Evaluation of Strategic Metals
Envisaging the Sustainable Management

Neodymium Flow and Stock Analysis in Portugal

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Abstract

Technology is continually developing, and with it, the demand for materials with particular properties is surging, some have troublesome supply chains and are regarded as 'Critical Raw Materials'. Amongst them, there's a group named 'Rare Earth Elements' (REE). These elements are important for state-of-the-art technologies including the so-called 'green technologies'. Having its primary production almost exclusively in China means that REE supply is highly dependent on its exportation policies, e.g. in 2011 China enforced an embargo resulting in prices surges. The European Union is working on solutions to reduce its criticality specifically by reducing its use, substituting with less critical alternatives or investing in secondary production. While reduction and substitution are easier to implement and possible for the majority of REE, there is one highly demanded element that cannot be fully replaced without performance loss – neodymium in magnets. The only viable solution to reduce neodymium criticality is to wager on recovery from waste. By recovering tonnes of neodymium (and other elements) already present within urban mines not only resolves the risky supply issues but also reduces the amount of unexploited waste and contributes for a regenerative system where waste is used to provide materials for new goods. Prospecting critical elements set the ground stone to start changing economies from linear to circular by providing important insight regarding the potential amount of an element that could potentially be recovered from its urban mines. This prospection concluded that in 2015 the Portuguese neodymium urban mine could potentially yield 38 tonnes.

Keywords

Critical Raw Materials, Rare Earth Elements, Neodymium, Material Flow Analysis, Urban Mine, Circular Economy.

1. Introduction

Society strives for constant technological development, consequently the demand for materials with inimitable properties surges, some of these highly required elements have troublesome supply chains, these are usually denoted as 'Critical Raw Materials' (CRM). Rare earth elements (REE), a group of 17 chemically similar elements are regularly amongst the critical element's lists, these are considered critical due to its high economic importance and its extremely unstable supply risk [1, 2].

Its worldwide reserves and extraction are almost exclusive to China who's already enforced an embargo in the past resulting in extreme price surges. To counteract the unstable supply chain, efforts are being focused on reducing its use, search for less problematic materials or to wager on recovery. And while the majority of REE can be reduced or fully substituted, others cannot and the only viable solution to reduce its supply risk is by waste recovery [1, 2].

The activity of exploiting waste containing economically important materials to recover them is usually termed *urban mining*, analogously to primary mining, the first stage in an urban mine exploitation is the prospection. This first step of the CRMs recovery chain is an indispensable step in the efforts to reduce these materials critically, therefore worthy of a thorough academic research [3].

2. Rare Earth Elements – A Summarized Review

2.1 Properties

Despite its name, REE aren't fundamentally rare, being plenteous in earth's crust. Yet, almost every REE are trivalent, have similar radius and can replace each other in the crystal lattices easily, leading to wide dispersions and low concentrations. Due to these reasons it's extremely difficult to extract and separate each individual element [1,4-9].

Based on the few chemical and physical differences, such as electronic configuration, REE can be divided into two sub-groups:

Light REE (LREE) – with unpaired electrons in the 4f shell. From lanthanum (La_{57}) to europium (Eu_{63}); and **Heavy (HREE)** – with paired 4f shell electrons. From gadolinium (Gd_{64}) to lutetium (Lu_{71}) and yttrium (Y_{39}) [10, 11].

A practical motive for this classification is that REE tend to segregate into either LREE-rich deposit (e.g. monazite) or HREE-rich (e.g. xenotime). There're discrepancies between the several REE classifications, often the difference being in the choice of the border element. For any purpose, this dissertation adopts the European Commission classification considering both yttrium and gadolinium as HREE and not classifying scandium as a REE [1, 4, 5, 10-12].

In REE, the valence electrons do not attach to the outermost shell, rather entering more profound 4f orbitals, since the outermost orbital is a fully occupied $6s^2$, chemical properties (which are mostly governed by the outmost electrons) are similar across all elements. Yet, physical properties are not affected by its electronic configuration, some elements like neodymium have complex potentials, whereas others like europium have sharply defined energy states, making REE useful for applications such as magnets or phosphors [1, 13].

2.2 Balance Problem

REE tend to occur aggregated, generally in either LREE-rich or HREE-rich minerals, however, the ratio of each element isn't the same. During production, every element present in the ore is extracted, this poses a problem as market demand for each element seldomly correlates with the ratio of elements in the minerals. This issue is denoted 'balance problem' and is the cause of market disruptions were simultaneously some REE are stockpiled while others are suffering shortages [12].

The most common solutions provided by academia for restoring balance are listed below [12]:

1. Promote research stimulus for high-volume applications using REE that are overproduced;
2. Invest in alternative materials/technologies for applications where highly demanded, yet scarcer elements are employed;
3. Produce REE with less common ores that have different compositions that might adapt better to the market needs;
4. Stimulate REE recycling endeavours, mainly for scarcer REE with high market demand.

2.3 Criticality

REE play a key role in implementing the so-called green technologies. Permanent magnets generators are often used in renewable energies. Also, the current flagship for environmentally friendly transportation (electric vehicles), could not exist without REE. The European Commission is known for its pro-environment advocacy, therefore it’s comprehensible that REE have high importance [1, 19, 20].

An estimated 81% of rare-earth oxides (REO) reserves are in China (around 65,840,000 tonnes), same nation being the main producer, having currently a projected 80-95% of worldwide primary production. China’s aggressive exportation constrictions, culminated in an exportation embargo in 2011 disrupting the market with price spikes [11, 2, 13].

Two entities were created by the European Commission, ERECON and EURARE, with the aim of developing REE industry and ending the high reliance on Chinese imports and reduce its critical status [11, 13, 14].

2.4 Processing

There are big challenges in the separation and refinement of each individual REE to purity of 99.9% (3N) or 99.9999% (6N). Its processing is complicated, energy-consuming, expensive and inefficient. Firstly, the ores are mined and then purified to produce a mixture of rare-earth compounds. These compounds have then to be separated into individual RE compounds, using intricate chemical separation methods. The most commonly used method is the solvent extraction method where a solvent extracts the desired elements and separation happens when the immiscible liquids are disengaged, being repeated until all elements are individualised. Only after separation, production of individual metallic RE is possible [1].

Though REE are considered the backbone for ‘green technologies’, they aren’t entirely eco-friendly, its primary production is highly hazardous for local environments. A typical Chinese leaching project yields 300 m^3 of soil removed, creating 2000 tonnes of tailings and over 1000t of toxic residual effluents. Additionally, the specific global warming potential of REE (CO_2-Eq per kg) is orders of magnitude higher than elements such as steel. Since its production volume is lower the actual impact is minor, but with increasing demand, production will increase and consequently emissions will exponentially increase. REE applications should consider its production impact, as these so-called green technologies come with an actual environmental cost [15, 16, 17].

2.5 Applications

RE main applications can be divided in two categories (most used REE in each application are shown as well) [1, 15]:

- **Process enablers** – (Around 35% of global consumption) RE are used in production but are not present in the final product [15]:
    - **Polishing powders -** Ce;
    - **Fluid cracking catalysts** –La, Ce.
- **Product enablers –** (Around 65% of global consumption) RE are added to other materials in order to give them unique properties which often are essential to assure best performance in the final product [15]:
    - **Permanent magnets –** Nd, Dy, Sm;
    - **Metallurgy and alloys –** No Specific REE;
    - **Auto catalyst –** Ce (Unlike FCC, they're integrated in the catalytic converter itself);
    - **Batteries alloys -** La;
    - **Phosphors –** Ce, La, Eu, Y, Tb;
    - **Ceramics & glassmaking** – Y, Ce, Er.

2.6 Substitutability, Forward look and Recycling

A solution to tackle REE criticality is to research alternative elements that can replace them effectively or developing alternative technologies that use lower REE contents (or even none).

Some, technologies are already being effectively replaced by 'low REE' alternatives like NiMH batteries and fluorescent lamps (substituted by lithium batteries and LEDs respectively). Others are partially substitutable yet with performance losses, this being the case of neodymium in magnets. Didymium, a praseodymium-neodymium alloy can be used to reduce neodymium content, however with the cost of lower magnetic strength. Performance-wise, there's no material or technological alternatives to NdFeB magnets, therefore regarding specific applications (such as EV or wind turbines) neodymium is effectively unreplaceable [2, 18, 19].

With permanent magnets being the most important application in terms of value (53%) and volume consumed (24%), it's natural that neodymium is considered the most demanded, with an estimated growth rate of ~7% per year, with an overall increase between 2010 and 2020 being in order of 80%. With most REE markets declining, the magnet market expansion, and the fact that neodymium cannot be fully substituted, it's foreseeable that in the short term (~5 years) it'll be the only REE that'll remain highly critical [18].

REE recycling is still residual, with an average recycling rate of 1% in 2015. In spite of extensive academic commitment to researching this topic, rates are still low, mainly due to inefficient collection and complexity of the recycling procedure. Most research is performed at 'lab scale' and applies methods that aren't easily scalable to an economically viable industrial size. Nevertheless, with correct incentives and efforts it's possible to recycle at industrial scale [2].

3. Modelling Neodymium Stock & Flows

Material Flow Analysis, henceforward denoted MFA is a tool used to assess flows and stock of materials within a system with space and time boundaries defined. It's a simple material balance of input, stock and output of a system and its processes that allows to detect accumulation or depletion of stocks, environmental loadings, hibernating stocks, among others. MFA is a useful method for decision-making in resource, waste or environmental management providing policymakers with insight that can positively affect and improve inefficient legislation [20].

3.1 System Definition

This study aims to investigate stocks and flows of the substance neodymium, since its most relevant use is in magnets, the materials list was reduced to 'neodymium magnet containing goods', mainly wind turbines, hybrid/plug-in/electrical vehicles and EEE (Electrical and Electronic Equipment).

However, wind turbine technology (permanent magnet generators) that employs Nd does not exist in the chosen system and the percentage of vehicles with magnet-based electrical motors within the system is still negligible. For the aforementioned reasons, EEE is the focus of this investigation. But not every EEE possesses Nd within its components, thus the scope is reduced to a group of 14 different types of potential neodymium-containing equipment.

The modelling scope includes market penetration, consumption (and stocking) by end-users, end-of-life and waste management of the 14 selected EEEs for the selected spatial boundary of Portugal in the year of 2015 (Fig. 1). With the main goal of assessing neodymium's recycling potential being left untapped in Portugal, the early stages of the waste management are also considered and modelled.

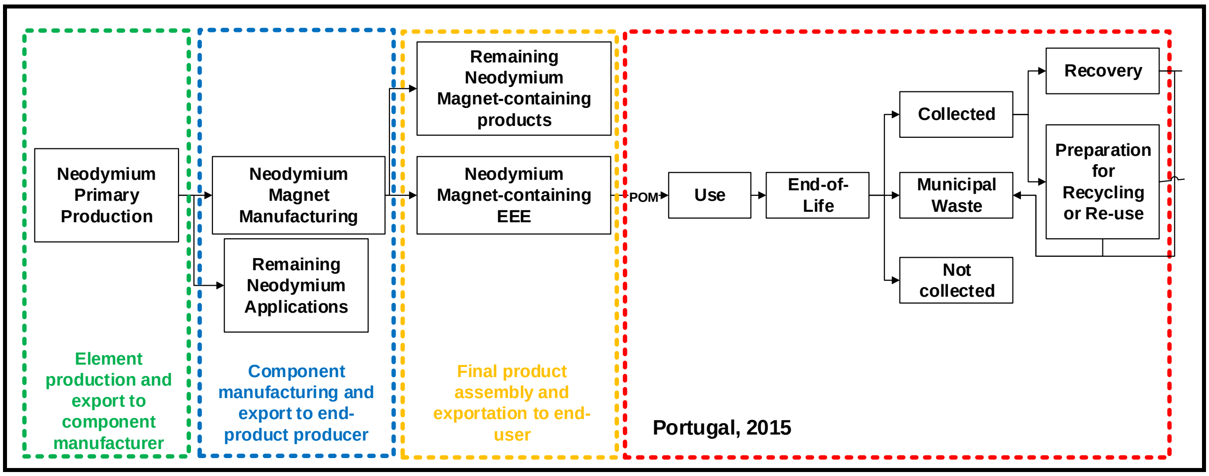

Figure 1 - *System Boundary where the Neodymium Flow & Stock analysis will be performed (in Red). The remaining boundaries represent steps the substance has undergone before arriving to the chosen system.*

3.2 Modelling the flows, stock waste and disposal

In order to model the amount (in kg) of neodymium flowing in the chosen system within selected equipment there're a variety of data that must be collected and thoroughly computed to obtain accurate results that can relate to reality.

Firstly, it’s necessary to determine the amount of each equipment that enters the market in the evaluation year (POM), that entered in previous years (i.e. stock already in use by the end-use), that reached its EOL (waste generated) and the destination of the WEEE (waste management). Furthermore, the average NdFeB magnet weight per equipment alongside its composition and market share are required to depict flows and stocks in ‘kg of neodymium’ instead of ‘number of units’.

4. Results & Discussion

4.1 Results

Material Flow Analysis is essentially an Input-Output (I-O) simulation of a selected substance within a given system. Table 1 and Sankey diagram portray the resulting I-O scenario (Fig. 2).

Table 1 – Neodymium flow and stock in Portugal for the year of 2015. Processes depicted: POM, stock and waste generated (WG). Unit: kilograms of neodymium.

UNU Key	**POM**	**Stock**	**WG**	**Waste generated**		
				Municipal waste	**Uncollected**	**Collected**
0104 – Washing machines	11 405	116 266	7 386	148	4 210	3 028
0105 – Dryers	1 663	20 666	969	19	553	397
0108 – Fridges	2 381	27 908	954	0	601	353
0109 – Freezers	7 755	84 699	3 977	0	2 505	1 472
0111 – Air conditioners	12 956	90 723	13 198	0	8 315	4 883
0114 – Microwaves	2 962	26 283	3 236	744	1 392	1 100
0204 – Vacuum cleaner	4 922	36 097	3 562	819	1 532	1 211
0205 – Personal care eq.	113	990	138	32	59	47
0302 – Desktop PCs	1 134	7 371	961	221	346	394
0303 – Laptops & tablets	445	3 622	707	14	537	156
0306 – Mobile phones	672	3 268	740	170	267	303
0404 – Video	449	2 572	331	76	142	113
0408 – Flat display TVs	553	8 605	615	12	468	135
0702 – Game consoles	886	3 435	891	205	321	365
TOTAL	48 296	432 505	37 665	2 460	21 248	13 957

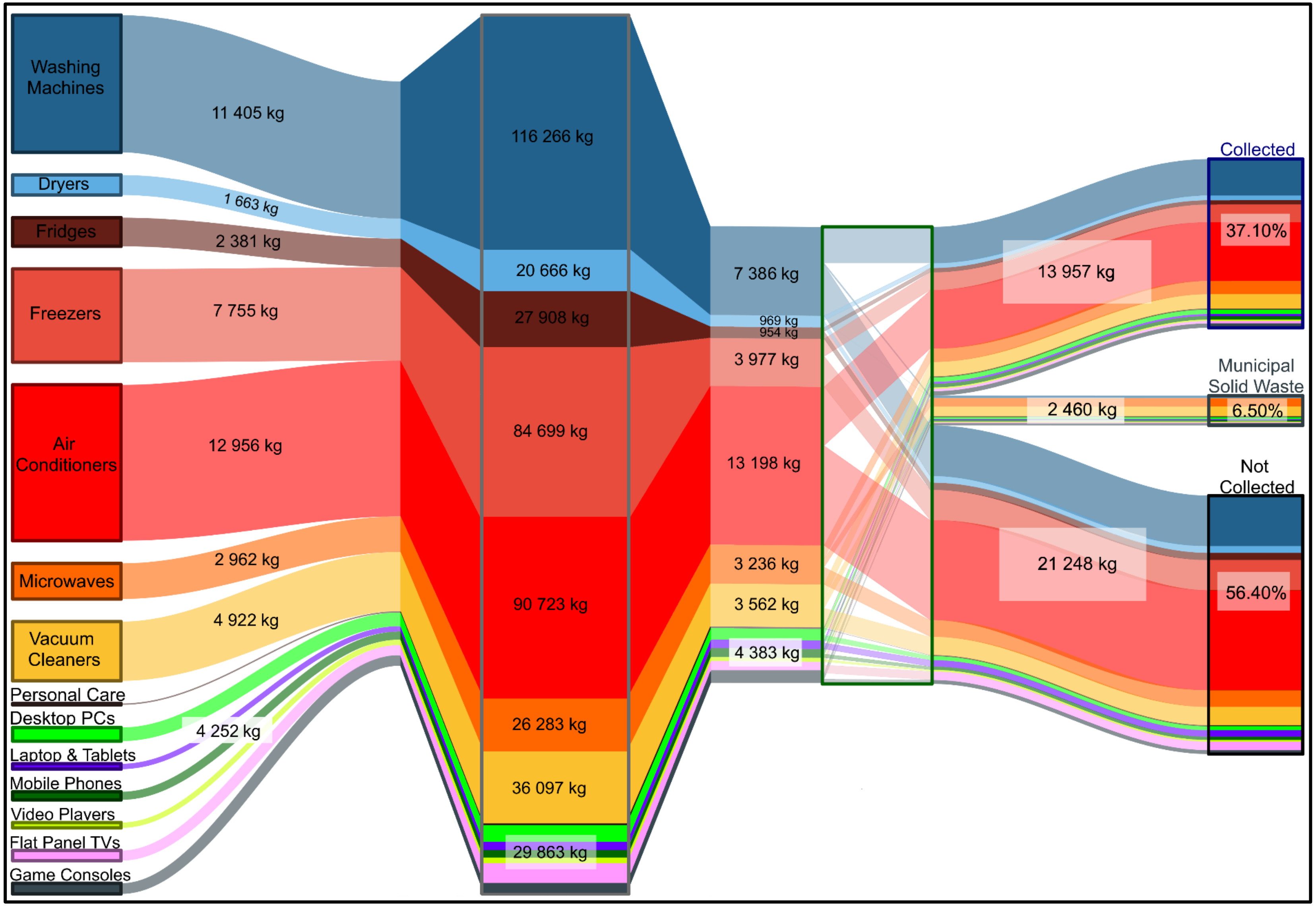

Figure 2 - Sankey diagram depicting the neodymium flow and stock (in kg of neodymium) in Portugal within selected EEE for the year of 2015. Totals: POM = 48 296 kg; stock = 432 505 kg; waste generated = 37 665 kg.

4.2 Urban Mine Prospection and 'Exploitation'

Effortlessly, the 14 EEE can be split into 3 different tiers (Table 2) according to the amount of neodymium present within them, easing the process of pinpointing the most potential sources within the system. Washing machines, air conditioners and freezers (tier I) hold the vast majority of the substance within the system, collectively containing more than half of the total amount present in stock (around 67.4%). Microwaves, vacuum cleaners, dryers and fridges (tier II) also yield significant amounts of neodymium, holding around a quarter of the total neodymium in stock (Fig. 3).

Table 2 – Classification of equipment according to their neodymium content in stock within the system.

Tier I – High (Above 15%)	*0111 – Air conditioners; 0104 – Washing machines;* *0109 – Freezers*
Tier II – Intermediate (between 4% and 15%)	0204 – Vacuum cleaner; 0108 – Fridges; 0114 – Microwaves; 0105 – Dryers
Tier III – Low (below 4%)	0302 – Desktop PCs; 0408 – Flat display TVs; 0702 – Game consoles; 0306 – Mobile phones; 0303 – Laptops & tablets; 0404 – Video; 0205 – Personal care equipment

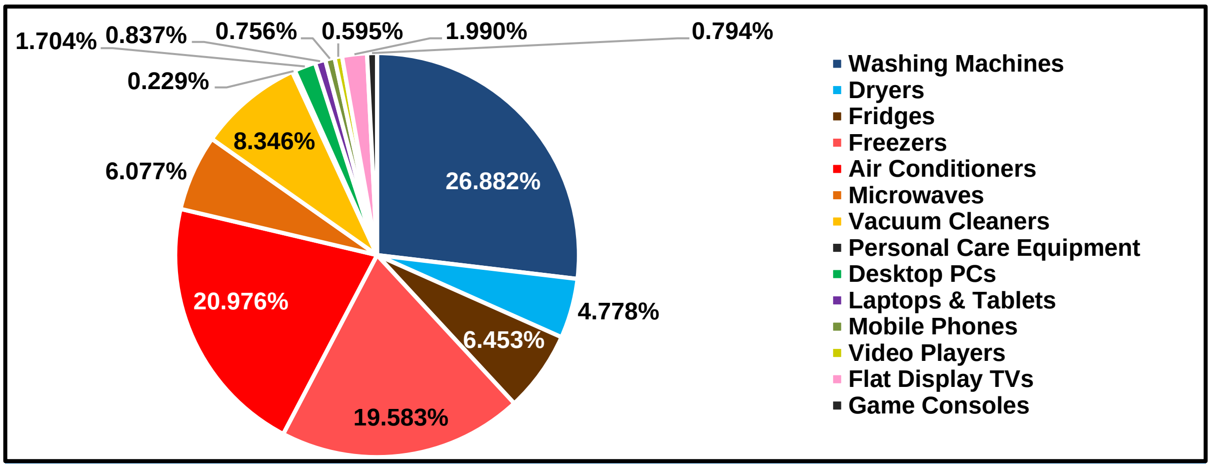

Figure 3 – Pie chart depicting the percentage (per UNU-key) of the total neodymium within stock (432 505 kg).

Above 90% of the total neodymium present within the system is within tier I and tier II, meaning that the remaining seven equipments (Tier III), contains minute amounts, holding collectively less than 10% of the total stock. From an exclusive perspective of prospecting sources for secondary metal production, 'tier I' equipments have the highest potential. 'Tier II' equipments can also yield reasonable amounts providing there's good collection and recovery. Tier III cannot be considered a relevant source as the others, the cumulative amount is much lower, nevertheless, an optimized process could render the neodymium present within them recyclable or recoverable by other methods. The 3-tier classification is valid and applies to not only to stock and POM but also to waste data.

Since the proposed classification is valid across the three main processes it can be concluded that (assuming an average EEE lifetime of 10 years) between the previous decade, the evaluation year and the following decade trends are similar with the same equipments yielding the largest potential to be sources of secondary neodymium (tier I and II).

4.3 Potential Neodymium Recovery

According to the results, in 2015 over 37 tonnes of neodymium were present within waste generated. Only 14 tonnes (37.1%) were reported as collected and 2 tonnes (6.5%) presumably ended up in landfills. An estimated 21 tonnes (56.4%) were not collected and are in an unknown standing. A potential maximum of 11.2 tonnes of Nd could have been recycled, this is around 23% of 2015 demand in Portugal (Table 3).

Table 3 – Overall Scenario of neodymium within WEEE urban mine in Portugal (2015).

	Maximum amount potentially recoverable (tonnes of Nd / % POM)	*Expected recovery (tonnes of Nd)*
Waste generated 2010-2015	205 (425%)	Unknown
Waste generated 2015	~38 (71%)	Unknown
Not collected/disposed 2015	~24 (43%)	Unknown
Collected (Portuguese rates)	~14 (29%)	Unknown
Recycling (2015)	~11.2 (23%)	None
Reuse (2015)	>11.2* (>23%)	Unknown, but substantial
Collected (Swedish rates)	~25 (55%)	NA
POM 2015	~48	NA
Stock 2015	~432	NA

*Assuming that, a ‘Not collected’ fraction is also officiously recovered through reuse in scrapyards.

No neodymium recycling is performed, but the components that contain NdFeB magnets (mostly motors and compressors for the case of Tier I and II equipments) are usually easy to extract and reuse in new or refurbished devices. Considering a best-case scenario, it can be assumed that those 11 tonnes collected could have been recovered and re-introduced in the market through reuse. Even the ‘not collected’ fraction that ends in scrapyards can also count for the amount of neodymium recovered through reuse. Unfortunately, there’re no data available indicating the amount of Nd being recovered through reuse (Table 3).

An urban mine should not be characterized solely based on a single year assessment, every year waste is generated and a large portion of it, is not collected, presumably remaining within the system indefinitely. Analysing the period of 2010-2015 shows that an estimated 205 tonnes of neodymium were generated within WEEE. It corresponds to almost half of all neodymium in stock at 2015 (432 tonnes) or 4.25 times the demand for the element in the same year. 64 tonnes were reported as collected, out of it 51.6 tonnes could have been potentially recovered. Yet, over 141 tonnes of the waste generated did not even enter recovery facilities. These uncollected tonnes would be able to cover the entire Portuguese Nd demand for over two years and a half without the need for any primary production (Table 3).

Moreover, the WEEE collection in Portugal (~34.5% for tier I and II) could be vastly improved. Considering that the improvements are only applied to Tier I and II equipments (leaving Tier III rates unchanged), if Portugal could achieve the Swedish rates (~75.6%), the recovery could theoretically climb to around 55% of its POM, this means that more than half of the Portuguese neodymium demand could potentially be supplied by secondary sources (Table 3).

5. Conclusions

Rare Earth Elements are a group of elements that have singular atomic configurations which provide them peculiar properties. Some of these properties are extremely useful in applications such as catalysts, battery alloys, phosphors and permanent magnets. The biggest issues regarding them are the supply and environmental risk. Over 80% of the world reserves and 95% of its primary production are in the unreliable Chinese nation and its extraction have large footprints as hazardous chemical compounds are required for its refining. Due to the aforementioned reasons, REE are considered to be critical raw materials. Moreover, there’s one particular application that requires additional attention: neodymium magnets. Unlike the remaining REE, there’s no equivalent alternative to neodymium that can achieve the same performances levels, and the demand for these magnets is set to continue its exponential increase through the years indefinitely until an effective substitute is encountered. In conclusion, Nd is the most critical REE.

Ultimately, this dissertation aimed to prospect a strategic element in a nation and analyse the possibilities of that nation adopting a regenerative economy. The conclusion is that, although due to inefficient collection and rapidly increasing demand, it wouldn’t be possible to sustain a national market solely on secondary production, it is possible to substantially reduce the dependence on primary production (effectively reducing the elements criticality). For instance, even in the worst collecting scenario, Portugal could reduce up to 23% its reliance on neodymium primary sources by recovering it from collected WEEE (this value could increase to 55% in a better-case scenario).

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