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Rare Earth Elements Recycling Potential Estimate Based on End-of-Life NdFeB Permanent Magnets from Mobile Phones and Hard Disk Drives in Brazil

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Abstract: Besides neodymium, the chemical composition of Neodymium–Iron–Boron (NdFeB) permanent magnets possibly contains other rare earth elements (REEs) such as praseodymium, dysprosium, and terbium. Among its applications, NdFeB magnets are essential for Hard Disk Drives (HDDs) in computers for data storage, in Mobile Phones (MPs), and in acoustic transducers. Because REEs were classified as critical raw materials by the European Union and the USA, the recycling of them has become an important strategy to diminish supply risk. Therefore, in this publication, the authors have uncovered the recycling potential estimate (RPE) of these four REEs from both end-of-life (EoL) secondary sources. The results were based on the time-step method, using in-use stock and sales data from Brazil over the last decade (2010–2019). Moreover, the NdFeB magnets were characterized by content and weight to a more accurate RPE. The EoL generation over the decade studied showed different scenarios for MPs and HDDs, mainly due to lifespan, social behavior regarding storage and usage, and resources. Under those circumstances, the RPE revealed 211.30 t of REEs that could return as raw materials in the last decade, of which approximately 80% is neodymium. Unfortunately, recycling rates are still too low, even more so in Brazil, which is problematic for the future REE supply chain and electronic waste figures.

Keywords: NdFeB magnet; recycling potential; rare earth elements; hard disk drives; mobile phones



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1. Introduction

Waste Electric and Electronic Equipment (WEEE) contain strategically important metals, from copper, gold, and platinum to the Rare Earth Elements (REEs). More recently, WEEE have been considered secondary raw materials due to the possibility of obtaining the same materials/compounds of ore exploration through recovery. Not only does it allow for the advantages of environmental conservation, energy savings, and a smaller carbon footprint, but also the valuable metals stay inserted in the economic circular chain. The European Commission [1] has classified REEs as critical raw materials considering the supply risk, assigning a substitution index above 0.9 on a 0–1 scale. Such a high index emphasizes the difficulty in metal substitution and uncovers an urge to develop recovery routes for these elements through sustainable recycling processes. Moreover, the worldwide criticality of REEs is mostly related to the concentration of processing, refining, and manufacturing solely in one country. The fact that China produces 80–85%, refines 95% of the REE metals, alloys, and magnet powders, and manufactures over 80% of the Neodymium–Iron–Boron (NdFeB) permanent magnets [2] (one of the main REEs in the industrial sector, reaching 31% of all metal consumption in 2016 [3]), is determinant for an unbalanced supply and demand [4]. Since 2011, after the price spike of REEs by 600–3000% compared to 2009 [5], researchers worldwide have focused their efforts on the recovery of REEs, mostly from end-of-life products containing NdFeB magnets [2,6].

The variety of uses for NdFeB magnets includes electric and electronic equipment. Habib [7] has classified the end-use products containing NdFeB magnets into three levels based on the mass per product, lifespan, and degree of accessibility for resource recovery. Level 3 has the smallest lifespan (1–6 years) and the smallest magnet size per product unit (1–15 g), which includes mobile phones (MPs), hard disk drives (HDDs), etc. As a result, the short lifespan of level 3 products allows for their rapid appearance in the waste flows whereas products in the other levels only enter the waste flows in the future, since their lifespan is extended. Consequently, HDDs and MPs have been the main focus regarding the recovery of REEs from NdFeB magnets. In 2007, it was estimated that global use of computers and audio systems accounted for 33.8% and 24.1% of all NdFeB magnet use, respectively, which in terms of mass corresponded to approximately 62,000 t [8]. Since then, many years have gone by in which these shares have changed, but unquestionably, NdFeB magnets from HDDs and MPs today have not yet lost their relevance regarding in-use stocks and recycling potential.

End-of-Life (EoL) generation estimation is an action to increase worldwide collection and recycling rates. Article 7 of the WEEE Directive [9] in force in the EU states that the Member States shall collect annually: (i) the minimum of 65% of the average weight of electrical and electronic equipment placed on the market (PoM) in the three preceding years or (ii) 85% of the WEEE generated on their territory. With that in mind, the estimation of WEEE generated provides the advantage that it should more accurately reflect the amount of waste arising that can thus be collected [10]. Additionally, WEEE generation estimation is important for the planning of collection and take-back systems provided by local governments, developing specific policies in which informal WEEE handling should be mitigated [11]. In order to keep monitoring WEEE generation, the use of data reporting with a satisfactory and harmonized methodology is essential [12]. Input–Output Analysis (IOA) models quantitatively describe the dynamics, magnitude, and interconnection of product sales (the flow of products into society), stocks (accumulation in the built environment), and lifespan (end-of-life after a certain period). Moreover, IOA is the most frequently used method with multiple model variations for estimating WEEE generation in many regional studies. There are a few models that use at least two of the previously cited variables, for instance, the time-step model wherein the change of stock within a period in a system equals the difference between the total inflows and outflows [13]. However, some limitations emerge when the sales data of the product is not accurate enough.

According to Rademaker et al. [14], until the late 2020s the global potential recycling supply of Nd would mainly come from end-of-life HDDs. Additionally, based on market growth and criticality towards REEs, pushed by wind generators and motors, scrap NdFeB magnets have been identified as a priority material for recycling in Europe [15]. The total amount of Nd accumulated by the in-stock market resulted in about 14,300 t in the EU in 2016, where voice coil motors (HDDs) represent more than 80% of secondary Nd reserves [16]. In addition, Material Flow Analysis (MFA) performed in the same study showed results where 50% of the annual Nd demand in the EU could be met by the domestic secondary supply during that year. Another study, performed in the EU again by Reimer et al. [17], showed that between 2018 and 2040, the overall realistic recycling potential would be 25,675 t NdFeB magnets, corresponding with 7100 t of Nd and 1100 t of Dy, in contrast to the 232,891 t of NdFeB magnets from the theoretical recycling potential in the same period, according to their assumptions.

Since there are no reported data in Brazil on the recycling potential of REEs in secondary sources of the NdFeB magnets from end-of-life MPs and HDDs, this work aims to estimate the missed REE quantities from WEEE. In-stock and sales data, as well as lifespan during the last decade (2010–2019), were adopted to calculate EoL generation according to the time-step method. In addition, the NdFeB magnets were evaluated with regards to their weight and chemical composition over the years, and the influence from technological changes that the NdFeB magnets were submitted to was also assessed. Finally, the

determination of the recycling potential estimate (RPE) of REEs contained in these magnets according to WEEE generation and NdFeB characteristics in this period were addressed.

2. Materials and Methods

Following the REE recycling potential estimate, firstly the EoL generation of MPs and HDDs was investigated using the time-step method, mostly due to data availability and because MPs and HDDs are suitable for non-mature markets, in which technological changes have a considerable impact on the lifespan of the equipment. Thus, according to Equation (1) [13,18] the estimation was calculated, in which sales in the evaluation year i and stock data for two consecutive years (i and $i - 1$) are factors taken into consideration and shown in Appendix A for the last decade in Brazil.

$$\text{EoL generation}_i = \text{Sales}_i - (\text{Stock}_i - \text{Stock}_{i-1}) \quad (1)$$

Secondly, an exhaustive random collection from final consumers of end-of-life MPs and HDDs was performed to quantify the weight and composition of NdFeB magnets. Based on the average lifespan shown in Appendix B provided by a few studies in Brazil, the dates of the manufacturing years considered for the RPE were 2005 through 2014 for HDDs and 2007 through 2016 for MPs. These data were collected as follows: for HDDs, the manufacturing year was observed on the label. If the year was not available, the HDD was not considered for the work. For MPs, the manufacturing year was researched online according to the brand and model, which was found printed on the chassis when the battery was removed. If no information was yielded or a doubt was raised, the MP was also not considered for the work. The sample size within each year varied from 3 to 29 for both MPs and HDDs. After manually dismantling each device, the NdFeB magnets were isolated, weighed, and proceeded to quantification using Optical Emission Spectroscopy Inductive Coupled Plasma (ICP OES—Agilent Technologies 5110, Santa Clara, CA, USA) through leaching (solid/liquid ratio of 1/20 g/mL concentrated nitric acid, 175 °C, and 20 bar) in a microwave (Multiwave, Anton Paar). The other parts, such as polymers, metallic chassis, printed circuit boards, and screws were correctly disposed of.

According to Schulze and Buchert [19], a recycling potential is an amount, in terms of mass, of REEs which can be supplied from secondary sources. Therefore, to relate the generation of MPs or HDDs with the mass of REEs (W), Equation (2) was used. Based on the weight and composition of NdFeB magnets, the final amount, in t , might be estimated.

$$W_{i,j,k} = \frac{\text{EoL generation}_{i,k} \cdot x_{j,k} \cdot z_{i-a,k}}{10^6 \left[\frac{\text{g}}{\text{t}} \right]} \quad (2)$$

where EoL generation was calculated by (1) (units), x is the composition (wt.%) of REEs, and z is the weight of the NdFeB magnet (g/unit). Index i corresponds to the year (2010–2019) analyzed, index j corresponds to Nd, Pr, Dy or Tb, index k corresponds to the EoL device type (MPs or HDDs), and index a corresponds to 3 or 5, which stands for the lifespan (in years) of the corresponding end-of-life device (Appendix B).

Other assumptions: (i) the weight of the NdFeB magnet (parameter z) was obtained for each year throughout the ten-year range except for the HDD in 2014, where the data was lacking. In this situation, the adjacent immediate year was used for the RPE calculation; (ii) the REE composition of NdFeB magnet (parameter x) was considered as an average value throughout the ten-year range for both end-of-life devices' technology.

3. Results

3.1. End-of-Life Generation

Mobile phones have shown a descending lifespan over the years, which was reported by a few authors in a Brazilian context (Appendix B), reaching 1.98 years for smartphones. A Chinese survey [20] also stated that in 2011 approximately 12% of consumers changed MPs in less than a year and in 2018 this number increased to 26%. In addition, in 2018 only

10% of consumers kept the same MP for more than three years. The main reason, reported by 44% of consumers in 2018, was the fashion pursuit. Consequently, Moletsane [21] projected 41.8 million t of MPs as end-of-life generation in 2014, increasing to 44.7 million t in 2016 and 48.7 million t in 2017. The study performed by Guo et al. [22] affirms that in China there were an estimated 800 million units of obsolete MPs in 2017 and, in comparison, worldwide MP users reached 7.74 billion units. Another report [23] estimated that 400 million units of MPs were discarded globally each year until 2012, and China alone contributes to one quarter of these.

In a Brazilian scenario, Araújo et al. [18] estimated 2250 t/year of waste MPs in 2008, meanwhile, UNEP [24] projected 2200 t/year in 2005. In Figure 1, it is revealed according to equation (1) and Brazilian data that the EoL generation of MPs initiated the decade in 2010 with 23.76 million units. Then, it reached a peak of 74 million units in 2015 when a subsequent declining behavior was observed, finishing 2019 with nearly 51 million units of EoL MPs. Considering that every MP weighs 62.30 g on average [25], the EoL generation in terms of mass equates to 1480 t, 4610 t, and 3186 t in 2010, 2015, and 2019, respectively, which is in agreement with the estimations provided in the previously cited studies.

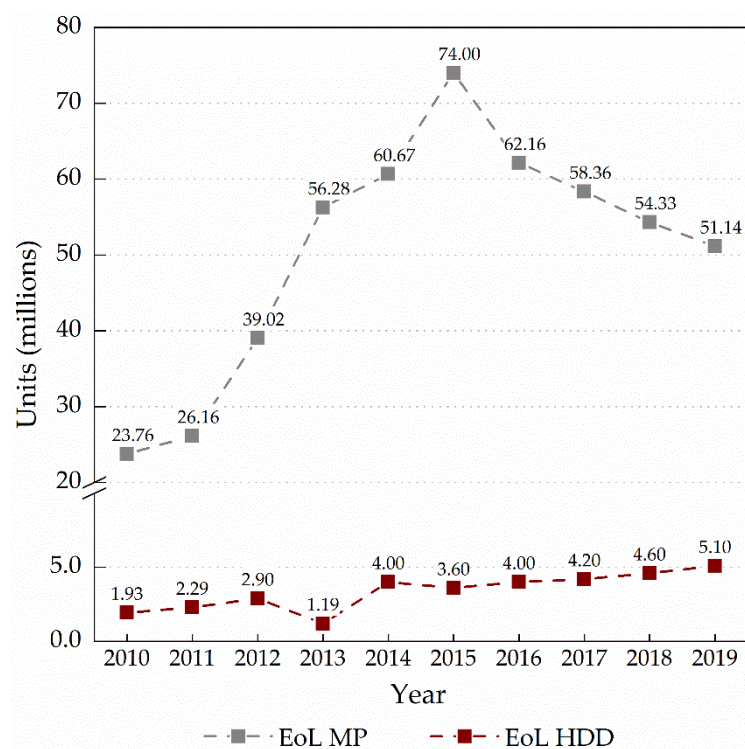


Figure 1. End-of-life generation (million units) of mobile phones (MPs) and computers (HDD) in Brazil throughout 2010–2019.

Moreover, Rodrigues et al. [26] reported that circa 60% of MPs in São Paulo city were acquired in the last two years and more than 30% within two to five years, comprising the period from 2014 to 2019. The same survey also showed that 52% of the out-of-use MPs stored by owners were functional, meaning that substitution is related to damage as well as programmed obsolescence. In addition, 47.3% of households have reported having discarded at least one MP up to 2019. Another study performed by Nowakowski [27] in Poland suggested the same behavior of storing, mostly for probable future use, and concluded that the tendency to stockpile is increasing due to newer MP models being offered by telecommunication companies in shorter periods of time. A different study [28] revealed that the top reason for substituting a MP is function upgrading, driven by fast technological advances. Although both studies were not based on Brazilian customers, the generated WEEE numbers revealed here suggest similarities. One of the reasons for

this is the reported change in mobile technology from 3G (third generation) to 4G (fourth generation) that began in 2015, according to ANATEL [29], and reached 62% of Brazilian users in 2019, in contrast with nearly 10% that remained on 3G and the other 10% on 2G (second generation). With new mobile technology advances, it is reasonable to follow better quality and velocity in internet connection with new suitable devices [30]. Despite slow economic growth, Brazil is currently expanding telecommunications (4G technology) coverage over urban areas but has been mainly focusing on remote areas over the last few years, where there is an opportunity gap, consequently encouraging dwellers to buy smartphones suitable for internet broadcast [31]. Overall, 558.58 million units of MPs were sold over a decade, while 505.88 million units of MPs were generated as waste, representing a high usage turnover of more than 90%.

When considering computer wastes, and consequently their HDDs, there are reports following the same increasing tendency of EoL devices as MPs over the years. An estimate in Chile reached a cumulative number of 165,300 t in 2020 [32] accounting for both notebooks and desktops from all sources (households, businesses, and governments). Worldwide, the ascending cumulative amount of computer waste started with 4.8 million units in the 80s, then jumped to 553 million units in 2000, and by 2015 it was estimated to be an astonishing amount of 2020–2073 million units [33]. In 2012 Brazil and Mexico generated 0.50 kg and 0.45 kg of computer waste/person/year, respectively [34].

Accordingly, Figure 1 shows that EoL generation of HDDs showed a slight increase from 2010 through 2019, ranging from 1.93 million units to 5.10 million units. Rodrigues et al. [26] argued that a Brazilian governmental social program called “Personal Computers for All” stimulated high volumes of acquisitions until 2011, when the program was terminated, resulting in 80% of computers from households in São Paulo city being purchased within this period. This was similar in other major cities across the country. In addition, the same survey revealed that computers were discarded mostly with the intention of reuse (73%) and recycling (22%). Henceforth, this is related to the low generation of EoL computers, which is interesting to observe since the stocks (Appendix A) are estimated to be high and increasing. The reason for this accumulation is linked to the fact that people tend to reuse personal computers, which can be upgraded, unlike MPs. Many governments and private campaigns reinforce the advantages of reusing and rebuilding on behalf of the economically disadvantaged population [35], even though a piece of research called PNAD (Pesquisa Nacional de Amostra de Domicílios, in Portuguese) conducted by IBGE [36] recently revealed that only 48.1% of residences used any computer to access the world wide web in 2018, a number 4.3% lower than the previous year. Therefore, the decade showed low usage turnover, approximately 21%, because only 33.82 million units of EoL HDD were generated in relation to the amount sold in the same period.

3.2. NdFeB Magnet Weight and Content

Because MPs were developed in the late 80s, technological evolution over the years has resulted in some significant changes. Initially, MPs had small displays and the battery, buttons, and circuits were a considerable size. In the following years, downsizing was the main goal until recently, when flat touchable screens became the most important attribute in smartphones, which today are used for entertainment rather than communication [28,37]. By evaluating the weight of the NdFeB magnets from acoustic transducers in grams, over the years of manufacturing and device technology (60 feature phones and 74 smartphones), the data were plotted in Figure 2. The first noticeable aspect was the NdFeB magnet weight heterogeneity (error bars) within the same year, which is related to different brands and their manufacturing designs (brands with the most repetitiveness: Motorola, Nokia, Samsung, Siemens, Sony, LG, and Apple). In fact, design particularities continue to be the key to selling success but consequently reduce the lifespan [38].

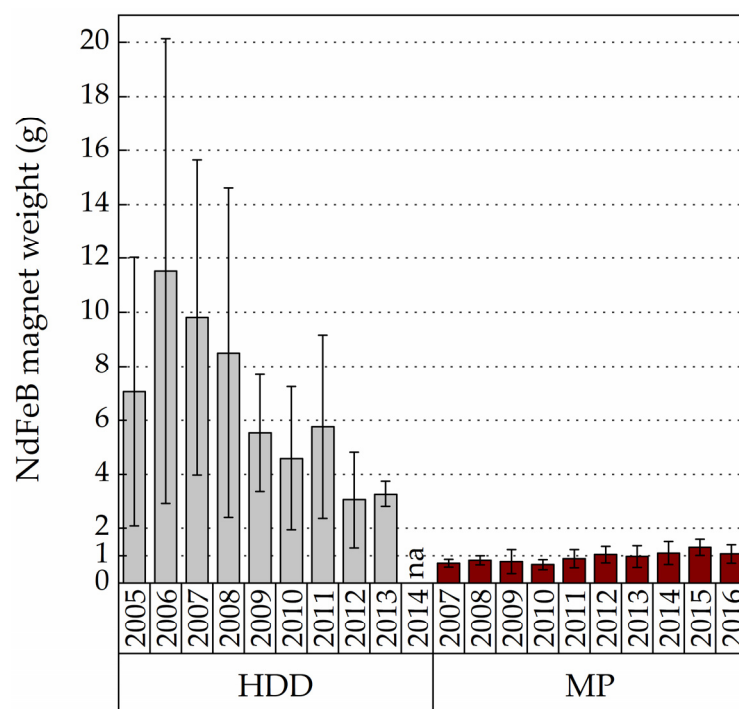


Figure 2. Average NdFeB magnet weight (g) of mobile phones (MPs) and hard disk drives (HDDs) from the years 2005 to 2016, according to the correspondent device lifespan. Note: na = not available.

Secondly, an ascending tendency within the 2007–2016 period was observed, mostly influenced by a transition in MP technology usage: obsolete feature phones were no longer observed in the collection waste flow from 2012 onwards in contrast to the opposite trend with regards to smartphones until 2009. Essentially, once the value of a smartphone had been highlighted, a feature phone’s value for money seemed far from ideal. In addition, the attractiveness of smartphones to customers throughout the years was influenced by many of the new technologies that were being incorporated. Consequently, the weight of the NdFeB magnet started to increase in 2009; however, due to constant redesign and advances in technologies, a stagnation yielded to consistency in efficiency. Nonetheless, the difference between the heavier and lighter NdFeB magnets showed once again that MP design and features followed no pattern among brands and models. The increase over the years ranged from an average of approximately 0.4 g to an average of nearly 1.3 g. In comparison, according to Ciacci et al. [16], voice coil motors in MPs account for 0.05–0.2 g Nd/unit and acoustic transducers account for 0.3–1.4 g Nd/unit, showing similar results. Likewise, Singh et al. [25] found 1.09 g on average in feature phones and 1.32 g in smartphones.

Collection from final consumers provided 106 desktop HDDs and only 10 notebook HDDs, resulting in over 200 NdFeB magnets, which were generally found in pairs attached to the voice coil system, generating the movement that allows reading and writing data in disks. The average weights of the NdFeB magnets in the HDDs were evaluated over the years of manufacturing and the data were compiled in Figure 2. The error bars represent the heterogeneity of each sampling year, in which a significant variation ranging up to 20 g between the lightest and the heaviest NdFeB magnet was observed. This behavior is mostly related to the different constructive details and designs resulting from differences in companies’ engineering (Samsung, IBM, Seagate, Western Digital, and Maxtor were the brands mostly found), requiring either more or less magnetic power from the magnets to fulfill the demands of storage or reading/writing speed. However, there is a noticeable decline in heterogeneity over the years, reaching less than ± 0.48 g in 2013. Another observation made was that the average weight shows oscillatory behavior over the years, for mostly the same reasons. According to Ciacci et al. [16], these permanent magnets

contain, in general, 0.6–2.1 g Nd/notebook unit and 3.7–7.8 g Nd/desktop unit, which was also verified here.

The influence of the NdFeB magnet weight in the HDDs was also evaluated with regards to the storage capacity in Gigabytes, showing increasing ratios (Gb/g) driven mainly by the drastically increased storage capacity, reaching up to 1000 Gb for both desktop and notebook HDDs, whereas the NdFeB magnet weight showed no proportional increase. Upon investigation, it was clear that the HDD technology developed by each company dictated how heavy their NdFeB magnet would have to be in order to perform as demanded.

The REEs content in NdFeB magnets from MPs within the period between 2005 and 2016 is shown in Figure 3. Since the error bars express heterogeneity lower than 1.26% (for Nd), it is affirmed that both feature phones and smartphones have had similar NdFeB magnet content throughout the ten-year range. In addition, it is well known that Nd and Pr can replace each other in the alloy without the depletion of major magnetic properties [39], thus these were possibly used interchangeably over the years, most probably due to price fluctuations. Tb-composition, which is related to Curie temperature, has remained practically constant and at low levels, although prices have also suffered the same peaks in 2011 and 2012. In recent years, the Dy-price (as oxide) reached high peaks [40] and consequently, the amount of Dy in the NdFeB alloy was reduced from 2007 to 2016. In 2017, Siemens AG stated their aims to eliminate Dy from the NdFeB magnet used for wind power due to price volatility [41].

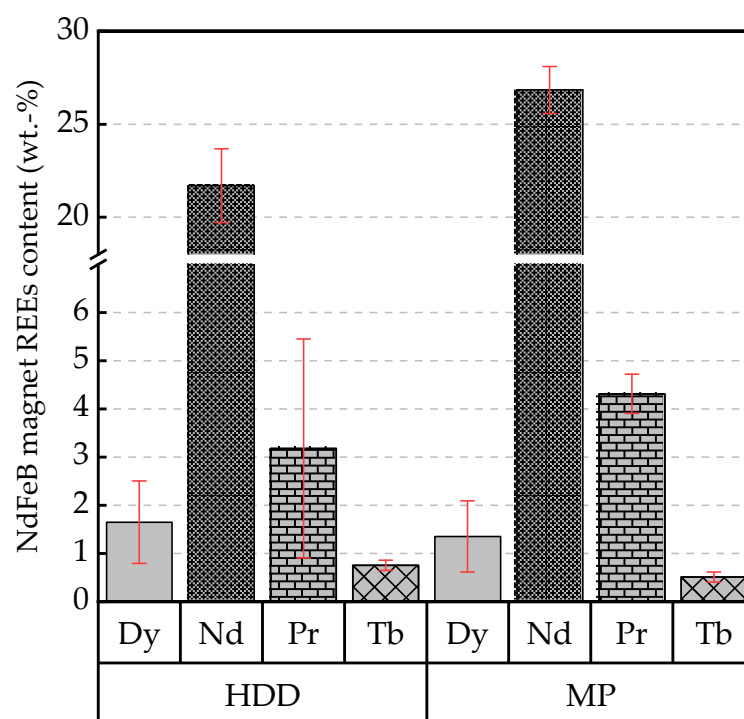


Figure 3. Rare earth element content (wt.%) in both HDD and MP NdFeB magnets within the 2005–2016 period according to the device lifespan.

Figure 3 also shows the chemical content of NdFeB magnets in HDDs following the same tendency. It was observed that again, possibly throughout the years 2005 to 2014, Nd and Pr showed balanced opposite composition variations among each other for the reasons discussed previously. The error bars showed $\pm 2.27\%$ content variation for the Pr, which was the highest among the REEs, possibly mostly driven by price fluctuations. The Tb- and Dy-contents varied less intensely. Moreover, the prices of the NdFeB magnets are difficult to track over the years since they are not a commodity [42].

3.3. Recycling Potential Estimate (RPE)

The WEEE situation in Brazil is poorly controlled, mostly guided by the informal recycling sector and the mixing of municipal solid waste destined to landfills or open dumpsites. As a result, an adequate WEEE recycling rate is estimated to be only 2% [11], whereas in Europe this number reaches 25–40% [43]. Brazil is still considered to be an emerging economy, which means the consumption of technology is continuously increasing, consequently demanding high REE rates and other important critical metals. A survey performed on Brazilian recycling facilities concluded that the complex components of WEEE are only sorted, dismantled, ground, and shipped abroad for foreign downstream companies to overtake the recycling process, which includes printed circuit boards (PCB) and HDDs [44]. Notably, the REE recycling rate in 2013 was estimated at 1% worldwide [45] and 8% was reported in 2017 in Europe [1]. Considering these facts, the RPE is not based on the collected WEEE, but on what could be achieved if a 100% collection rate was possible.

Figure 4 shows the recycling potential estimate in t, from hard disk drives (a) and mobile phones (b) for each REE, separately, for every year during the period of 2010–2019. Notably, MPs provide a higher RPE of REEs on average than HDDs (160.85 t and 50.45 t (Table 1), respectively), mostly due to the significant difference in EoL generation since each REE content varied less than 5% from one device to the other (seen in Figure 3), and the weight of the NdFeB magnets also showed up to 10 g of difference (seen in Figure 2).

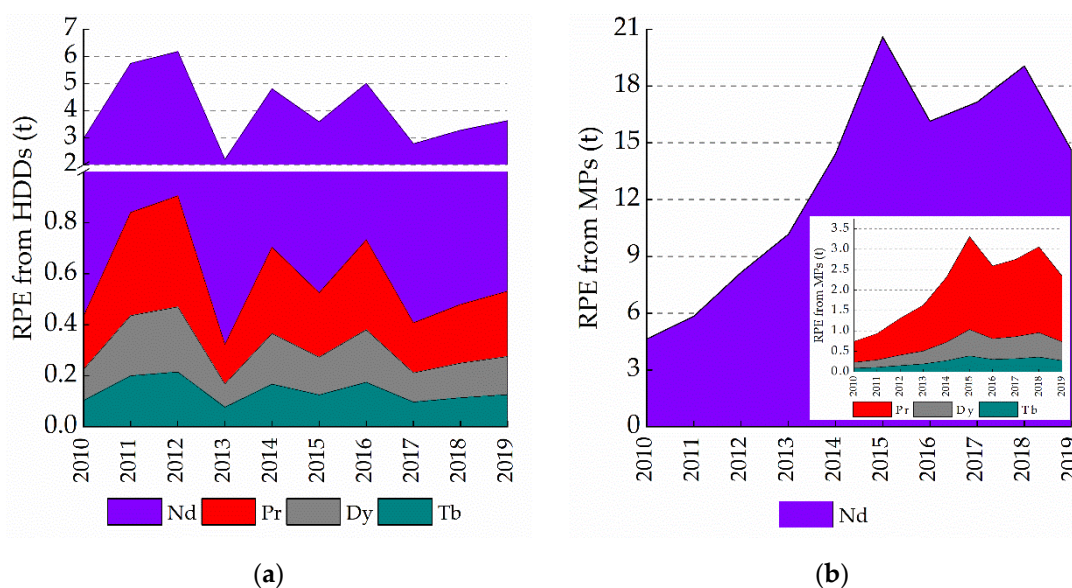


Figure 4. Recycling potential estimate of REEs from (a) hard disk drives and (b) mobile phones in the period of 2010–2019.

Table 1. RPE (in t) from HDDs and MPs for each REEs and the sum within the period of 2010–2019.

EoL Device RPE	Nd	Pr	Dy	Tb	REEs Sum
HDD	40.12	5.88	3.05	1.40	50.45
MP	130.76	21.01	6.59	2.49	160.85

Throughout the decade, a contrast between the two main factors in consideration was observed for HDDs: despite the EoL slightly increasing, the weight of the NdFeB magnet is reportedly decreasing over the years, resulting in a stagnation in RPE for all REEs, as shown in Figure 4. The highest peak was observed in 2012, with approximately 6 t of Nd, 1 t of Pr, 0.5 t of Dy, and 0.2 t of Tb, mainly due to the second highest NdFeB magnet weight being recorded in 2012, having been manufactured in 2007 (taking into account the lifespan of 5 years). The lowest peak in 2013 was due to the lowest EoL generation.

Conversely, the RPE from MPs for all REEs behaved in an ascending trajectory following the EoL generation, in which the lowest peak was in 2010 with approximately 5 t of Nd,

0.7 t of Pr, 0.2 t of Dy, and 0.1 t of Tb, and the highest peak was obtained in 2015. From 2016 onward, because the weight of the NdFeB magnets slightly increased and the EoL generation decreased, the RPE for all REEs remained constant in elevated amounts. Although reverse logistics is increasing as a common practice among Brazilian consumers and should be applied according to the Brazilian law, a survey reports that 31.6% of households contain out-of-use MPs, something characterized as the “treasure effect”, a cultural act of keeping items with value for future usage [26]. Furthermore, around 18% of Brazilians discard MPs in the regular municipal solid waste [46]. In addition, a survey revealed that 24% of Brazilians are still not aware of the environmentally correct method of disposal for electric and electronic equipment such as computers and MPs, while at the same time 17.9% of household respondents affirmed to have discarded a computer recently [26].

According to Table 1, the lowest difference between RPE in MPs and HDDs is in terbium: 78.23%, meaning that this is the most stable REE in terms of content throughout years, brands, and devices. In contrast, Pr presented the highest difference, 257.29%, reinforcing the heterogeneity in the observed content.

Regarding these heterogeneities in the weight and REEs content of the NdFeB magnets, low and high scenarios can be practiced according to the low and high values obtained in this research for both MPs and HDDs. For instance, the RPE from MPs and HDDs may be 43% and 81% higher, respectively. On the other hand, in a pessimistic scenario, the RPE from MPs and HDDs could also be 61% and 161% lower than the average amounts, respectively.

4. Discussion and Conclusions

Detailed research that collects data from WEEE, which is the source of multiple critical raw materials, is important in shedding light on RPE, not only in terms of correct disposal but also to prevent metals with market value from going to waste. Through revealing how many t of REEs could return to the production chain, for instance, RPE allows future policies to be developed in Brazil since the country is still outdated regarding their WEEE management. In addition, estimates are highly necessary in supporting the planning of take-back schemes in the country, which must be progressive and start at cities [47]. Despite having REE mining resources, the supply risk concern regarding these metals is neglected and not examined the way it should be.

Recently, Ciacci et al. [16] have reported, based on an MFA performed for Nd from secondary sources, that roughly 50% of the annual metal demand in the EU could be met by the domestic secondary supply at current levels, indicating that these secondary sources could partly close the metal cycle in the EU if the potentials were turned into actual capacity. Additionally, voice coil motors from HDDs are one of the devices that the same authors identified to likely have the most decisive effect on ensuring supplement to primary neodymium production in virtue of the relevant neodymium in-use stock, and considerable annual outflows from use if efficient strategies for recovery and recycling are to be implemented.

Moreover, according to the scenario results reported by Schulze and Buchert [19], the overall worldwide demand for NdFeB magnets in 2015 and 2030 was estimated at around 80–112 kt and 240–633 kt, respectively, for both low and high demand scenarios. Most of these amounts would be used in motors for industrial and small automotive parts, followed by wind generators. In a Brazilian context, a study performed by Ocharán et al. [48] evaluated that from 2018 to 2030, only considering the wind energy sector, there will be a demand of 1815 t of NdFeB magnets, in contrast to a production of only 824 t, following an increasing tendency in this type of clean energy.

The importance of WEEE quantification and the RPE of REEs allows for planning enhancements in governmental assistance, guided mostly by Sustainable Development Goals and public health. Moreover, these kinds of studies boost decision-making in terms of recyclability, who is involved and who is affected, the economic factors, and legislative environmental strengthening.

A decade of data compilation on NdFeB magnets in MPs and HDDs covered technological changes, such as the dominance of smartphone technology. Moreover, the sampling of NdFeB magnets among different brands for both WEEE and the ten-year period, provided a statistically strong representative generalization, mainly regarding the chemical composition findings of the NdFeB magnets. However, the reduced sampling size for NdFeB magnets from notebooks and the lack of data for the HDD manufacturing year of 2014 are considered limitations on the research, mostly because donations were the only collection source, and the authors therefore had no control. Furthermore, assuming that manufacturers have total liberty in choosing the size, shape, and composition of their NdFeB magnets, the heterogeneity in magnet weight in both MPs and HDDs demonstrates the difficulty of stipulating the exact amount of recycling potential.

The observed heterogeneity in weight among the NdFeB magnets was impressive, varying from ~25 g to 0.3 g in both MPs and HDDs, which is a significant factor mostly influenced by the device design, model, and brand. In addition, there seems to be a tendency to diminish the NdFeB magnet size, and consequently the weight, which entirely affects the recycling potential of the REEs from these sources. By analyzing their chemical composition, NdFeB magnets from MPs and HDDs showed similar characteristics. The factor price in the composition of the NdFeB magnets seemed to be relevant throughout the years and directly affected companies' decisions in producing the alloy. In fact, REE content was not reported to consist of less than 20 wt.% as a sum in this or any other publication, which is a positive aspect of facilitating recycling.

Overall, within the 2010–2019 period, HDD and MP waste generation in Brazil represents a recycling potential estimate of 170.88 t of Nd, 26.89 t of Pr, 9.64 t of Dy, and 3.89 t of Tb. At first glance, these numbers seem insignificant, but considering a wind turbine with 600 kg of NdFeB magnet/MW [49] and an Nd-content of 20 wt.%, then it would be possible to install more than a thousand new wind generators, not to mention all the carbon footprint avoided from ore exploration. When converting t into monetary gross, according to the REE pure metals (>99%) quotation of December 2020 from the Institut für Seltene Erden und Strategische Metalle [50], the RPE would be worth approximately US\$ 22 million from MPs and HDDs combined. However, it is universally well known that a 100% recycling rate cannot be achieved. This obstacle is well exemplified by the WEEE treatment plants in Denmark that in the year 2014 alone, received 60 t of HDDs, which comprised 1.6 t of NdFeB magnets. However, the maximum theoretical amount based on the research would be 4.5 t of NdFeB magnets, which demonstrates that only 35% of the end-of-life computers HDDs were successfully collected [51]. In Brazil, overcoming conflicts between waste picker organizations and the recycling industry is reported as the main difficulty in integrating these organizations into the reverse logistics process. These conflicts range from the cooperative's lack of management capacity and the associations of waste pickers to the unwillingness of manufacturers, distributors, and retailers to work cooperatively, especially concerning cost-sharing [52].

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Appendix A

Table A1. HDDs (computers) and MPs sales and stocks from 2009 to 2019 in Brazil (million units).

Sales and Stocks in Brazil	Computers		Mobile Phones		
	Year	Sales ¹	Stocks ¹	Sales ²	Stocks ³
	2009	-	55.93	-	173.97
	2010	12.00	66.00	52.77	202.97
	2011	14.59	78.30	65.42	242.24
	2012	16.20	91.60	58.59	261.81
	2013	18.99	109.40	65.57	271.10
	2014	22.60	128.00	70.30	280.73
	2015	20.40	144.80	51.09	257.81
	2016	14.20	155.00	48.41	244.07
	2017	12.00	162.80	50.78	236.49
	2018	12.00	170.20	47.04	229.20
	2019	12.40	177.50	48.61	226.67

¹ [53]; ² [54]; ³ [29].

Appendix B

Table A2. The lifespan in years of end-of-life devices according to different authors in Brazil.

Lifespan	Smartphone	Feature Phone	Notebook	Desktop
	Years			
Abbondanza and Souza (2019) [11]	1.98	2.46	4.54	6.78
Echegaray (2015) [55]		3.0		4.0
UNEP (2009) [24]		4.0		5.0
Araújo et al. (2012) [18]		4.5		5.0
IDEC (2013) [56]		2.6		3.1
Average		3.09		4.74

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