efficiency losses in new metal production and preprocessing and end-processing in the end-of-life stage.

3. RESULTS

Figure 2 shows that in the short term (<2015), the global recycling of 0.5 Gg neodymium from EOL wind turbine generators, hybrid and electric vehicles, and HDDs in PCs potentially covers 11–15% of the total REO demand. For dysprosium this is 0% (Figure 3), as EOL HDDs do not contain dysprosium and REPMs from wind turbines and hybrid or electric vehicles will not yet have entered waste streams. In the midterm (~2020), the sharp increase in the REO demand results in a lower PRSR: five percent for neodymium and around one percent for dysprosium. The forecast for total quantities in 2020 are 0.45 Gg for neodymium and 0.011 Gg for...
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supply around 50% of the required REO for new HDDs. This means that the forecast amounts of EOL HDDs have the potential to be recycled. Understanding how the potential recycling quantities per source relate to the REO demand is crucial.

Due to their long lifetimes, it will not be until the late 2020s that wind turbine and hybrid vehicle recycling will slowly become a dominant source. Dysprosium will follow a similar trend.

Figure 3 shows the potential recycling quantities of neodymium and dysprosium by source. Until 2020, EOL HDDs will be the main source for the recycling of neodymium. Due to their long lifetimes, it will not be until the late 2020s that wind turbine and hybrid vehicle recycling will slowly become a dominant source. Dysprosium will follow a similar trend.

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Figure 4 shows the potential recycling quantities of neodymium and dysprosium by source. Until 2020, EOL HDDs will be the main source for the recycling of neodymium. Due to their long lifetimes, it will not be until the late 2020s that wind turbine and hybrid vehicle recycling will slowly become a dominant source. Dysprosium will follow a similar trend.

Table 2 lists the data behind Figures 2–4. It adds data on how the potential recycling quantities per source relate to the REO demand of each source. It is clear that with neodymium, the forecast amounts of EOL HDDs have the potential to supply around 50% of the required REO for new HDDs. This might create incentives for individual HDD manufacturers to collect and recycle EOL HDDs.

The analyses were also performed at EU-27 level. Recycling potential is especially important to the EU-27, as it is a region that typically consumes a large volume of products containing REEs but has few natural resources. Figure 5 shows the potential recycling results for neodymium in the EU-27, in comparison to the global scale. More EU-27 results are provided in Section C1 and C2 of the SI.

The potential recycling quantities follow a similar trend within the EU-27 to a global level. In the long term (2030), the potential recycling supply ratios should be slightly lower. Until 2020, the global REO demand will rise at a higher rate than within the EU-27, which results in a slightly higher EU-27 recycling supply ratio. This difference can be explained by the influence of the rapidly growing developing countries largely outside the EU-27.

With neodymium (see Figure 6), the in-use stock is steadily increasing. The constant upward trend indicates a further increase in EOL flows after 2030. A similar trend is found for dysprosium (Figure S11 of the SI). Until 2015, HDDs comprise a dominant part of the neodymium stock. From then onward wind turbines and the automotive sector become dominant categories.

The estimated global in-use stock of 11 Gg neodymium in 2011 is significantly lower than the estimated amount in previous research of 41 Gg neodymium (equivalent to 48 Gg neodymium-oxide) for "wind turbines", "automobiles", and "computers" in 2007.16 Whereas Du and Graedel took Chinese production data on NdFeB magnets as their basis for calculations, we took the actual shipment and placement of applications as our premise.

In theory, the results of both approaches are expected to match. Differences within the product category definitions could partially account for the difference in results.

Quite how one can account for the difference remains unclear. The results therefore require detailed discussion. The modeling in this research was kept relatively straightforward and the input data fully transparent, thus making the results as a whole transparent to facilitate such discussion.

4. DISCUSSION

If climate change is to be tackled, society will need to switch in the next three to four decades to a carbon-lean energy system. Rare Earth Elements play a crucial part in this transition as they are vital to many high tech and especially green tech products and services including wind turbines, hybrid and fully electric vehicles and highly efficient lighting systems including LED. The supply of these materials is constrained by several factors. Although new operations are starting up worldwide, both the mining and the processing of these materials is still dominated by one single country: China. Furthermore, new mining and processing operations are technically difficult, capital-intensive and commercially risky to initiate, and finally, REE recycling from postconsumer waste is still negligible. Increasing the postconsumer waste recycling rate is often advanced as one of the ways to reduce dependence on virgin production.

This study has explored EOL NdFeB magnet recycling in a bid to reduce the criticality of rare earth elements. The focus was on neodymium and dysprosium recycling from NdFeBs in three main REE applications: wind turbines, hybrid and electric vehicles, and HDDs in PCs.

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With the sharp increase in REO demand for emerging technologies, the potential recycling supply ratio for neodymium will drop to five percent toward the year 2020, whereas for dysprosium it will remain zero percent. Sharply increasing the potential recycling quantities and high in-use stocks will, in line with conclusions from previous research, bring significant recycling potential in the long term (2030).

Results indicate that worldwide the recycling potential for the coming decades is limited when compared to the demand for finished products. Because of the low waste volumes, the advantages in economies of scale of recycling are unlikely to be achieved. The absence of mature processes for preprocessing and end-processing further reduces the current recycling potential. However, the forecast EOL volumes do offer opportunities for developing recycling technology through pilot projects. Such pilot projects will, in the long term, help to build a recycling industry for handling larger volumes.

Since the beginning of this decade, global governments and industries, in particular in Europe, Japan, and the U.S.A., have started to invest in developing REE recycling technology from the whole value chain perspective by increasing collection rate, improving physical separation efficiency, developing efficient metallurgical processes for recovery and refining REEs from potential secondary REE resources. The NdFeB magnet is one of the most important secondary resources for neodymium and the sole recycling source for dysprosium. Promising techniques are being developed, such as the successful powdering of NdFeB through hydrogen separation at room temperature and atmospheric pressure (decrepitation) to subsequently produce new sintered NdFeB magnets.32

For consumer products, one recycling challenge is the physical dismantling and up-concentration of small NdFeB magnets in diversified scrap. REPM in wind turbines and EV/HEV vehicles is much more easily dismantled and physically up-concentrated, and even reuse is possible after refurbishing. In general, efficient metallurgical separation and refining processes remain the main challenges. It is estimated that approximately five to ten years is required to set up a recycling practice.10 Policy makers should therefore also explore other REE criticality reduction strategies, such as substitution and supply route diversification.

The presented results indicate a general trend that is typical for the emerging technologies metal market: sharply increasing demand and an EOL time-lag. Recycling will only become a significant lever after the time-lag and demand has stabilized. That does not, however, imply that there is no recycling potential for certain specific applications, actors (e.g., HDD producers) or regions (e.g., EU-27). In the latter case, it can decrease dependency on virgin materials or even create a surplus, given the fact that the REO content in collected EOL flows and the REO demand are not evenly distributed in geographic terms.

In this research the recycling potential was not calculated for audio systems, although they represented 24% of the in-use stock of Nd and Dy in NdFeB magnets in 2007.16 Adding audio
systems to the calculations could increase the forecast EOL flow totals but would not alter the main time-lagged EOL flow trends that the scenarios show.

Comparing the amount of REO in EOL flows to the demand for REO indicates the potential significance of recycling. Two important factors were excluded: first that REO that can be retrieved from EOL flows will be lower due to losses during the preprocessing and end-processing of old scrap. Second, there will be losses when manufacturing products containing REE. These losses were not included in our future REO demand calculations, so that the potential recycled material contribution to the total supply will be lower than estimated in this study. This further supports the main conclusion of this research concerning the limitations of recycling as an REE criticality reduction strategy.

We have presumed that growth in demand will not be influenced by supply constraints. However, supply constraints are forecast and could reduce demand when substitute materials and technologies are developed. Examples are NdFeB-free electric motors for use in cars and wind turbines with air-cooling, which reduce operating temperature and thus the need to add dysprosium to the NdFeB magnet.

Simply having a recycling strategy is unlikely to solve rare earth element supply chain issues. Billion dollar industries that rely on relatively small REE industry for primary supplies, depend just as much on subsequent steps in the REE supply chain. This is especially important since one country (China) dominates all subsequent steps in the REPM production chain. Therefore, a recycling strategy should preferably be placed in the broader strategy of developing an industry in the smelting and refining of REOs, the fabrication of alloys and powders and the manufacturing REPMs.

Further research should focus on extending the forecast EOL flows to encompass more applications and on fine-tuning key assumptions through expert discussion and detailed industrial research. In our research, different key assumptions concerning lower-bound and upper-bound scenarios did not lead to divergent conclusions. Furthermore, in a more regional and dynamic mass flow analysis the EOL flows can be compared to actual regional REO consumption, rather than to the REO content in applications shipped in and out of regions. A regional potential recycling supply ratio could then be established to provide more specific data for policy makers. Finally, an option that deserves more attention is the possibility of storing certain EOL products with NdFeB magnets for future recycling when total volumes, REO prices and the state of recycling technology improves.

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