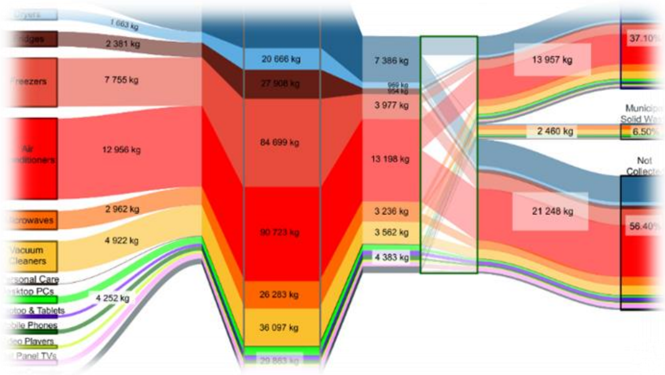

Evaluation of Strategic Metals
Envisaging the Sustainable Management

Neodymium Flow and Stock Analysis in Portugal

Francisco Pinheiro Vaz Capucha

Thesis to obtain the Master of Science Degree in

Materials Engineering

Supervisors: Prof. Fernanda Maria Ramos da Cruz Margarido

Dr. Carlos Alberto Gonçalves Nogueira

Examination Committee

Chairperson: Prof. Maria Emília da Encarnação Rosa

Supervisor: Prof. Fernanda Maria Ramos da Cruz Margarido

Member of the Committee: Dr. Patrícia de Carvalho Baptista

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Em memória do meu pai, que me mostrou o mundo da ciência e tecnologia…

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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

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Resumo

A tecnologia está em constante evolução e consequentemente a procura de materiais com propriedades singulares aumenta. Alguns apresentam cadeias de fornecimento problemáticas e são denominados de ‘Matérias Primas Críticas. Um destes grupos chamado ‘Terras Raras’ (TR), são importantes para tecnologias de topo, nomeadamente as tecnologias verdes. Sendo a maioria da sua produção primária na China, o fornecimento de TR está fortemente dependente das suas políticas de exportação. Em 2011 o governo Chinês fez cumprir um embargo às Terras Raras, consequentemente o seu preço aumentou. A União Europeia procura soluções para reduzir a criticidade, apostando na redução, substituição por elementos não-críticos e/ou produção secundária. Enquanto a redução e reutilização têm uma implementação simples e são aplicáveis à maioria das TR, existe um elemento que não pode ser substituído devido às perdas substanciais de desempenho – o neodímio em imanes. A única solução para a redução da criticidade do neodímio é a aposta na reciclagem de resíduos. Ao recuperar toneladas de neodímio (e outros elementos) presentes em minas urbanas, não só se reduz o risco de fornecimento como se reduz a quantidade de resíduos inexplorados, contribuindo para um sistema regenerativo onde os resíduos são utilizados para fornecer matéria-prima para novos bens. A prospeção de elementos críticos, abrem caminho para a mudança de economias lineares para circular ao fornecer a quantidade de materiais que pode ser potencialmente recuperada das suas minas urbanas. Esta prospecção, chegou à conclusão de que, em 2015, a mina urbana de neodímio em Portugal poderá ter gerado 38 toneladas.

Palavras-chave: Matérias Primas Críticas, Terras Raras, Neodímio, Análise do Fluxo de Materiais, Mina Urbana, Economia Circular

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List of Acronyms

AMC Average Magnet Composition
AMW Average Magnet Weight
ANC Average Neodymium Content
AO Auto Catalyst
BE Belgium/Belgian
Ce Cerium
CRM Critical Raw Materials
CRT Cathode-Ray Tube
Dy Dysprosium
EC European Commission
EEE Electrical and Electronic Equipment
EI Economic Importance
EOL End-Of-Life
Er Erbium
ERECON European Rare Earths Competency Network
EU European Union
Eu Europium
EV Electric Vehicle
FCC Fluid Catalytic Cracking
Gd Gadolinium
HDD Hard Disk Drive
Ho Holmium
HREE Heavy Rare Earth Element(s)
IMF International Monetary Fund
I-O Input-Output
IRR Internal Rate of Return
La Lanthanum
LED Light Emitting Diode
LREE Light Rare Earth Element(s)
Lu Lutetium
MFA Material Flow Analysis
Nd Neodymium
NdFeB Neodymium-Iron-Boron
NiMH Nickel-Metal-Hydride
PET Positron Emission Tomography
PHEV Plugin-Hybrid Electrical Vehicle
Pm Promethium
PMDC Permanent Magnet Direct Current
PMG Permanent Magnet Generator
Pr Praseodymium
PT Portugal/Portuguese
RE Rare Earth(s)
REE Rare Earth Element(s)
REO Rare Earth Oxide(s)
ROW Rest of the World
Sc Scandium
Sm Samarium
SmCo Samarium-Cobalt
SR Supply Risk
SW Sweden/Swedish
Tb Terbium
Th Thulium
UNU United Nations University
US United States

WEEE	Waste Electrical and Electronic Equipment
Y	Yttrium
Yb	Ytterbium

1. Introduction

1.1 Context and Problem Definition

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, owing to several reasons such as rarity, complex refining, resource location or geopolitical tensions. When a raw material is crucial for economic development, but its supply is instable usually is denoted as 'Critical Raw Material' (CRM). The European Union (EU) compiles triennially a CRM list, and since its conception, a group of 17 elements is always listed – the Rare Earth Elements (REE) [1].

REE are a group of metallic elements that are vital for numerous state-of-the-art technologies, including the 'green technologies' (environmentally friendly alternatives for already existing technologies), these elements play an essential part in EU's plan to become less hazardous to the planet. But REE have two main issues. Firstly, its worldwide reserves and extraction are almost exclusive to the People's Republic of China who's already enforced a REE embargo in 2011 resulting in extreme price surges. And secondly its primary production is highly complex, expensive and hazardous for the local environment [1].

To counteract the unstable supply of REE, efforts are being focused on either reduce its use, search for less problematic material alternatives or to wager on recovering these elements from end-of-life goods. And while the majority of REE can be reduced or fully substituted, thus decreasing its demand (and consequently its critical status), others will not be easily replaceable and the only viable solution to reduce its supply risk is to source it internally by recovering it from waste [1].

In a world where materials demand is increasing and more waste is being generated, a clear resolution is to design processes for a regenerative economy, this is to reduce both waste and primary production through repair, reuse or recycling of waste. This system is usually denoted as 'circular economy'. Since several tonnes of critical materials (such as REE) are already available in every nation within waste, recovering it should be a natural option to ease its supply risk, hence alleviating its critical status and contributing to a regenerative system where waste becomes the building blocks for new goods.

The activity of exploiting waste containing economically important materials to recover them is usually termed 'Urban Mining'. And analogously to primary mining, the first stage in an urban mine exploitation is the prospection, i.e. to search and pinpoint the anthropogenic equivalent of mineral veins. In this case, to study the exact type of waste that bears the desired elements in its constitution, so the collection can be specialized and improve the recovery efficiency, thus contributing to a nation's effort to adopt a regenerative circular economy [2].

This first stage of the CRMs recovery chain (prospection) is an indispensable step in the efforts to reduce these materials critically, therefore worth of a thorough academic research.

1.2 Research Questions

This dissertation has three main objectives, respectively developed and guided by following a set of research questions which will be answered through the essay.

1. **Investigate REE in a detailed manner to understand its criticality.**
   a. What are REE?
   b. Why are REE considered critical?
   c. Is there any solution to lessen its criticality?
2. **Analyse demand for REE and identify which element(s) is(are) the most critical and will remain critical.**
   a. Which REE(s) is(are) and will be the most critical?
   b. Why it will remain (or become) the most critical?
3. **To study the anthropogenic incidence of the most critical REE in Portugal, during a recent year, using the method 'Material Flow Analysis' in order to prospect its potential recovery by urban mining.**
   a. What is the 'Material Flows Analysis' method and how is it implemented?
   b. How is the most critical REE distributed within Portugal?
   c. Can its incidence be related and pinpointed to specific goods?
   d. How much could be this urban mine potentially yield?
   e. How is it recovery being handled? Can it be improved? Is recycling possible?
   f. Can the secondary production sustain the demand?

1.3 Publications

Work developed for this dissertation will result in two publications, indicated below, which are currently in submission.

- F. Capucha, F. Margarido, C.A. Nogueira. "Rare Earth Elements – A Review", Journal of Cleaner Production, 2019
- F. Capucha, F. Margarido, C.A. Nogueira. "Neodymium Flow and Stock Analysis in Portugal", Journal of Environmental Science and Technology, 2019

1.4 Document Structure

This dissertation is divided into five chapters arranged between two interconnected sections:

The first section, named "Rare Earth Elements – A Review" encompasses chapter 2 and it stands as the dissertation's literature review. It aims to understand Rare Earth Elements critical status by studying its physicochemical properties, applications, production, recovery and other related matters.

Ultimately, chapter 2 determines the most critical REE to be neodymium, setting the target material to be analysed in the following section – “Neodymium Flows and Stock Analysis in Portugal”, comprised of chapter 3 and 4.

Chapter 3 elucidates the method “Material Flow Analysis” and demonstrates how neodymium flows and stock were modelled by detailly describing each modelling step, from system definition to the results.

Chapter 4 displays and interprets the results obtained discussing their meaning and impacts investigating the potentiality of the nation to adopt a regenerative circular economy system for the target element.

Chapter 1 and 5 functions as the bridge between sections. The first chapter introduces the topic, presents the dissertation main objectives and establishes the connection between the sections, i.e. the most critical REE, neodymium. Whereas chapter 5 closes the dissertation by stating its conclusions, answering the research questions and briefly discussing the main challenges and limitations and how they provide the ground for further developments regarding this topic, in the future.

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2. Rare-Earth Elements – A Review

2.1 Definition & Properties

'Rare-Earth Elements', henceforth referred as '*REE*', is the designation given by the International Union of Pure and Applied Chemistry - IUPAC for a group of 17 elements with similar chemical properties, namely the 15 lanthanides as well as yttrium ($_{39}Y$) and scandium ($_{21}Sc$). The lanthanides consist of the following elements: lanthanum ($_{57}La$), cerium ($_{58}Ce$), praseodymium ($_{59}Pr$), neodymium ($_{60}Nd$), promethium ($_{61}Pm$), samarium ($_{62}Sm$), europium ($_{63}Eu$), gadolinium ($_{64}Gd$), terbium ($_{65}Tb$), dysprosium ($_{66}Dy$), holmium ($_{67}Ho$), erbium ($_{68}Er$), thulium ($_{69}Th$), ytterbium ($_{70}Yb$) and lutetium ($_{71}Lu$) [3].

Despite its name, REE aren't fundamentally rare, being plenteous in earth's crust. Some *Abundance Tables* even state that the abundance of most REE (excluding promethium, terbium and lutetium) is larger than precious metal like gold, and some like cerium are more common than copper. Note that the data provided by *Abundance Tables* do not imply that more abundant elements are easier to extract, it simply provides a projection for the quantity of a certain element in the planet's entire crust. For these instances, it is useful to understand the concept of *Mineralogical Barri*er [1, 4-6].

Mineralogical Barrier refers to the critical point where the grade of an ore reaches such a low percentage (Fig. 1) that the ratio between extraction energy and mass recovered increases exponentially. This increment is due to the separation process, since typical concentration techniques cannot be applied in extremely dispersed elements (at the atomic level). Minerals must be chemically broken down in order to separate the desired atoms from the remaining, these processes are energy-demanding, and the amount recovered is small [1, 7].

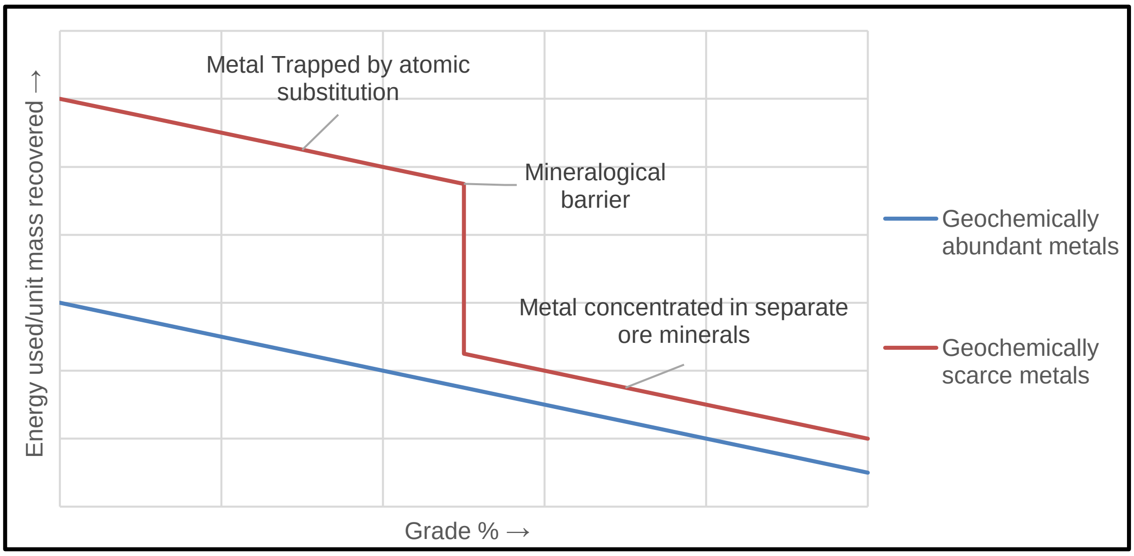

Figure 1 – Relationship between the ore grade and extraction energy/unit of mass for abundant and scarcer elements and the indication of the 'Mineralogical Barrier". Adapted from [7].

Almost every REE are trivalent (with exception of Ce^{4+} and Eu^{2+}), have a similar radius and can replace each other in the crystal lattices easily, leading to its wide dispersion and triggering the typical occurrence of different REE within the same mineral. Due to these reasons, the grade of REE minerals normally lies below its *Mineralogical Barrier*, thus being extremely difficult to extract and separate each individual element. Moreover, REE do not occur naturally in metallic form existing in the form of oxides, phosphates, carbonates or halides, and, out of the 200 known minerals only a small fraction (less than 10) are potentially viable for mining, with bastnaesite, xenotime and monazite being the most common. Economically exploitable REE natural resources are effectively scarce [1, 6, 8-12].

Based on the few chemical and physical differences, such as electronic configuration, REE can be divided into two sub-groups [6, 13]:

- **Light REE (LREE)** – With unpaired electrons in the 4f shell. From lanthanum (La_{57}) to europium (Eu_{63}) [13, 14].
- **Heavy (HREE)** – With paired 4f shell electrons. From gadolinium (Gd_{64}) to lutetium (Lu_{71}) and yttrium (Y_{39}) [13, 14].

Yttrium is factually light (second lightest REE with an atomic mass of 88.9u), but due to its ionic radius (very similar to dysprosium, Y - 180pm to Dy - 177pm) it is usually considered a HREE. Scandium, the lightest REE (atomic mass 45u), is often considered as neither LREE or HREE, since it has no feature that can truly characterise it as part of any of the sub-groups. 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). Usually, REE with the higher the atomic number tend to be scarcer, therefore HREE are less abundant than LREE, with cerium being the most abundant LREE and yttrium the most abundant HREE [1, 6, 8, 13-15].

There're discrepancies between the several REE classifications, often the difference being in the choice of the border element between 'light' and 'heavy', some authors even suggest the introduction of 'Medium REE'. For instance, U.S. Geological Survey refers gadolinium with its half-filled 4f shell with seven unpaired electrons as a LREE, however, the European Commission (EC) considers it a HREE, for the remaining elements there's a relative global consensus. For any purpose, this dissertation adopts the European Commission classification considering both yttrium and gadolinium as HREE and does not classify scandium as a REE [1, 13, 14].

At the atomic level, lanthanides display unusual electronic configurations. Typically, higher atomic number implies more electrons in the outermost orbital, however, for lanthanides the valence electrons do not attach to the outermost shell, rather entering in more profound 4f orbitals. Since lanthanides outermost orbital is a fully occupied $6s^2$, chemical properties (which are mostly governed by the outmost electrons) are similar across all elements. A noteworthy consequence is the *Lanthanide Contraction* (Fig. 2), a greater-than-expected reduction of ionic radii with increasing atomic number. Due to its inner-shell nature (i.e. proximity to the core), electrons in 4f orbitals are highly attracted to the nucleus, thus, with increasing atomic number they contract, and since 4f orbitals poorly shields the external electrons from core charge, the entire electronic cloud contracts [1, 16].

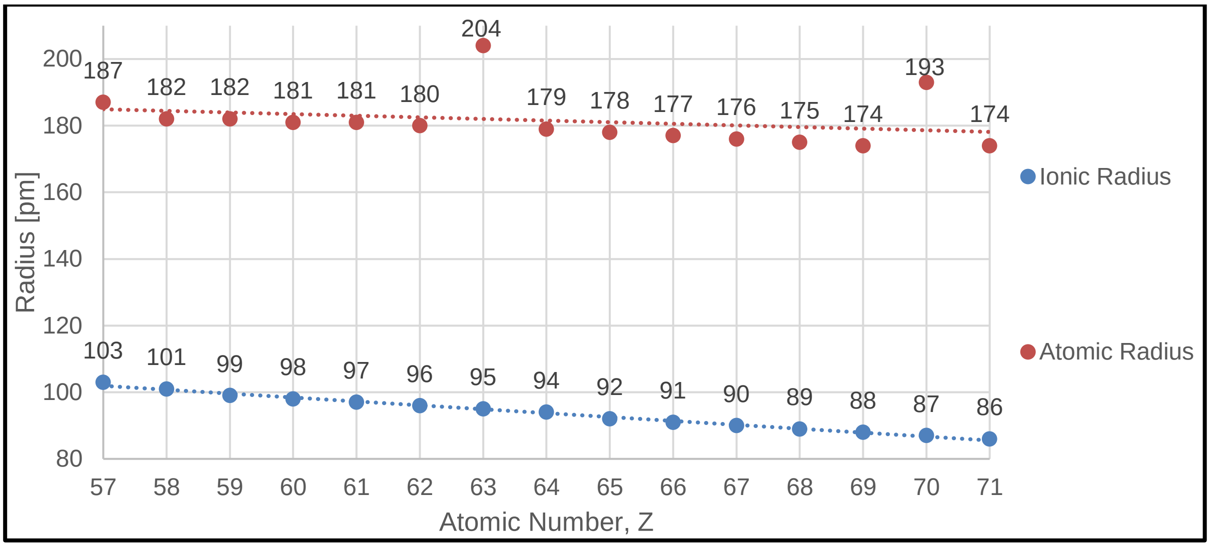

Figure 2 – Ionic and atomic radius of all lanthanides in picometers depicting the 'Lanthanide Contraction'. Adapted from [1].

Due to *Lanthanide Contraction* it's common to discover REE ores with calcium, thorium or uranium in its composition, as the radii of most REE ions (which are trivalent) are similar to ones of Ca^{2+}, Th^{4+} or U^{4+}. This information is particularly useful for the case of thorium and uranium, which are hazardous elements and must be handled appropriately when being separated from the REE [1, 16].

Unlike chemical properties, the physics of REE are not significantly affected by its unique electronic configuration, demonstrating varied behaviours, this being a major point where each element is set apart from others. Some elements like neodymium and samarium have complex potentials, which is why they are used for high-performance magnets, whereas others like europium or yttrium have sharply defined energy states which are useful for applications such as phosphors [1].

2.2 The 'Balance Problem'

As referred, REE tend to occur aggregated, generally in either LREE-rich or HREE-rich minerals, however, the ratio of each element isn't the same, depending on numerous factors like atomic number or the geographical origin of the mineral. During production, all elements present in the ore are extracted, this poses a problem as market demand for each element is dissimilar and seldom correlates the ratio of elements in the mineral composition. This issue denoted by 'Balance Problem' is the cause of several market disruptions where simultaneously some REE are being stockpiled while others are suffering shortages. Major consequence is market instability [15].

For instance, if at a given period there's higher demand for a scarcer element, the more abundant ones that are extracted with it, are stockpiled decreasing their price, hence the scarcer element price must increase to cover the production costs, which is shared by all REE extracted from that source. An ideal scenario would see a balance between the supply and demand for all REE, to have a market driven by natural abundance of each element, however, it doesn't happen as technological developments are regularly based on material's properties rather than its availability [15].

Worldwide LREE market is currently driven for neodymium to produce magnets, thus creating an excess of lanthanum, cerium, samarium and praseodymium. Lanthanum has a high demand for producing Fluid Cracking Catalysts (FCC), cerium is applied in catalysts and polishing, Praseodymium is used as an alloying element in NdFeB magnets, and SmCo magnets make use of samarium, however the demand it's not enough to consume the stockpiles of the latter three. As for HREE market, is presently driven by dysprosium which is also used in NdFeB magnets, while the demand of yttrium and erbium is in balance, the rest of heavier REE do not have high volume applications [15].

Moreover, REE market is highly volatile, in a period of a few years the elements that drive the market can change completely, and a least essential element can become the most needed or vice-versa. E.g. in the 1960s europium was the most critical element as it was the only source to produce vivid red phosphor for CRT monitors, since it was one of the scarcer REE, there was a large oversupply of other REE such as samarium. Nevertheless, in 1970s-1980s demand for samarium increased for the production of samarium/cobalt magnets and that element was brought to balance. At the time, neodymium and dysprosium had no industrial use and were stockpiled, nowadays it's exactly those elements drive the LREE and HREE markets respectively [15].

Essentially, REE market trends are strongly dependent on factors like technological evolution and discontinuation of older technologies. For example, the phosphors used in fluorescent lamps require europium, terbium and yttrium, yet with LED technology ascendance, phosphor production ought to decrease, which could lead to stockpiling of those REE if no alternatives applications are found [15].

The most common solutions provided by academic circles for restoring supply/demand balance are listed below [15]:

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 within European Union

In 2008, to address growing concerns about securing supply of indispensable raw materials, European Union (EU) created the 'European Raw Materials Initiative', that periodically releases a list for the 'Critical Raw Materials' (CRM for short). Revised every 3 years since 2011, it aims to identify the most important raw materials for European industry that have high supply risk. It assesses criticality using a methodology developed by the European Commission (EC) which is based on two variables: Supply Risk (SR) and Economic Importance (EI) [14, 17].

- Economic Importance, EI – This parameter attempts to rate the importance of a given material to the European economy, related with potential consequences that can occur in case of an inadequate supply [17];
- Supply Risk, SR – Assesses the risk of insufficient supply of a given material to meet European industry demand. It's calculated using factors such as import dependence, political status of an external supplier, primary/secondary production within the Union, and the Substitution Index (quantitative estimation of the substitution potential) [17];
- Criticality – If a given raw material has both parameters above thresholds established by European Commission, it's considered to be Critical [14, 17].

2017 report studied 78 raw materials and considered 43 to be critical, including 15 REE, solely excluding promethium which has no stable isotope in nature and scandium which is not considered as REE by the European Commission (Fig. 3). The report addresses REE as two separate group: LREE and HREE, i.e. data was obtained using arithmetic averages of the results from each individual RE included in those groups. Note that lanthanum and erbium aren't considered critical, but since REE are evaluated as groups, these elements are considered critical as well [18].

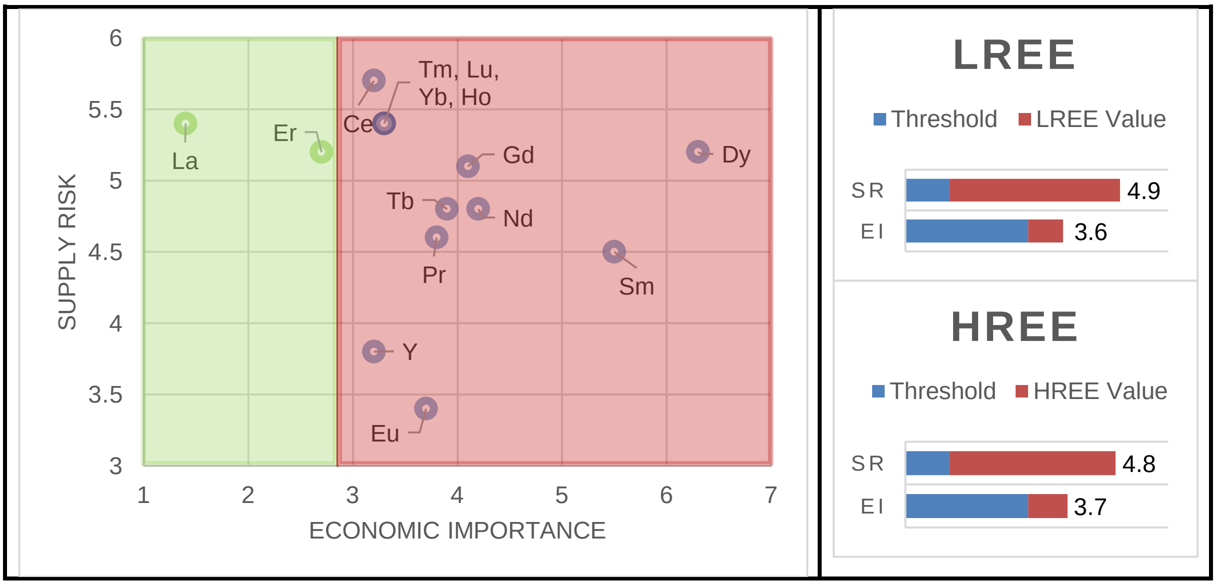

Figure 3 – SR and EI, for the individual REE in the EU (left). For the groups of LREE and HREE (right). Threshold (Critical area in red): Supply Risk – 1; Economic Importance – 2.8. Adapted from [14].

2.3.1 Importance

REE play a key role in implementing the so-called *green technologies*. Permanent magnets generators are often used in turbines that produce energy by seizing the power of wind, river flow or ocean waves uses REE magnets. In current technology, all Hybrid/Plug-in vehicles and some fully electric vehicles (EV), the current flagship for environmentally friendly transportation, could not exist without REE. For instance, to produce a permanent magnet motor capable of moving a vehicle, yet compact enough to fit inside of it, requires neodymium/praseodymium magnets. Some even use nickel metal-hydride (NiMH) batteries which have high percentages of lanthanum to provide the best performance [14, 19, 20].

Together with other environment-protective applications, such as energy-saving lamps (fluorescent lamps) or catalysts that prevent toxic gases to reach the atmosphere, it's valid to state that REE are the backbone for the worldwide technological quest to become environmentally friendly. The European Commission is known for its pro-environment advocacy, therefore it's comprehensible that REE have high economic importance [14, 19, 20].

2.3.2 Production

The main reason for critical status of REE in Europe, is the very high supply risk due to EU complete dependence on imports which come mostly from unreliable sources that could potentially spark supply shortages, hindering European technology industry. An estimated 81% (around 65,840,000 tonnes) of the worldwide Rare-Earth Oxides (REO) mineral reserves are located in China (Fig. 4), same nation is also the main primary producer, having currently a projected 80-95% of worldwide primary production in 2015 (Fig. 5) [18, 21-24].

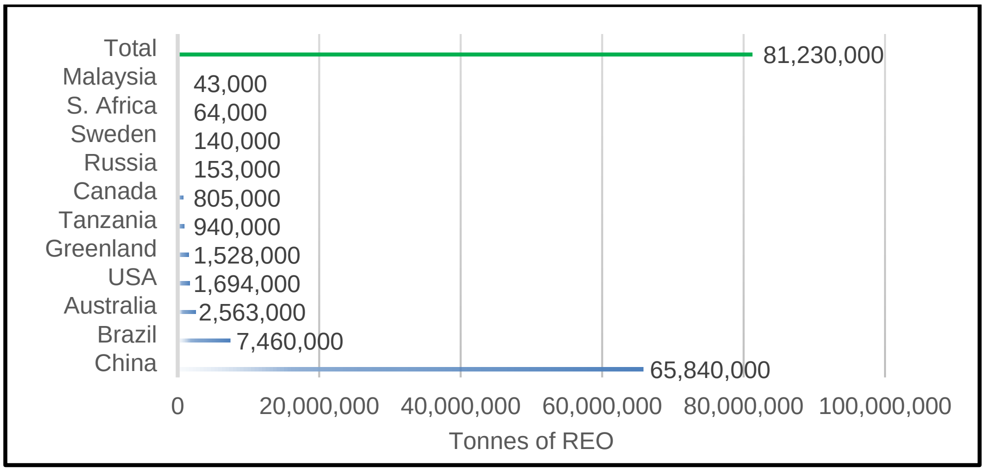

Figure 4 – Global mineral reserves of rare-earth oxides (REO). Adapted from [18].

Besides China, countries that yield substantial amounts of REO are Australia, United States and Russia. Recently (between 2014 and 2016) there were two new REO mining ventures by non-Chinese private corporations, *Molycorp* (in USA) and *Lynas* (in Australia and Malaysia). During that period there were noticeable reductions in Chinese global production quota. Yet, financial issues caused *Molycorp* to indefinitely halt its REO production in October 2015, and, stricken by debt, *Lynas* activity were partially idled around the same period. Because of delayed availability of the statistical data to the public (seldom post-2015 statistics are available), at the moment it's not possible to assess the real impact of *Molycorp* and *Lynas* financial difficulties. Russian extraction projects are more modest but stable with production being secured by *Solikamsk,* though REO it's not their focal mining activity [18, 21].

Margins of error for REE production statistics are substantial, primarily due to high incidence of undocumented and uncontrolled REE informal markets, fuelled by illegal exploitation. This can be perceived on Figure 5, where the EC (pie chart on the left) refers China's production share to be 95% in 2014, whilst USGS considers it to be around 80.7%, for this case European Commission considered an estimated illegal production for its statistical calculations [18, 21-24].

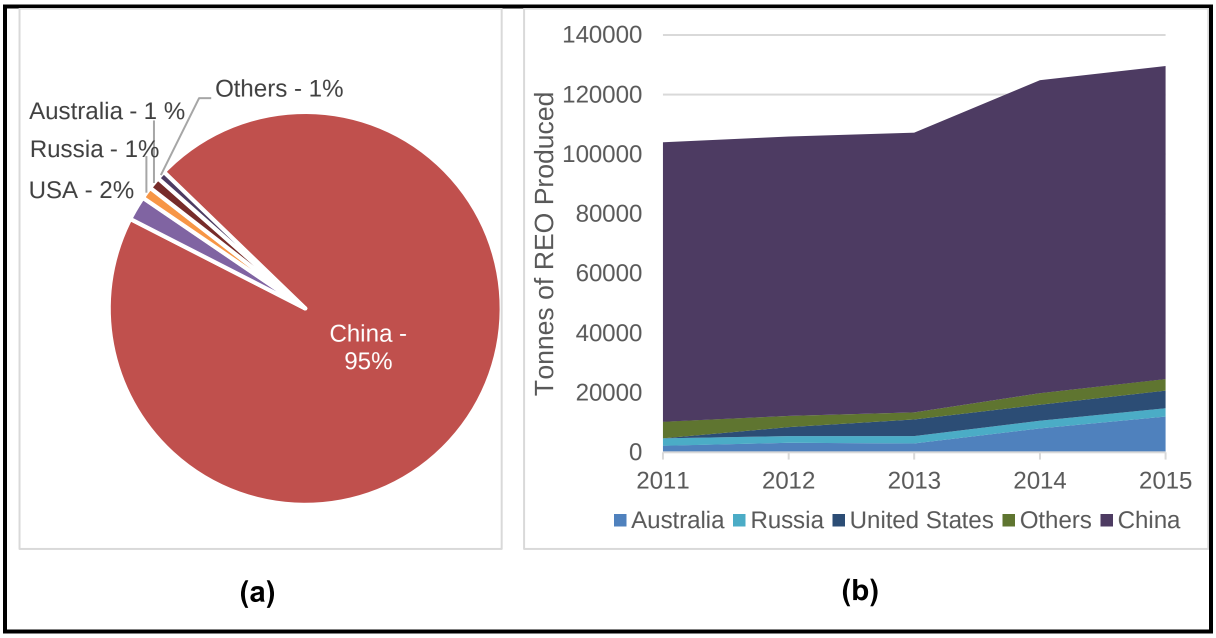

Figure 5 – (a) Global primary REO Production, total estimated production (average 2010-2014): 135,650 tonnes. (b) Global production trends of REO between 2011 and 2015. Adapted from [18, 24].

Moreover, between 2008 and 2013 there were noticeable reductions in China's production and exportation, a direct consequence of the efforts to reduce illegal and inefficient production, combined with tightening of export quotas to promote internal consumption. Still, in recent years with the fall of western ventures and consolidation of new politics, China recovered and retained its quasi-monopoly of REO production [18, 21].

Regarding production in the European Union, there's no primary production currently, yet the EC is assessing the possibility for exploitation of two large deposits localised in Greenland and Sweden to tackle China's dominance. Nevertheless, with high production cost, low-profit margin and environmental issues, near-future mining endeavours on Europe soil are not foreseen [18].

2.3.3 Trade: Market Demand & Pricing

Since REE production started at an industrial scale, its demand has been growing steadily (Fig. 6), mostly due to development and spreading of technologies that require properties that can only be provided by REE. There are efforts to decrease the amount of REE used but an almost exponential rising of sectors such as hybrid/electric vehicles or wind turbines will keep the demand for some unreplaceable REE [21].

Additionally, not only China has the largest reserves and is the biggest producer but it's also the major consumer with a consumption of around 109,500 metric tons in 2015, this is a direct reflection of China's immense investment in the field of High-Tech Industry. Therefore, most nations acquire RE-containing products already assembled, rather than fabricating them locally, explaining the very low primary REE consumption rate of EU and US industry, 4 and 3 percent respectively [22].

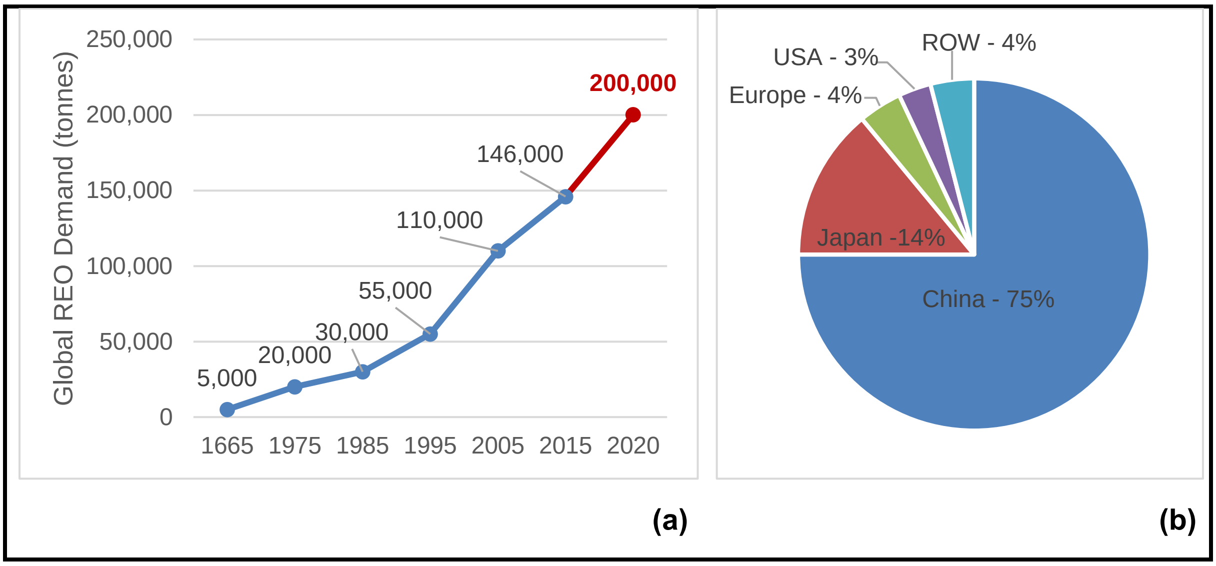

Figure 6 – (a) Evolution of the global demand for REO between 1965 and 2015 and prediction for 2020; (b) Market demand share pie chart in 2015. Adapted from [20].

Chinese importing strategies seriously hindered European industry efforts to develop healthily, as its newly focus on internal consumption sparked aggressive exportation constrictions, which culminated in an exportation embargo in 2011. As a direct consequent of the biggest REO producer exportation embargo, global REE market was completely disrupted causing prices to spike in 2011 (Fig. 7). In the following years China was forced to loosen its exportation policy, thus stabilizing the prices [21].

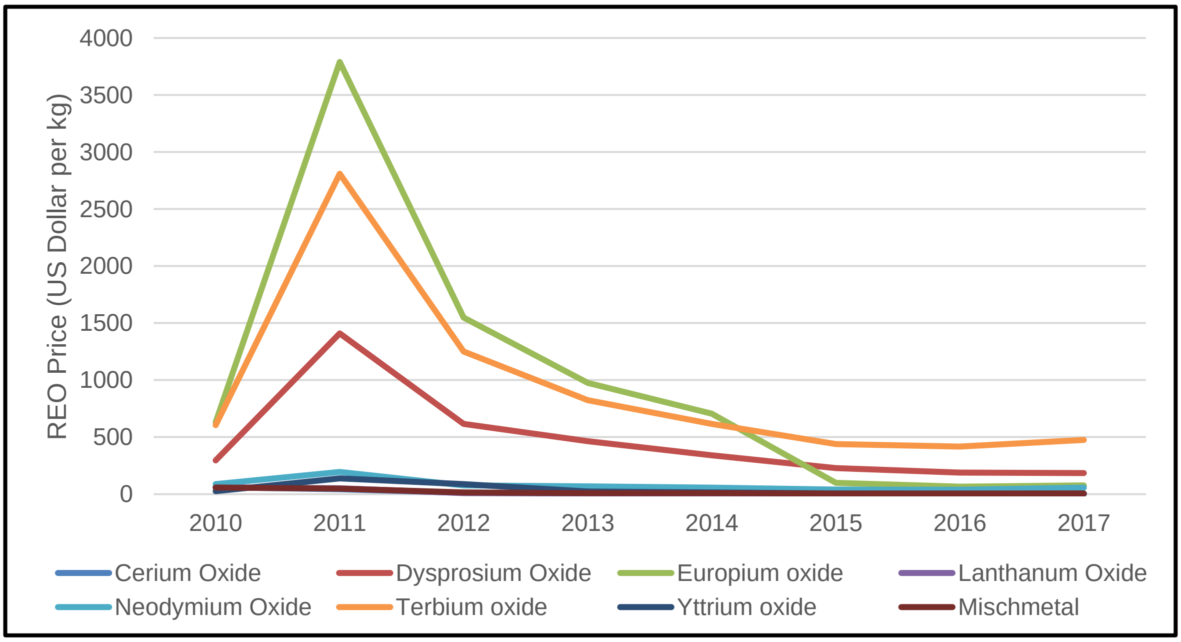

Figure 7 – Evolution of the prices of some REOs between 2010 and 2017. Mischmetal = mixture of 65% cerium oxide and 35% lanthanum oxide. Adapted from [25, 26, 27, 28].

As stated, the 'Balance Problem' has a large impact in the REE market volatility. As seen in Figure 7, europium oxide prices were above 500 US dollars per kg in 2010 and after 2015 is valued less than 80 US dollars per kg. A consequence from CRT technology discontinuation and the decline of fluorescent lamps which are two main applications where europium was widely used [15].

2.3.4 Response Strategies

Latest EU import data is regarded 2014, by then, 40% of imports came from China, 34% from the United States and 25% from Russia, but since US stopped producing REO back in 2015, it's probable that China's percentage increased (Fig. 8). This is an issue as China is not a reliable importer [1].

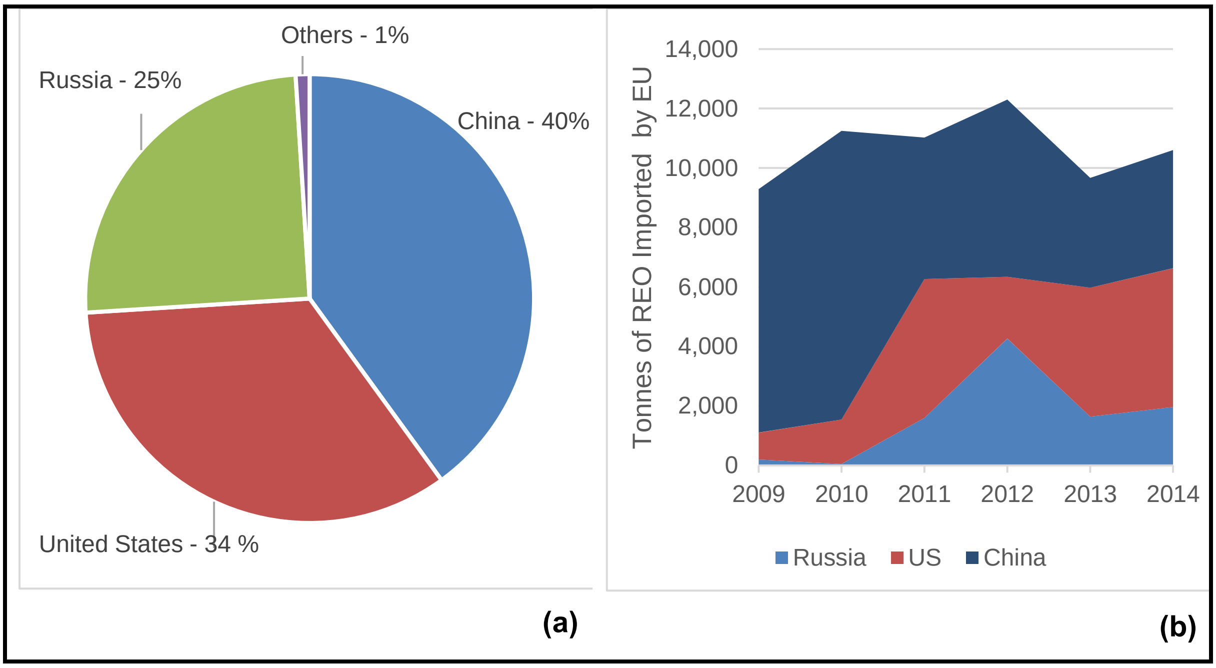

Figure 8 – (a) EU imports of mixed REO (average 2010-2014), total imports: 8000 tonnes. (b) Main suppliers of REO of EU between 2009 and 2014. Adapted from [18, 23].

Currently, EU's REO consumption is very low (4% of worldwide demand), with most of REE arriving at European soil already integrated in finalised products (e.g. NdFeB magnets from China). Two entities were created by the EC with the aim of developing REE industry and ending the high reliance on Chinese imports, presented below is the timeline of its genesis [14, 21, 22]:

1. Around 2008, *European Raw Materials Initiative* was created to identify the most critical raw materials by 2011 the first Critical Raw Materials list was published, including all REE [14];
2. Acknowledging the criticality of REE and its growing demand in different market sectors, EC established two REE-focused entities in 2013:
    a. *European Rare Earths Competency Network* (ERECON) – a network of 80 European Rare Earth experts that have the task of examining key challenges and develop recommendations to provide a secure and sustainable REE supply for the EU [21];
    b. *EURARE* – a project that aims to set the basis for developing a sustainable European REE industry [22].

It's expected that the work of these projects will culminate in a sustainable and sturdy European REE industry, however it's not possible to predict the success of such efforts and for now China still has the quasi-monopoly of production, consumption and exportation [21, 22].

2.4 Processing

Due to its similar oxidation state and radius, RE can replace each other in crystal lattices easily. This creates big challenges for separation and refinement of each individual REE to purity of 99.9% (3N) or 99.9999% (6N). It's not surprising that processing is complicated, energy-consuming, expensive and inefficient. The first stages of mining, beneficiation, leaching/purification produce a mixture of Rare-Earth compounds. Those mixed RE compounds have then to be separated into individual RE compounds, only after the separation, production of individual metallic RE is possible [1, 18].

REE has a complex supply chain and it can be sold at any stage: RE minerals mixture, mixed RE compounds, individual RE compounds and finally individual elements. As expected, the more processed the product, the more expensive, yet it's seldomly sold in the metallic form. Most common stage in which REE are purchased is either as individual compounds or mixture of different compounds. If obtained individually it's relatively easy to process into metal using common metallurgy techniques, but if it's obtained as a mixture there's the need to separate individual elements for its final use. EU does not have the capacity for beneficiation or any of the previous processing steps, but there are two industrial plants (*Solvay* in France and *Silmet* in Estonia) that have the capacity for REE separation. Therefore, the least processed product that Europe has the capacity to import and process is as unseparated concentrated compound mixtures [18, 22, 29].

REE processing is a particularly important step due to its high complexity and it's not often described in reports, production steps are briefly described below and resumed on figure 10 [1]:

1. **Mining –** most REE mining operations are either underground/ open pit hard-rock operations (drilling/blasting), dredging operations or by-product mining [22, 29].
2. **Beneficiation –** terminology used for the process in which gangue is removed from raw ore, producing concentrates of the desired ore. After mining, ore-bearing rocks are crushed and milled to physically disaggregate the target minerals from the tailings. Note that in most cases RE minerals are part of tailings and not the target minerals (by-product mining). Considering different properties between each mineral it's possible to select, isolate and extract the target mineral. If the ore has coarse grains, it's possible to perform physical separation methods, like gravity separation, but for smaller sizes flotation is required, for this a collector is adsorbed to the ore's surface separating it from the gangue. More intricate ore (e.g. RE-bearing clay) cannot be physically separated and skips directly to leach stage, which is less efficient as unwanted elements can also be leached [18, 22, 29].
3. **Leaching and precipitation of RE Mixtures –** beneficiation products are immersed in alkaline or acid solutions to dissolve the RE and produce a mix of REE carbonates or other compounds.
4. **Chemical Separation –** the most critical stage, it's an extremely difficult and complex task owing to the similar chemical and physical properties between each element. It's accomplished by availing small differences in basicity caused by *Lanthanide Contraction*, these differences influence the solubility, ions hydrolysis and complex species formation [1, 22, 29].

There are three main chemical separation technologies being employed by industry [1, 22, 29]:

a. **Fractional Step Method –** working principle based on the solubility difference of each compound, it's an extensive process that requires hundreds of reiterations to separate each element. Inefficiency of this method makes it unachievable at industrial scale [22].

b. **Ion Exchange Method –** started as a technique to separate uranium and thorium from RE containing mixture, but it also performs separation. In a single operation it's possible to separate the elements into high purity metals using differences in the formation of complex species. This method is prolonged and inefficient, nonetheless, it's considered a good option to produce extremely pure products (up to 7N or 99.99999%) [1, 22].

c. **Solvent Extraction Method –** most common procedure, it can be performed using compact equipment, it's relatively fast, continuous and it supports larger quantities. An immiscible organic solvent is added to a RE pregnant solution and it's forcibly stirred. The solvent extracts the desired elements and separation happen when the immiscible liquids are disengaged. This process is repeated until all elements are individualised (Fig. 9). Main disadvantage is its high investment cost [1, 22].

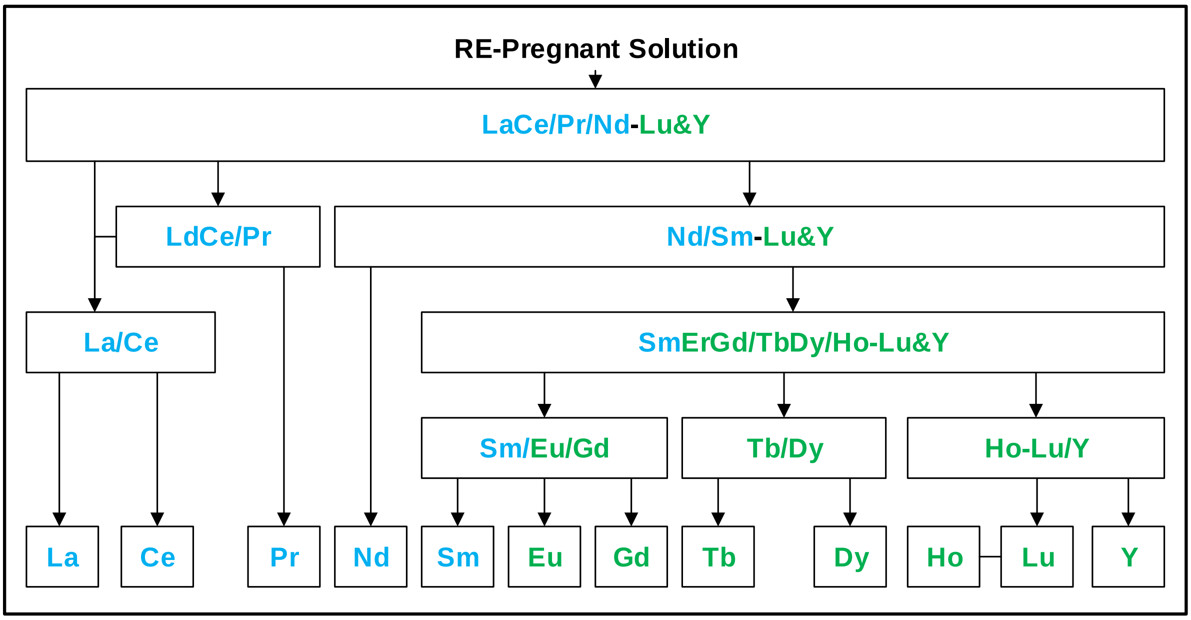

Figure 9 – Example of a REE solvent extraction schematics. Adapted from [22].

5. **Metal Production -** final stage is the production of high-purity RE metal. Most employed technique is salt electrolysis, analogous to aluminium production. RE compounds are mixed with a fluoride-based electrolyte in a steel cell that's heated until 1050 ºC (setup contains a carbon anode and a tungsten cathode). At such temperature, redox reactions occur forming CO/CO_2 in anode and RE metal in the cathode. Because this process occurs above the melting point of REE, any formed metal melts and drips into a tungsten crucible [29].

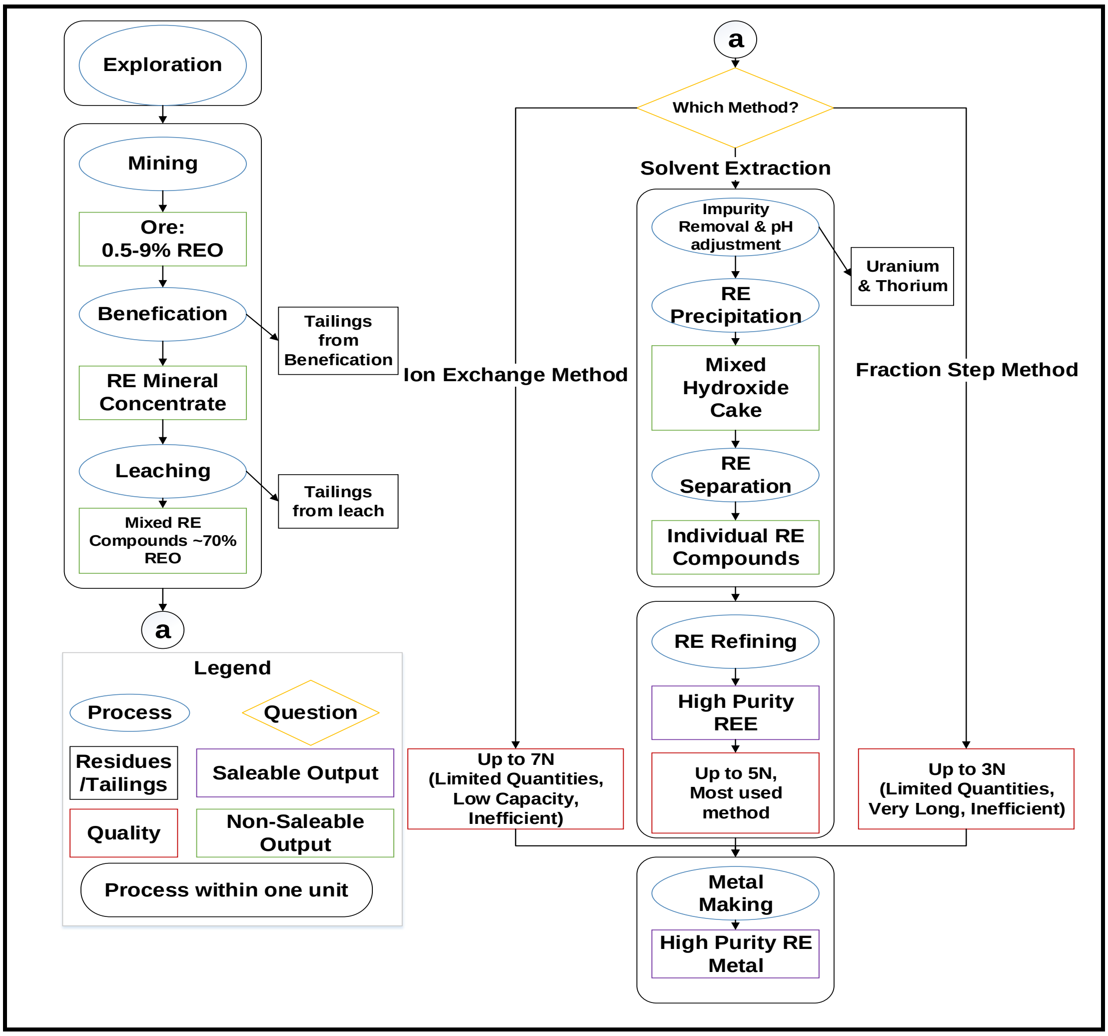

Figure 10 – Diagram representing the generic REE production, from mining to metal making. Adapted from [22].

2.4.1 Environmental Footprint

Though REE are considered the backbone for 'Green Technologies', they aren't entirely eco-friendly. Primary production is highly hazardous for the local environment. Even *assuming* that all future applications would be in green technologies, thus 'diluting' the production impacts, environmental consequences from REE production cannot be ignored, with issues starting immediately with mining. Typically, RE ores contains radioactive elements in its composition, the most common being uranium and thorium. Tailings and wastes from RE processing mustn't be disposed negligently, as radioactive elements can pollute water resources affecting local communities and wildlife [30, 31].

On Figure 11 are depicted a comparison of the two environmental variables – global warming potential and human toxicity to produce each REE, aluminium and steel using the CML 2001 evaluation method. Note that, in the case of dysprosium and neodymium the only available data is for the global warming potential and for the oxide form. Both global warming potential (measured in kg of CO_2-Equivalent emitted per kg produced) and human toxicity potential (measured in Kg of Dichlorobenzene-Equivalent released per kg produced) of REE are shown to be higher than elements such as steel or aluminium, often orders of magnitude above [30, 31].

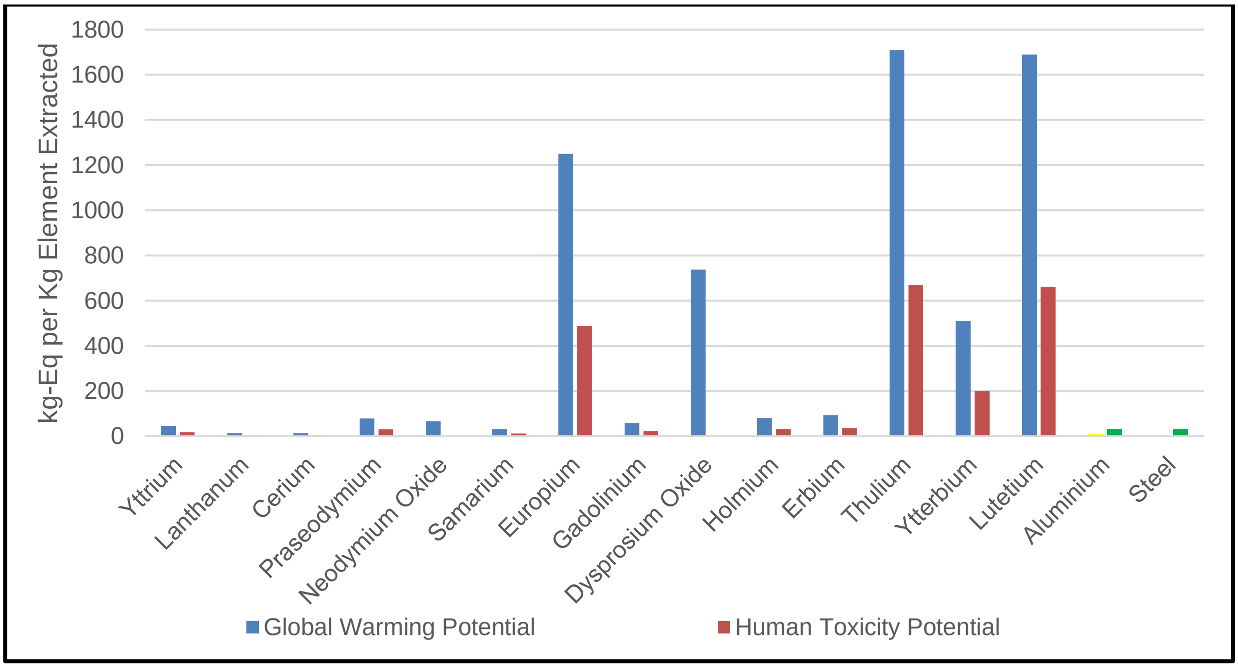

Figure 11 – CML 2001 environmental impacts of the REE production. Units: GWP – kg CO_2-Eq/kg extracted, HTP - Kg of Dichlorobenzene-Equivalent/kg Extracted. Adapted from [30, 31].

The intrinsic low grade of RE ores is a major factor affecting its environmental impact. For instance, a typical Chinese leaching project yields 300 m^3 of soil removed, creating 2000 tonnes of tailings and over 1000 tonnes of toxic residual effluents. Moreover, the entire process (especially separation and refining) consumes large energy amounts that usually doesn't come from renewable sources [29, 30].

Leaching and separation uses hazardous chemicals, such procedures should have safety and environmental guidelines for handling and disposing, however, most of Chinese production units (especially illegal explorations) do not have such concerns [29, 30].

Figure 12 confirms that in most cases, the biggest footprint comes from refining/separation. Impacts from REE production are much higher when one considers *emissions per kg extracted*, however worldwide production of steel or aluminium is tremendously higher, and its global impact is much larger. The local impact from REE production is more relevant, and with increasing demand, consequences for workers and nearby communities/wildlife will worsen [29-31].

REE applications should carefully consider its production impact, as these so-called green technologies come with a real environmental cost. Most common solutions proposed by academics to mitigate such impacts are shown below [29-31]:

1. Recycling and/or Reuse – avoids the most impacting steps, Beneficiation and Separation, as REE in the end-of-life products are usually refined and separated. Additionally, there's no danger of releasing radioactive tailings/effluents;
2. Substitution – use of non-REE materials with comparable properties that have less hazardous production without perceptible performance losses;

3. New processing technologies – development of more efficient and less hazardous production methods. E.g. *EuRare* team developed a novel processing technology that's allegedly more efficient and less harmful to the environment [22, 29].

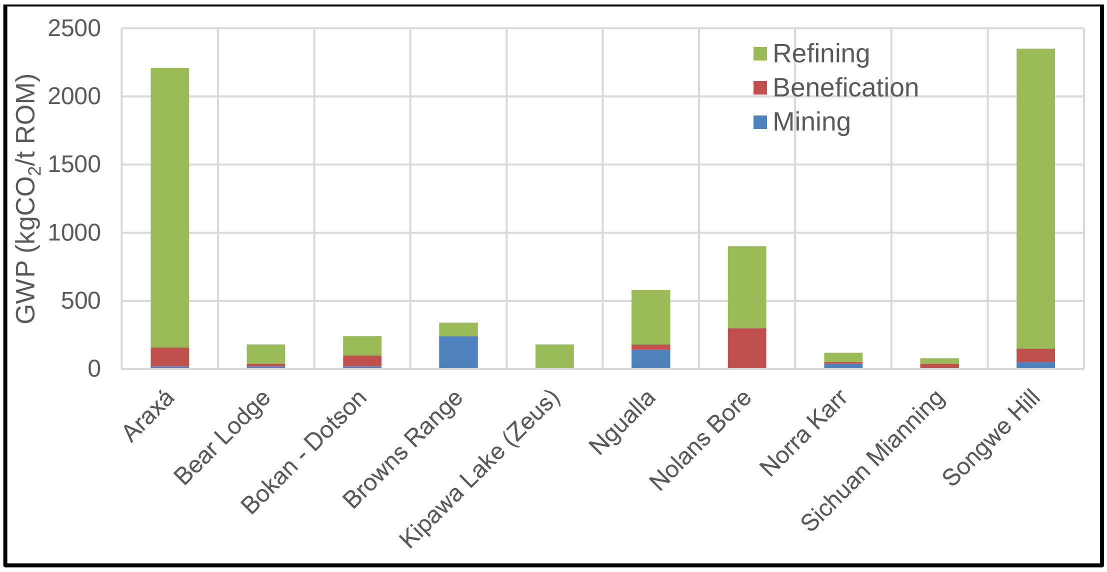

Figure 12 – Global warming potential for each REE production step in production units around the world. Adapted from [30].

2.5 Applications

There's a broad variety of uses for RE. Most aim to increase performance and efficiency and/or reduce consumptions/emissions of already existing technologies by adding RE to existing materials and vastly improving its properties, e.g. adding Nd to magnets can increase its magnetic force up to an order of magnitude. There're also applications whereas REE or RE-compounds are directly applied, making use of its distinct properties e.g. cerium oxide in polishing powder. RE main applications can be divided in two categories (most used REE in each application are shown as well) [1, 29]:

- **Process Enablers** – (Around 35% of global consumption) RE are used in production but are not present in the final product [29]:
  - **Polishing Powders -** Ce;
  - **Fluid Cracking Catalysts** – La and 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 [29]:
  - **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**.**

Individual RE used for each application are shown in Table 1, which also makes the distinction of functionality within each application: It can be as major functional element (i.e. has a key impact on the final properties), e.g. samarium in high temperature magnets. Or it can have a minor functional use (less essential and other elements can also attain similar final properties), e.g. glass colouring [1, 18].

Table 1 – Main applications of the individual REE, divided by the percentage used in each application. Adapted from [1, 18].

REE ***Use***	***Eu***	***Tb***	***Gd***	***Er***	***Dy***	***Y***	***Ho Lu Yb Tm***	***Ce***	***Nd***	***La***	***Pr***	***Sm***
Magnets		32%	97%		**100%**				**37%**		**24%**	**97%**
Metallurgy								6%	12%	3%	11%	
Batteries						7%		6%	13%	**10%**	12%	
Catalysts								**43%**	6 %	**67%**	10%	
Polishing								**11%**		5%	10%	
Glass				74%		4%	100%	**31%**	8%	10%	8%	
Phosphors	**96%**	**68%**		26%		**46%**		**1%**		2%		
Ceramics						**35%**		**2%**	11%	2%	15%	
Others	4%		3%			8%			10%		10%	3%
Legend	**X%**	Major function			x%	Minor function				None/residual use		

Product-wise RE market is currently driven mainly for manufacturing permanent magnets (around 24% of total REE consumption) and fuel cracking catalyst (around 21%), followed by polishing, metallurgy, other catalysts and battery alloys (Fig. 13). The main large volume applications of REE are briefly described hereafter with emphasis on permanent magnets as it is considered the most critical and important RE application for the future [32-34].

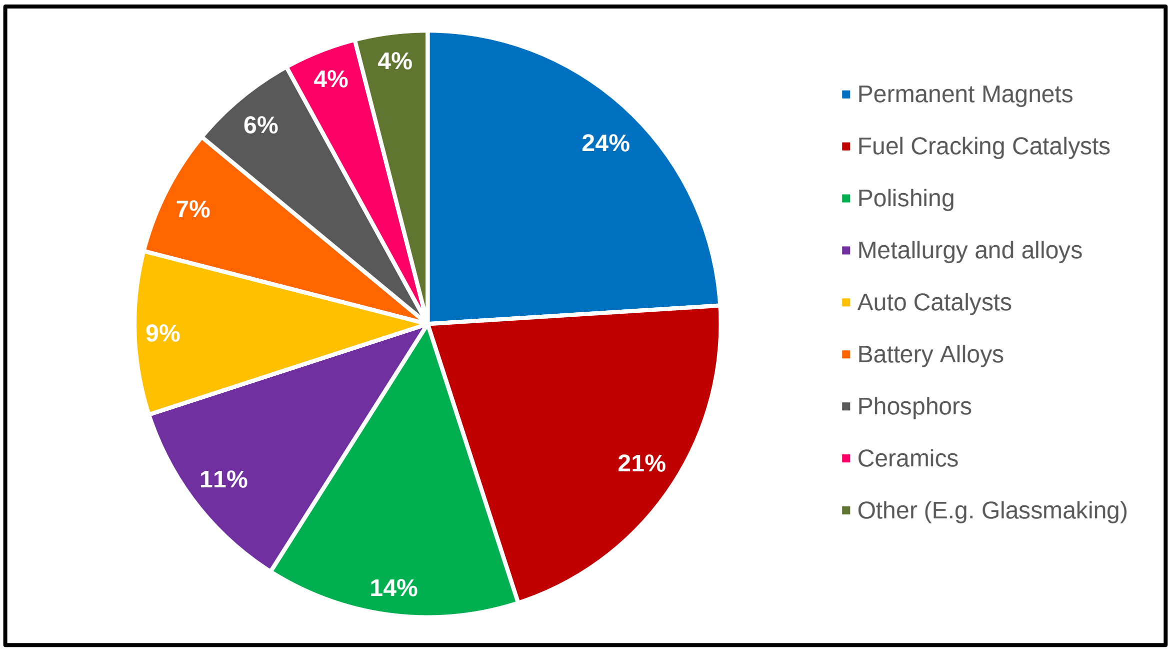

Figure 13 – REE global consumption by end-use in 2016: total 155,000 tonnes. Adapted from [32, 33].

2.5.1 Permanent Magnets

Permanent Magnets are a class of materials that after being exposed to a strong external magnetic field, retains its magnetic properties. It can generate its own magnetic field without needing external energy. REE have been used in permanent magnets for several decades, with samarium-cobalt (SmCo) magnets being first developed in late-1960s, by the mid-1980s the first neodymium-iron-boron (NdFeB) magnets were developed. Due to superior magnetic strength (~2.5 times higher) and affordability (around 84% is i\ron), NdFeB magnets have basically replaced their SmCo counterpart [8, 21, 35].

Figure 14 depicts the magnetic field of RE magnets to be superior to those of non-RE magnets. Up to this date, there's no development of any magnet-making material that can attain higher strength than NdFeB, hence Nd magnets will probably be, for the next decades, the strongest in the market [18, 21].

NdFeB magnets are powerful because they possess high saturation (related with the amount of magnetism a material can 'store') and have high resistance to demagnetization. As known ferromagnetic materials have in its microstructure magnetic domains that align in the same direction after being exposed to an external magnetic source. When all the domains are aligned, the material reaches its saturation, at this level Nd magnet achieves the strongest magnetic field of all magnets [36].

Because the crystalline structure of Nd magnets is tetragonal, it creates a 'high uniaxial magnetocrystalline anisotropy', meaning that crystals have an axis that can magnetize with relatively low energy. This phenomenon occurs due to electrostatic interactions between Nd's 4f cloud and the crystal structure. $Nd_2Fe_{14}B$ tetragonal crystals subjected to strong magnetic fields align along this 'low energy' axis, and when domains are lined along an 'easy axis' the resistance to demagnetization increases, because it's a very stable alignment. Consequently, NdFeB magnets can lift up to 1300 times its weight, to attain similar strength a ferrite magnet would have to be 18 times more massive. Thus, the biggest advantage of these high-performance magnets is miniaturization [34, 36, 37].

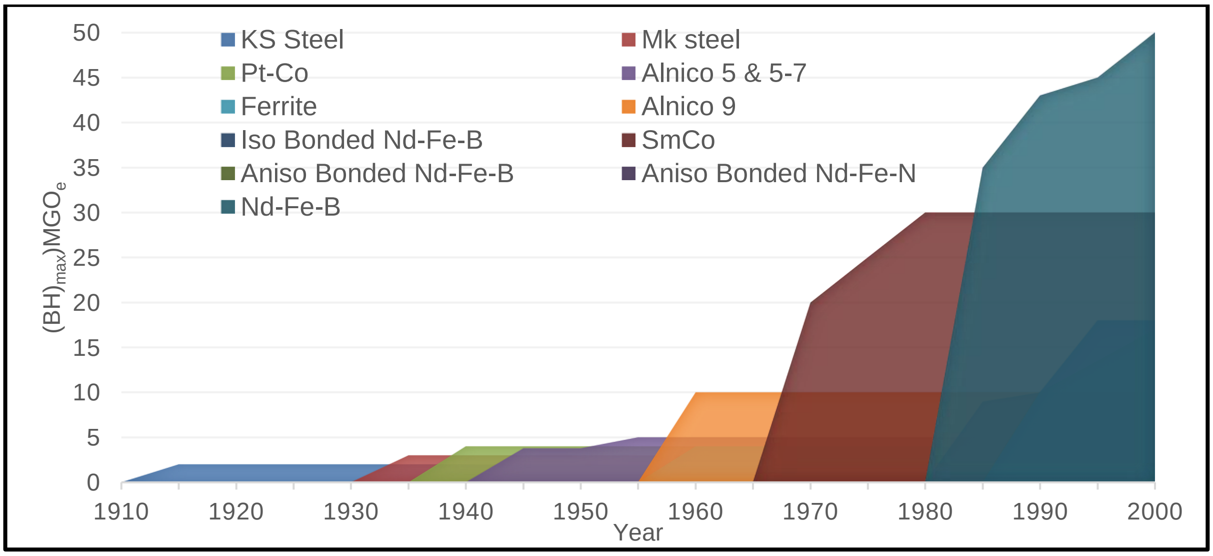

Figure 14 – Magnet making materials through the years, and its maximum magnetic field (units - mega gauss-oersted). (Note: MK Steel is a steel alloy containing Ni and Al and KS steel is a steel alloy with Co, W and Cr). Adapted from [21].

Magnet miniaturisation revolutionised markets that depend on the magnetic force but also in weight/volume of the magnet, such as earphones, HDD, electric motors and alternators. For instance, a ferrite magnet-based motor capable of moving a vehicle would be massive and heavy, therefore not able to move it efficiently. While, REE allows the existence of very high-performing, yet compact and light, magnets [8, 21, 35].

Nd magnets are the strongest, however its working temperature and oxidation resistance are mediocre, there could be the need for protective coatings and alloying elements for some applications. HREE (typically Dy, but Tb is possible) can be added in small quantities to increase coercivity (Resistance to Demagnetization) at high temperatures (Fig. 15) [18, 21, 34, 35].

A pure $Nd_2Fe_{14}B$ magnet loses its magnetism permanently above 310ºC, with performance reduction starting at 80ºC, adding ~4 wt% Dy working temperatures can increase up to 220ºC. This addition comes with a cost, as the iron in the lattice and Dy couples antiferromagnetically reducing magnetization and HREE addition increases the overall price. Although, the magnetic power of alloyed Nd magnets is still superior than most, the maximum working temperature and oxidation resistance aren't as good as the SmCo magnets, which are better suited for high-temperature (Curie Temperature up to 800ºC) and corrosive environments [18, 21, 34, 35].

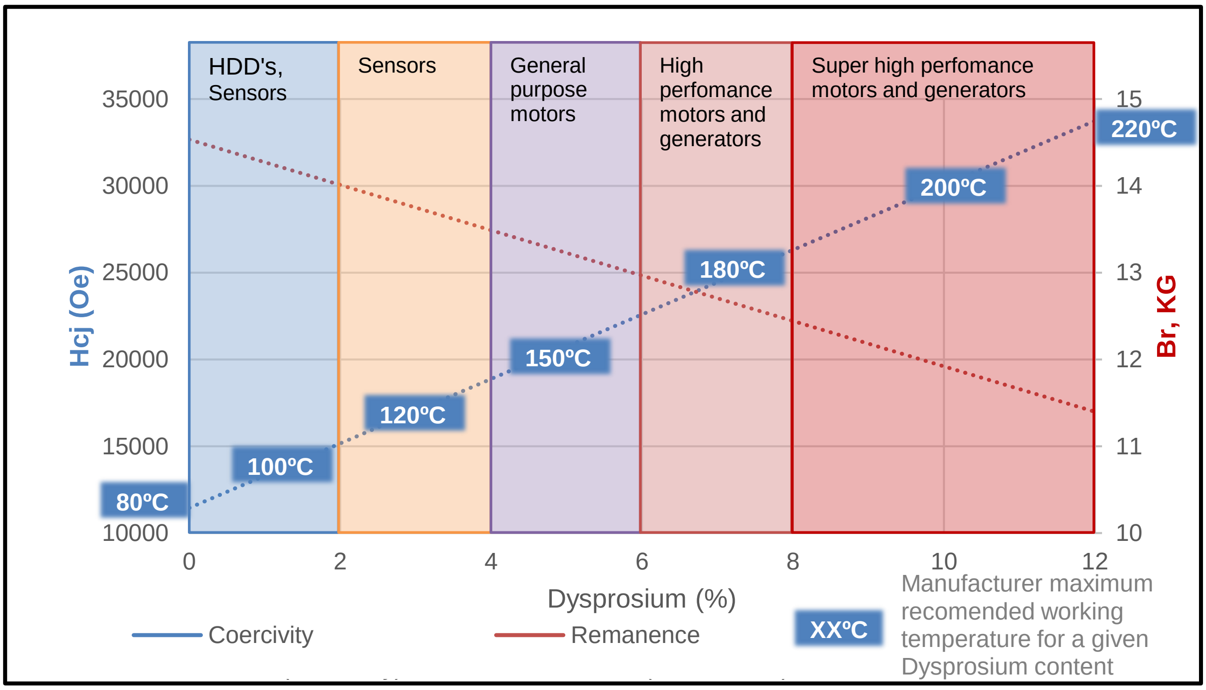

Figure 15 – Evolution of coercivity (in oersted) and remanence (amount of magnetization left after the external field is removed, in kilogauss) with the amount of dysprosium used in a NdFeB magnet. Adapted from [37].

In terms of volume, Nd magnets consumption is applied mostly in environmentally friendly applications, namely vehicles and wind turbines. The majority of hybrid, plug-in and a rising number of pure electric vehicles, uses brushless permanent-magnet direct-current electric motor (PMDC) which contain high-performance magnets with the following average composition 31% Nd; 4.5% Dy; 2% Co; 61.5% Fe; 1% B. Dy is essential to deliver the high temperature coercivity needed, as the average working temperature of an electric motor is around 160ºC [8, 21, 34, 35].

Knowing that around 3.6 gr of Nd and 0.55 gr of Dy is used per kW, a motor (or combination of motors) with a total output of 277kW, which is usual in electric motors for PHEVs, would use around 1kg of Nd and 152 grams of Dy. By 2040 several western countries, as well as India and China, will ban traditional combustion-only vehicles, with predictions saying that by 2050 the number of Plugin-Hybrid Vehicles (PHEV) sold will be 150 million [8, 21, 34, 35].

If each PHEV uses about 1 kg of neodymium, the demand just for PHEVs in 2050 would be around 150,000 tonnes which are the current demand for all REE combined. These figures don't even consider fully Electrical Vehicles (EV) which can potentially use more Nd as more power is required to assure full electric drive at any speed (a single EV can have up to 4 individual motors) [8, 21, 34, 35].

The other major carbon-reducing technology where NdFeB magnets are employed in wind turbines that use permanent magnet generators (PMG), these generate electricity through induction as a permanent magnet passes through copper wire coils. The strength of the magnetic field influences the amount of electricity produced, stronger magnet induces higher currents, therefore Nd magnet offer the best performance possible. Additionally, these magnets allow the manufacture of lighter alternators, which eases the installation procedure and leans the stress on the structure. The weight of magnets in alternators is considerable, wind turbines contains around 700-1200 Kg per MW. Note that unlike vehicles with motors, the magnets used in alternators do not require Dy since wind turbines makes use of the wind to cool the magnets. Between 1- 2 million tonnes of alternators are expected to be used on wind turbines by 2050 [18, 34, 35].

Nd magnets can be manufactured using two distinct methods (Fig. 16). In the first method an ingot is pulverized into microcrystalline scale by hydrogen decrepitation and jet milling; the powder is then pressed and sintered in vacuum. Thereafter the magnet is heat/surface treated and cut to a desired form, being termed Sintered Magnets. For the second method, thin ribbons of $Nd_2Fe_{14}B$ produced by melt spinning are pulverized and mixed with a polymer which is subsequently either pressed or injected into a mould, producing Bonded Magnets [34].

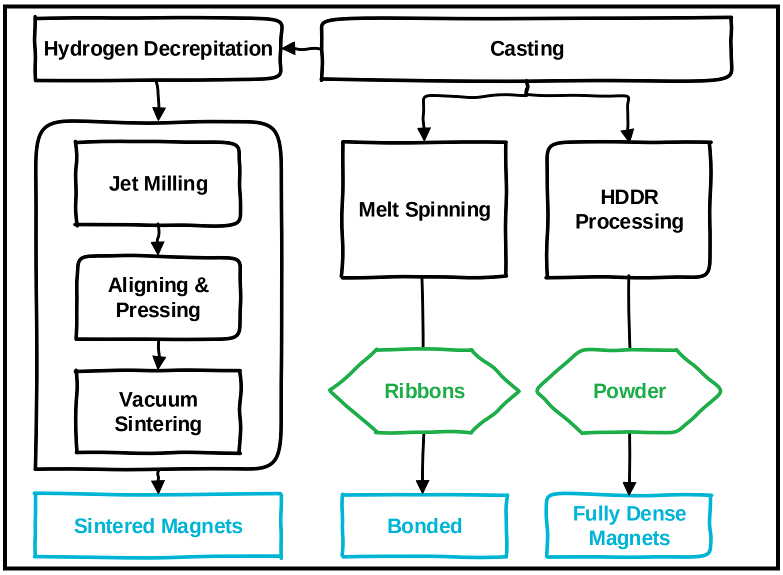

Figure 16 – Production of NdFeB magnets. Adapted from [34].

Because sintered magnets are produced from magnetically aligned microcrystalline sized powder, they achieve greater remanences, whereas ribbons contain random-oriented nanosized grains. Nonetheless, bonded magnets can be formed in complex shapes. In 2014 an estimated 79,500 tonnes of NdFeB magnets were produced, 10,000 of which were bonded and around 70,000 were sintered [34].

2.5.2 Catalysts

Catalysts are constituents that increase a chemical reaction rate, without participating directly in the reaction itself, this is achieved by reducing the activation energy (energy required to carry the reaction), only a small portion is usually consumed. There are two main catalytic applications for REE: Fluid Catalytic Cracking (FCC), accounting for around 21% of the total REE use and Auto Catalysts which accounts for around 9% of REE consumption [8, 22, 38].

- **Fluid Catalytic Cracking (FCC)**

FCC catalysts are used in the petroleum industry to refine crude oil into gasoline, diesel, distillates, and other lighter oil products/fuels. It's attained by breaking down larger crude oil molecules into lighter molecules. The role of the RE in FCC (lanthanum oxide but also cerium oxide) is to increase energy efficiency and yield of gasoline obtained by being able to break down heavier oil fractions while maintaining effectiveness. RE are also responsible for discontinuation of leaded gasoline [8, 22, 38].

FCC consists of spherical particles made from an amorphous matrix (usually silica-alumina) which holds the active component (zeolite) and a binder (usually clay), zeolites are dispersed on the matrix which has large pores and voids to allow mass transport. The RE act to stabilize the structure and chemistry of the active component that's used as 'molecular filter' [8, 22, 38].

- **Auto Catalysts and other Combustion Engine Exhaust Catalysts**

These catalytic converters are essential for the environment by transforming pollutants created during the combustion in engines into less hazardous compounds. This technology is not 100% efficient, nevertheless without its existence, emissions from combustion engines would be higher [8].

Cerium carbonate and cerium oxide are used as catalyst substrate and in the oxidising catalytic system, they play an important role in controlling of the reactions, increasing catalytic efficiency and helps increasing overall working temperature. It's accomplished by preventing the formation of alpha alumina phase, increasing the oxidant power of the system and easing water-gas transformations. Moreover, cerium component reduce the amount of platinum and other precious metals necessary, reducing the cost of producing [8, 22].

2.5.3 Polishing Powders

Polishing powders are used to finish surfaces of other products while not being part of the final product, giving it a clean, glossy or mate finish depending on the grain size and procedure. Cerium oxide is the most used RE compound for glass and electronics polishing [8, 22].

It's especially suitable for glass polishing as it removes material both chemically and mechanically, allowing faster polishing. The more common applications are display panels, flat glass, optical glass, mirrors and silicon microprocessors [8, 22].

2.5.4 Phosphors

Phosphor is a substance that luminesce, this is, that emits light after being radiated by a highly energetic radiation such as UV. Phosphors have multiple uses, however some of them, like Cathodic Ray Tube screens (CRT) are being discontinued, currently the most common use is in fluorescent lighting. A fluorescent lamp is composed by a glass tube coated in phosphor and filled with a rare gas (often argon). Inside the tube there's a mercury droplet which releases small amounts of mercury vapour that fills the tube. Inside occurs an electric discharge, mercury ionizes effortlessly (compared with the rare gas), the ionization emits a strong ultraviolet radiation that bathes the fine phosphor particles that coats the glass that subsequently fluoresces [39].

Emitted spectrum depends on mercury vapour emission and the composition of phosphors used. A typical white fluorescent lamp is created by combining 3 different phosphors that emits the RGB colours (Reb, Blue, Green). Usually all 3 phosphors are doped with RE, several compounds are possible, some examples are presented below [39, 40]:

- **$LaPO_4$:Ce^{3+}, Tb^{3+}** – applied in Green Phosphor in lamps, CRTs, Displays, et cetera [40];
- **Y_2O_3: Eu^{3+}** – employed in Red Phosphor in fluorescent lamps, CRTs, et cetera [41];
- **Y_2SiO_5: Ce** – used in Blue Phosphor in CRTs, fluorescent lamps, et cetera [41].

Generally, yttrium, gadolinium and lanthanum are used as host material in the phosphor body, whereas elements such as europium, cerium, terbium are used as the active part. The luminescence characteristics are due to **d -> f** transitions, which occur in the visible range after excitation with ultraviolet radiation. Trivalent RE phosphors are used due to its highly-efficient energy transfer and high temperature stability [18, 40, 42].

2.5.5 Battery Alloys

Nickel-metal hydride batteries (NiMH), are a class of batteries related to nickel-cadmium batteries. However, NiMH have longer live-cycles, higher stability and have no 'memory effect'. Cadmium is replaced with a metal hydride which makes the battery less hazardous. NiMH is consisted of a nickel cathode and a hydride-forming anode, the electrodes are isolated from each other by a separator and all constituents are impregnated with an alkaline solution (usually KOH) that allows ions conduction [43].

The simplified electrochemical reactions that occur in both electrodes are shown below (direct direction represents charging and inverse discharging) [43]:

$$\boldsymbol{Nickel\ Electrode}: Ni(OH)_2 + OH^- \leftrightarrow NiOOH + H_2O + e^-$$

$$\boldsymbol{Hydride\ Forming\ Electrode}: M + xH_2O + xe^- \leftrightarrow MH_x + xOH^-$$

While charging, the Ni^{2+} cathode oxidises to Ni^{3+} and H_2O is reduced to hydrogen in the anode which is absorbed by the hydride-forming material, a reverse reaction occurs during discharging. During reaction, only OH^- ions in the electrolyte flow from one electrode to the other, there's no consumption [43].

The anode, that must be able to absorb the hydrogen gas produced, is generally composed by an $\mathbf{AB_5}$ type of hydride-forming compound, where "**A**" represents a REE or mischmetal and "**B**" one or more transition metals. Lanthanum-based alloy $LaNi_5$ is often used as anode, as is able to absorb large amounts of hydrogen gas to form the hydride $LaNi_5H_6$. Curiously the density of hydrogen inside this hydride is larger than its liquid form (a cubic metre of $LaNi_5H_6$ holds 88kg of hydrogen whereas a cubic metre of liquid hydrogen weighs 71kg). To reduce cost lanthanum-rich mischmetal can be used with small performance loss. The biggest demand for REE-based batteries is from Hybrid Vehicles, for instance, each Toyota Prius contains between 10-15 kg of lanthanum, but NiMH technology can also be used in more traditional applications such as rechargeable portable batteries [34, 43].

2.5.6 Metallurgy

- **Cast Iron, Steel and Stainless Steel**

One of the first applications for RE was mischmetal, an alloy entirely made of REE metals (typical composition: 48-56% Ce, 25-34% La, 11-17% Nd, 4-7% Pr). Mischmetal is usually added in cast iron as a minor alloy to reduce impurities such as oxygen and sulphur. Cerium is used to reduce cracking by binding to sulphide inclusions forming rounded particles. Yttrium can be used in highly alloyed stainless steel (up to 5%) to increase temperature and oxidation resistance as well to improve the ductility. Cerium can also be added as hardening agent for this class of steel [8, 22].

- **Magnesium Alloys**

Low creep and high-temperature magnesium alloys (e.g. engine blocks) usually have ~2-3% of yttrium, neodymium and/or gadolinium to improve heat resistance. To improve castability, weldability and allow thin-walled castings ~3.5% of REE is added. Additionally, praseodymium can also be used to improve strength and corrosion resistance [22].

- **Super Alloys**

Super Alloys are a class of alloys that are used in applications that involve harsh environments (high-temperature and oxidising mediums) such as jet engines. Yttrium is the main RE, being used to improve the oxidation resistance at high temperature, cerium and lanthanum can be used as well [8, 22].

2.5.7 Glass & Ceramics

- **Decolouring Agent**

The first commercial use of RE (cerium) in the glass industry was as decolouring agent by removing impurities from the glass (mostly iron oxide) [8, 22].

Cerium is also applied as a glass stabiliser to protect the glass against high-energy radiation. This protection is attained by hindering the oxidation of metallic ions present in glass preventing its darkening [8, 22].

- **Colouring Agent**

One of the first use of RE was for glass colouring and it’s still applied, a notable case is erbium which is the only element capable of making a truly stable pink coloured glass, other elements used are: neodymium (Red), praseodymium (Green), cerium (Yellow/brown) [8, 22].

- **Optical Glass**

REO are important for optical glass such as camera lenses. Lanthanum is commonly used to increase the refractive index and lower dispersion of low silica optical glass. REO are added to glass to filter specific wavelengths: e.g. neodymium and cerium are used in sunglasses to provide UV protection whereas samarium filters infrared light. REO are also applied in optical fibre with erbium, lanthanum and cerium being used as dopant to enhance the refractive index of communication cabling, Nd-doped glass is used in temperature sensors and ytterbium is added to high power optical fibres [8, 22].

- **Structural Ceramics**

Toughness and strength of structural ceramics can be stabilised and improved by adding REO (mostly yttrium and cerium oxide). Additionally, the crystal structure of yttria (**Y_2O_3**) makes it suitable to be used as a sintering compound, meaning that it allows to reduce sintering temperature, reducing production costs [8, 22].

- **Functional Ceramics**

Ceramics employed in specialty electronics (sensor, dielectric and piezoelectric ceramics) use REO. For instance, the addition of neodymium tunes the capacitor’s capacitance under temperature changes, while lanthanum and cerium stabilise its dielectric constant and increases its lifespan [8, 22].

- **Refractories**

Yttrium (and cerium to some extent) oxide is essential in refractory ceramics, Y_2O_3 is employed in refractory manufacturing (lining of furnaces, molten metal crucibles, et cetera) protecting the refractory material (usually zirconia) allowing it to withstand higher temperatures [8, 22].

2.5.8 Other Applications & In-Development Technologies

- **Nuclear Energy**

REO such as gadolinium oxide have the ability to absorb neutrons and remain stable at higher temperatures. Consequently, they’re used as neutron absorbers in nuclear reactors and as neutron absorbing coatings/shields. Other REE such as europium are used in the control rods to help regulate the reaction operations as its good neutron absorber as well [8, 22].

- **Magnetic Refrigeration**

This new technology is totally dependent on REE (gadolinium and neodymium mainly) and it's a very efficient method to refrigerate when compared to standard technologies. It's based on a phenomenon termed "Magnetocaloric Effect", in which a magnetic field is applied to a magnetic solid and, as the field is reduced, the electrons within the solid start to spin at a higher energy state absorbing energy in the form of heat, hence reducing the temperature. A typical Magnetic Refrigeration apparatus uses a gadolinium alloy as 'refrigerant' which is surrounded by neodymium magnets. The movement of the permanent magnets changes the field which consequently causes the refrigeration effect in the alloy. gadolinium is used as it exhibits this effect vigorously. The technology is still being developed, while having some issues which hamper the production of the first commercial units, it has a big potential to replace current cooling technologies which are less efficient and environmentally harmful [8, 22].

2.6 REE Substitutability

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 (Table 2) [18].

Table 2 – REE applications that have valid substitutes (material or technology substitution). Adapted from [18].

Application	*Observation*	*RE**	*Alternative elements*	*Alternative technologies*
FCC (Catalyst)	Not easily substitutable	La Ce	Ce La	-
Auto Catalyst	Material substitution is possible	Ce	La, Nd, Pr	-
NiMH Batteries	Shift to Li-Ion batteries is currently trending	La Nd	Co Co	Li-ion, NiCd or lead-acid batteries are alternatives.
Metallurgy	Material substitution is possible	Ce Gd Pr La	Ca, La, Nd, Gd Pr Gd Ce, Nd, Gd, Ca	-
Polishing	Material substitution is possible	Ce La	Ce, Pr, FeO, Al_2O_3 Ce, FeO, Al_2O_3	-
Phosphors (Lighting and Displays)	Rise of LED lighting means there is a viable fluorescent lamps competition	Er Gd Tb	Y, Gd Eu, Y, Tb Eu, Y	LED which contains 1000 times less phosphor than fluorescent lamps.
Magnets	Nd/Dy content can be reduced by advanced manufacturing or by material substitution but in that case with performance loss Wind turbines have a clever cooling system and do not require Dy.	Dy Gd Nd Pr Tb	Tb, Gd Dy, Tb Pr Nd Dy, Ga	Ferrite, SmCo or AlNiCo magnets can replace NdFeB magnets in some applications.

**Applications or REE that do not have any valid substitute (Eg. Sm in magnets, Eu in red phosphors, or any ceramic REE application) are not shown.*

Some elements are substitutable, for example dysprosium in magnets can be effectively replaced by terbium with small performance losses, while others, like samarium in high temperature magnets, are simply unreplaceable [18, 34].

Other elements are partially substitutable yet with performance losses, this being the case of neodymium in magnets. Didymium, a PrNd alloy can be used to reduce neodymium content, hence reducing the magnets price, however this partial substitution comes with the cost of lower magnetic strength (though higher than most non-Nd magnets). Praseodymium-only magnets can be produced with some performance losses which can be improved with good product design, nonetheless total substitution isn’t feasible in large scale as praseodymium is less abundant than neodymium [18, 34, 35]

Cerium and gadolinium-based magnets are possible and cheaper than its RE counterparts, however, they have the lowest magnetic strength, making them an unfit substitute for specific applications. All these alternatives will surely be explored in the near future in an attempt to reduce neodymium’s demand, however, for high-performance applications there’s absolutely no alternative that’s fully equivalent [18, 34, 35].

Two widely available REE-dependent technologies are being replaced by ‘low REE’ alternatives: NiMH batteries and fluorescent lamps [18].

Lanthanum or mischmetal is required to create the anodes in NiMH batteries, but Lithium-Ion batteries do not require any REE (some might use for specific purposes, but it’s not essential for its function). NiMH batteries will continue to be used, but only in niche applications. The trend points to the dominance of Lithium-ion batteries which have a higher energy density and overall performance [18, 40, 42].

Typical fluorescent lamps use around a gram of REE whereas LED lamps use only milligrams, with the content of a single fluorescent lamp it’s possible to produce around 1000 equally performing LED lamps, reducing the demand (in volume) for REE phosphors. In the past, manufacturing high-power LEDs was a very complex process and only low-power LEDs were produced for informative low-intensity light (e.g. standby light in electronic devices) [18, 40, 42].

Newer manufacturing methods allow the production of affordable, efficient and high intensity LED lamps that even outperform fluorescent ones. With the current trend being the adaptation of LED in depreciation of fluorescent lighting, REE demand for phosphors will be reduced (Table 3) [18, 40, 42].

Table 3 – Average amount of REO used per energy-efficient lamp (g/unit). Adapted from [42].

Range of content	*Y_2O_3 (g)*	*EuO_3 (g)*	*Tb_4O_7 (g)*
Fluorescent lamp	1.0975-1.1981	0.0913-0.103	0.0515-006084
Compact fluorescent lamp	0.7035-0.768	0.0585-0.066	0.033-0.039
LED	0.0047-0.0051	0.0004-0.0004	0-0

Curiously most of alternative elements for RE-dependent technologies are in fact other REE, since these technologies require properties that only lanthanides can attain. It might seem preposterous to replace REE with other REE, but if the alternative is more common and affordable, the substitution can effectively bring some market balance, even decreasing the product price [16, 32].

For some applications demand can be so high that an individual element cannot comply, therefore, if various elements can perform the same function, the demand can be divided between them. This is a foreseeable scenario of the magnet's additions, in which dysprosium can be replaced by terbium, but instead of being fully substituted, terbium can help lessen dysprosium market demand and keep the balance in a rapidly increasing market. Other applications and elements can be substituted as well, but there aren't any notable cases worth mentioning [16, 32].

2.7 Forward Look

With permanent magnets being the most important REE application in terms of value (53%) and volume consumed (24%), it's a natural assumption that its key raw material is considered the most critical. The incessant demand for cleaner technologies drives the growth of NdFeB magnets market, it's estimated that it'll increase in a rate of ~7% per year, with an overall increase between 2010 and 2020 being in order of 80%. Its main active element, neodymium, is considered highly critical, since it's impossible to fully replace it. The other REE currently significant for magnets, dysprosium, is estimated to lose its critical status since its content can be reduced with advanced manufacturing techniques and it can be effectively replaced by terbium, with little to none differences (Table 4) [34].

Currently the number of full electrical vehicles that employ permanent magnet motors rather than induction motors is increasing due to its higher efficiency and reliability. A notable case comes from the prolific *Tesla, Inc.* (that previously only employed induction motors) recently announcing that its '*Model 3 Long Range*' will use permanent magnet technology. If the trend continues amongst manufacturers it'll impose an additional strain on the already strained neodymium market, amplifying its critical status. In contrast, phosphors market is projected to decline owing to the rise of LED lighting in detriment of fluorescent lighting. And REE batteries alloys is estimated to decrease in the following years as well, since NiMH batteries are being superseded in favour of the lithium-ion (Table 4) [32-34, 44].

As EU and other countries slowly evolve into 'fossil fuel free' nations, it's expected that markets of FCC will decline since demand for oil-based products will decrease. For the same reason auto catalyst production will reduce. The remaining markets are expected to remain relatively stable unless affordable and equally performing alternatives are discovered [32-34].

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 [34].

Causing a balance issue, as more abundant elements (such as cerium and lanthanum) will be overproduced, and mining ventures have to be vastly increased to accommodate the overly high demand for neodymium which will bring further environmental and geopolitical issues [34].

Solutions are required and for the specific case of neodymium, the best option is to invest in secondary production. Recycling or reuse of NdFeB magnets are a valid solution to tackle this issue, decreasing the need for primary production, which consequently reduces environmental impacts and dependence on Chinese production and exportation [34].

Table 4 – REE current main applications, criticality and market balance. Adapted From [34].

REE	*Current main large volume application*	*REE relative criticality**	*Market in balance at present and near future?*
La	NiMH Batteries, Optical Glass, Green Phosphor, Catalysts, Mischmetal;	Normal	Oversupply;
Ce	Polishing Compound, Catalyst, Decolouring agent, mischmetal;	Normal	Oversupply;
Pr	Green Glass Colourant, Ceramic Pigment;	Normal	In balance;
Nd	NdFeB Permanent Magnets;	Highest, it will become the most critical	In balance as it drives the market;
Sm	SmCo Permanent Magnets;	Normal	In balance;
Eu	$Y_2O_3:Eu^{3+}$ Red phosphor for lamps;	Normal	Slight oversupply (and increasing) as fluorescent lamp market decreases;
Gd	NdFeB Permanent Magnets, Green Phosphor, Magnetic Refrigeration;	Normal	In balance;
Tb	Green Phosphor for lamps;	High, but decreasing	In balance, oversupply likely as fluorescent lamp market decreases, unless it's applied on magnets;
Dy	NdFeB Permanent Magnets;	High, expected to decrease	In balance;
Lu	(Niche) Scintillator phosphors in PET scanners;	Normal, but it can become high	In balance, potential shortage in future;
Y	$Y_2O_3:Eu^{3+}$ Red phosphor for lamps, Yttria stabilized Zirconia (YSZ), Ceramics.	Lower	In balance, oversupply expected as fluorescent lamp market decreases;

**Individual REE criticality according to the Department of Energy (DOE) of the United States. Not related with the European Commission "Critical Raw Materials List" in which all REE are considered critical.*

2.8 Recycling

Recycling of REE is still residual (Table 5), with an average recycling rate (excluding some exceptions) 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 (Fig. 17). Most research is performed at 'lab scale' and applies methods that aren't easily scalable to an economically viable industrial size [12].

Table 5 – Worldwide REO production vs the 'end-of-life recycling input rate' for individual REE. Adapted from [18].

REE	*REO world production (Avg. 2010-2014, in tonnes/year)*	*Recycling input rate (in 2015)*	*Source secondary material (if known)*
La	35,146	1%	Not specified
Ce	51,430	1%	From Polishing Powders
Pr	6,500	10%	Not specified
Nd	22,391	1%	Not specified
Sm	2,714	1%	Not specified
Eu	407	38%	From EOL fluorescent lamps
Gd	2,307	1%	Not specified
Tb	407	6%	From EOL fluorescent lamps
Dy	1,357	0%	Not specified
Er	950	1%	Not specified
Lu, Th, Ho, Yb	1,799	1%	Not specified
Y	10,300	31%	From EOL fluorescent lamps

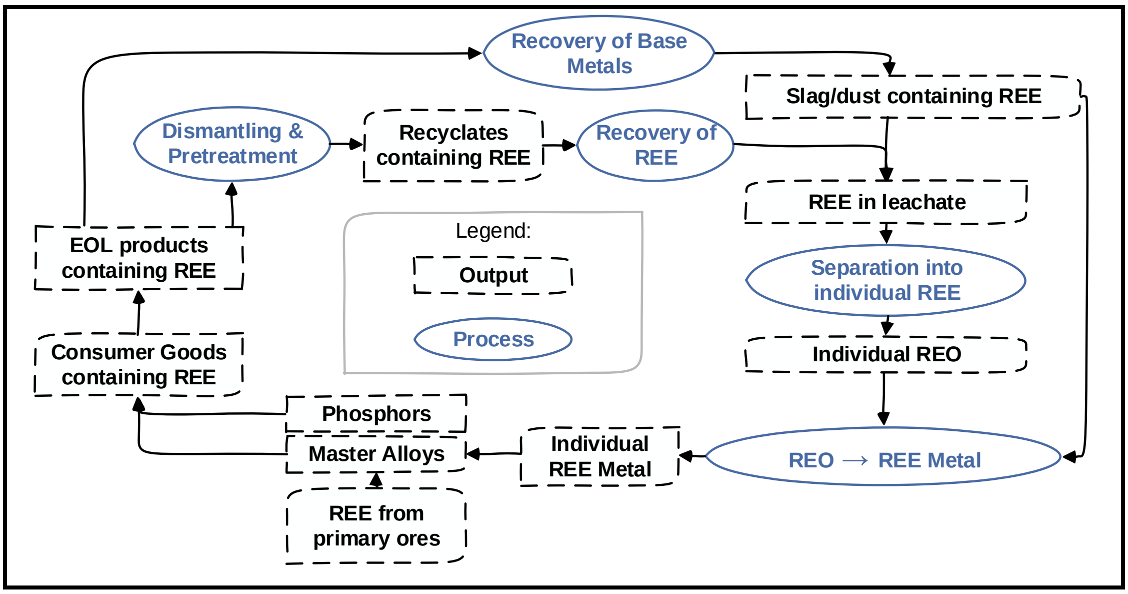

Figure 17 – Diagram showing the closed loop in the life cycle of REE for its main applications. Adapted from [12].

It's worth to mention that lack of financial incentives also justifies current rates. For instance, the only products that were recycled to some degree were fluorescent lamps, and reason is not arbitrary. This particular case, in which industrial-scale RE recycling was promoted, happened in 2011, when Chinese embargo caused REO prices to spike. Since primary raw materials for phosphors were so expensive (europium oxide reached 3790 dollars per kg), there was a natural demand for cheaper sources, hence, *Solvay* opened a plant at La Rochelle and started to recycle EOL fluorescent lamps. As soon as the price of europium (since 2015 it's lower than 100€ per kg) and other RE dropped, recycled REO was no longer deemed competitive and in the end of 2016, *Solvay* closed the plant [18].

In this case, it was not a monetary or governmental tax-cut incentive, rather being a response to market instability, still it proved that with correct incentives it's possible to recycle REE at industrial scale [18].

Closing the loop provides a solution the most critical issues in western countries: balance problem and dependence on Chinese production. EOL products are effectively ores with less complex microstructures and absent of hazardous elements such as thorium, making REE more easily extractable when compared to primary sources. Exploring these 'urban mines' reduces the need for primary raw materials, lessens the negative impact of its production, and by targeting the most critical elements the balance problem can be attenuated [12, 45, 46].

A brief description is given on REE recovery from three major applications: permanent magnets, fluorescent lamps and nickel metal hydride batteries. Note that catalysts, one of the larger applications (in volume), are not considered. This is due to the fact that cerium and lanthanum used in FCC and auto catalysts have low intrinsic value with little to none interest in recovering it. Precious metals (platinum, palladium or rhodium) in auto catalysts are already efficiently recycled, with REE ending in slag, however the concentration in the slag is low and it has a residual value. [12, 45, 46].

2.8.1 Permanent Magnets

By 2020 the estimated amount of REE present in in-use magnets will be around 300,000 tonnes, knowing that during production around 20-30% of material input is lost to manufacturing scrap, roughly 100,000 tonnes of magnets new scrap would have been produced at that time. Additionally, in the same period there'll be around 20,000 tonnes in EOL magnets (Table 6). Acknowledging that neodymium will become the most critical REE, its recovery from permanent magnets should consider of one as of the highest priorities for recycling industry [12, 45, 46].

Table 6 – Recycling potential for permanent magnets. Adapted from [12].

Estimated REE in stocks in 2020 (tonnes)	*Estimated average lifetime (years)*	*Estimated REE old scrap in 2020 (tonnes)*	*Pessimistic scenario: recycled REE in 2020 (tonnes)*	*Optimistic scenario: recycled REE in 2020 (tonnes)*
300,000	15	20,000	3300	6600

There are three main sources for recovering REE from permanent magnets: manufacturing scrap (new scrap); waste electrical and electronic equipment (WEEE) and large devices (vehicles and wind turbines). Depending on the source, the recovery procedure can vary (Fig. 18) [12, 45, 46].

- **Direct Reuse of the Magnet**

Direct reuse of magnets in the same application is a practical method since it does not need any processing and does not produce any waste. However, it’s usually only applied on large magnets used in EV’s and wind turbines. The average service period of these magnets is very long (above 10 years) and its implementation is recent, therefore the amount of EOL large magnets is negligible [12].

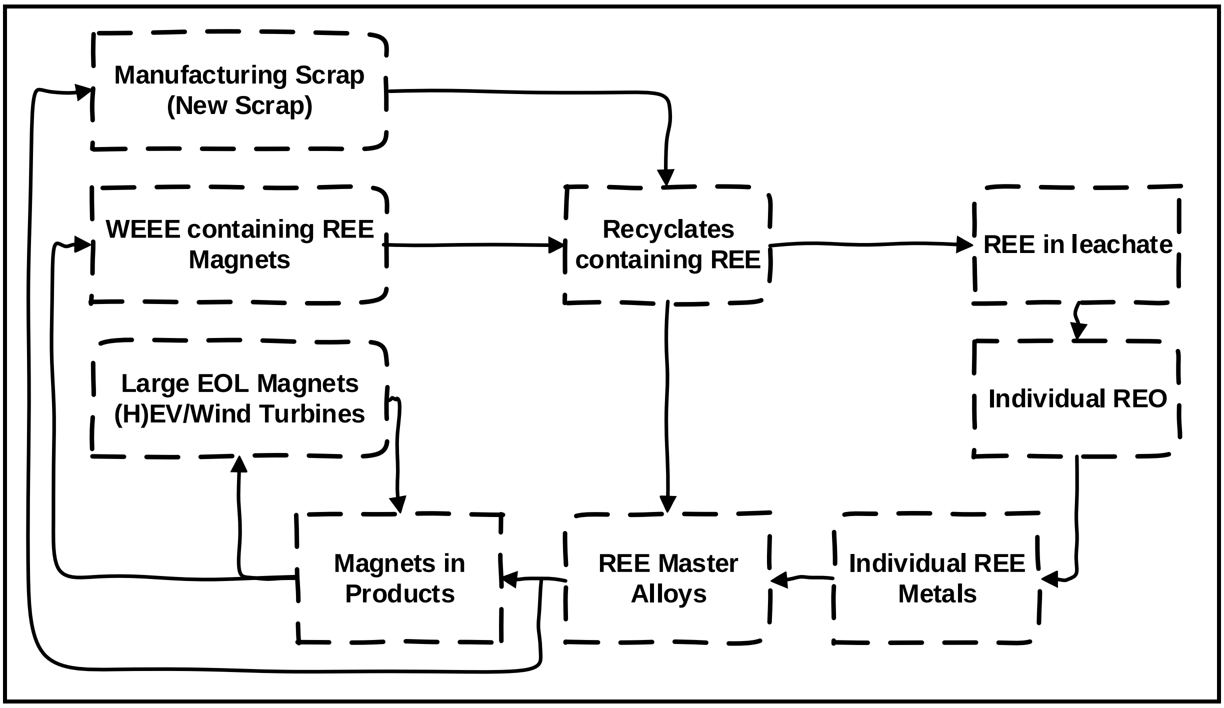

Figure 18 – Permanent magnets simplified recycling flowsheet. Adapted from [11].

- **Direct Reuse of the Alloy**

The remaining classes of magnets usually need to be further processed, but in applications where alloy composition is similar regardless the manufacturer or year of manufacture (such as HDDs), magnets can be directly powdered or melted to create master alloys for producing new magnets. The energy input required is lower than neodymium recovery, and no additional processing is needed (e.g. chemical attack to remove unwanted elements). Nonetheless, magnets used as source must have a very narrow composition distribution, limiting the amount and type of magnets eligible. Additionally, oxidised magnets are not usable in this method as well, due to the oxidation changing the bulk composition [12].

Manufacturing scrap alloys can be directly used if it comes from a single source and it’s not mixed with other scrap. If around 20-30% of REE is lost in form of new scrap, *in loco* recycling units greatly reduces manufacturing waste and decreases raw materials importation providing both economic and environmental benefits [12].

- **Hydrometallurgical recovery of REE from Magnets**

A way to broaden the eligibility composition distribution is to use methods that can have almost any kind of alloy as input and selectively extract only the desired elements [12].

One of those methods is hydrometallurgy. The input can be of almost any type and composition, oxidised or not oxidised, using the same procedures that are used to extract REE from primary sources. Though this method uses large quantities of chemicals (some hazardous), releases large amounts of waste water and requires multiple steps until a new magnet is obtained [12].

- **Pyrometallurgical recovery of REE from Magnets**

Hydrometallurgical route for recycling magnets shares the same disadvantages as primary production: large consumption of chemicals consequently resulting in high amounts of waste water. The pyrometallurgical route also allows the input of alloys with different compositions, oxidised and not oxidised. But, unlike hydrometallurgy, it doesn't require chemicals and it does not produce any waste water. Note that, producing master alloys by direct smelting is a pyrometallurgical process but is only possible if the input material has the same composition and it's not oxidised [12].

This route usually requires fewer steps to obtain master alloys or metallic REE, but in order for the source material to reach its liquid state, very high energy input is required, which renders this process energetically inefficient. Although these processes do not generate any waste water, they might generate large amounts of solid wastes that need to be handled as well [12].

2.8.2 NiMH Batteries

NiMH batteries use either pure lanthanum or mischmetal, thus it can be a decent source of REE (Table 7). Usually only Ni is recycled from spent batteries to be used in stainless steel production, Co and REE are lost in slag. There are hydrometallurgical processes to recover cobalt, nickel and REE from EOL batteries by leaching its scrap, and then selectively precipitate the desired elements. Since this recovery process is very similar to primary production, it has the same disadvantages, namely the consumption of chemicals that consequently result in large volumes of hazardous waste water.

Table 7 – Recycling potential for nickel metal-hydride batteries. Adapted from [12].

Estimated REE in stocks in 2020 (tonnes)	*Estimated average lifetime (years)*	*Estimated REE old scrap in 2020 (tonnes)*	*Pessimistic scenario: recycled REE in 2020 (tonnes)*	*Optimistic scenario: recycled REE in 2020 (tonnes)*
50,000	10	5,000	1,000	1750

2.8.3 Fluorescent Lamps

Even though fluorescent lamps are being replaced by LEDs, the amount of them currently in use around the globe is still large and its demand hasn't stopped yet (Table 8). There's then a need to correctly handle large volumes of EOL lamps. Large amounts of REE are recoverable and can ease the strain caused by primary production [12, 45].

Table 8 – Recycling potential for phosphors in fluorescent lamps. Adapted from [12].

Estimated REE in stocks in 2020 (tonnes)	*Estimated average lifetime (years)*	*Estimated REE old scrap in 2020 (tonnes)*	*Pessimistic scenario: recycled REE in 2020 (tonnes)*	*Optimistic scenario: recycled REE in 2020 (tonnes)*
25,000	6	4167	1333	2333

Phosphors are a rich source of REE (mainly yttrium, europium and terbium) and its recycling process is straightforward, which makes them particularly viable for recycling. There are three possibilities for recycling phosphors from fluorescent lamps: Direct reuse of the extracted phosphor mixture, physicochemical separation of individual phosphors components for reuse, or recovery of REE content by chemical extraction (Fig. 19) [12, 45].

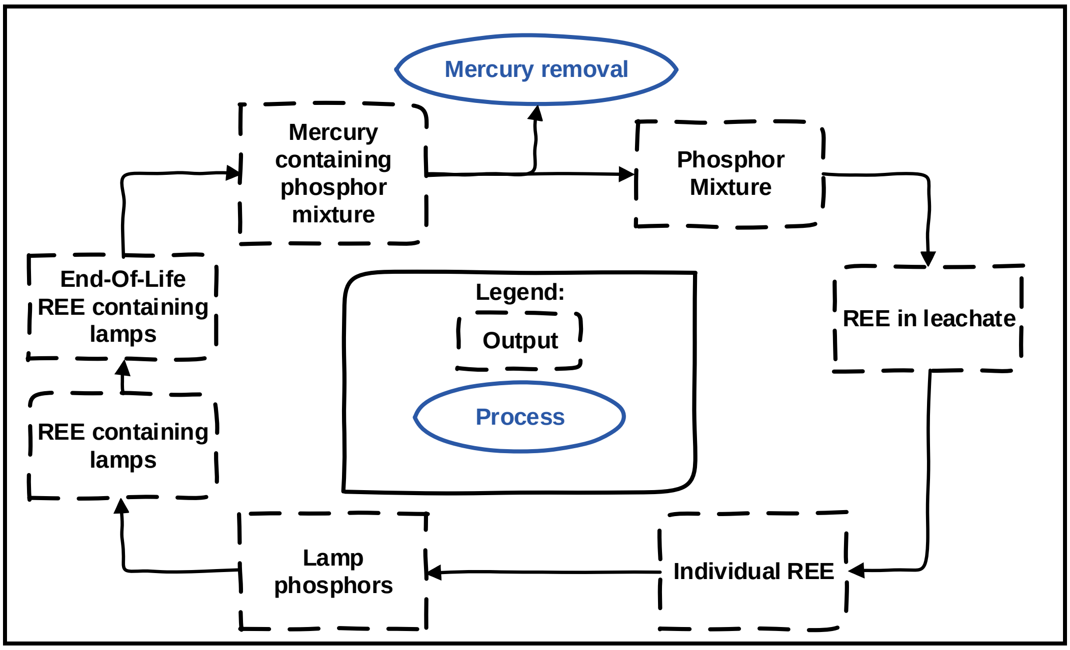

Figure 19 – Fluorescent lamps simplified recycling flowsheet. Adapted from [12].

- **Direct reuse**

The most simple and affordable solution. Phosphors are extracted from EOL lamps and directly employed on new lamps without any processing. However, new lamps must be exactly the same kind of EOL ones [12, 45].

Each kind of fluorescent lamp makes use of certain phosphors mixtures to deliver different colours and tones, being influenced by several factors: type of lamp, desired colour, resources available, manufacturer and even the location of the manufacturing unit. Direct reuse forces a recycling unit to separate the lamps by type, to avoid unwanted phosphor combinations, it's essentially only possible if the manufacturer recycles their own EOL lamps. This procedure cannot be implemented *ad infinitum* as phosphors deteriorate during the lamp's lifetime, with recycled versions already presenting poorer performance when compared with a primary-source lamp [12, 45].

- **Physicochemical separation of the phosphor's components for reuse in new lamps**

This process tries to solve the main disadvantage from the previous method by separating the mixture of each EOL lamp into its individual components. It's achieved by froth flotation and obtains individual phosphor fractions, which can be used in new mixtures that can be applied to different models. This method uses limited amount of chemical substances, but the ones used are hazardous. It's a fairly simple process if very high purity is not required, but to attain high purity the process becomes more complex. Phosphor deterioration is still an issue, and separation influences the particle size which can affect the phosphor's performance [12, 45].

- **Recovery of the REE content by chemical extraction**

Phosphor mixtures usually contains a high percentage (up to 27.9 wt%) of REE, mainly yttrium, europium and terbium, these elements can be recovered by attacking the phosphor mixture with strong chemicals and extracting the REE by precipitation or solvent extraction. REE obtained is very pure and can be used on any applications. Like primary production, this process requires several processing steps, consumes large quantities of strong and hazardous chemicals generating large amounts of contaminated water [12, 45].

3. Modelling Neodymium Stock & Flows

3.1 Methodology – 'Material Flow Analysis'

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. Built on the first law of thermodynamics – the law of mass conservation, it contemplates anthropogenic systems, like countries, as 'living organisms' allowing a researcher to investigate its metabolism. This is, 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 (Figure 20). 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 legislations [47].

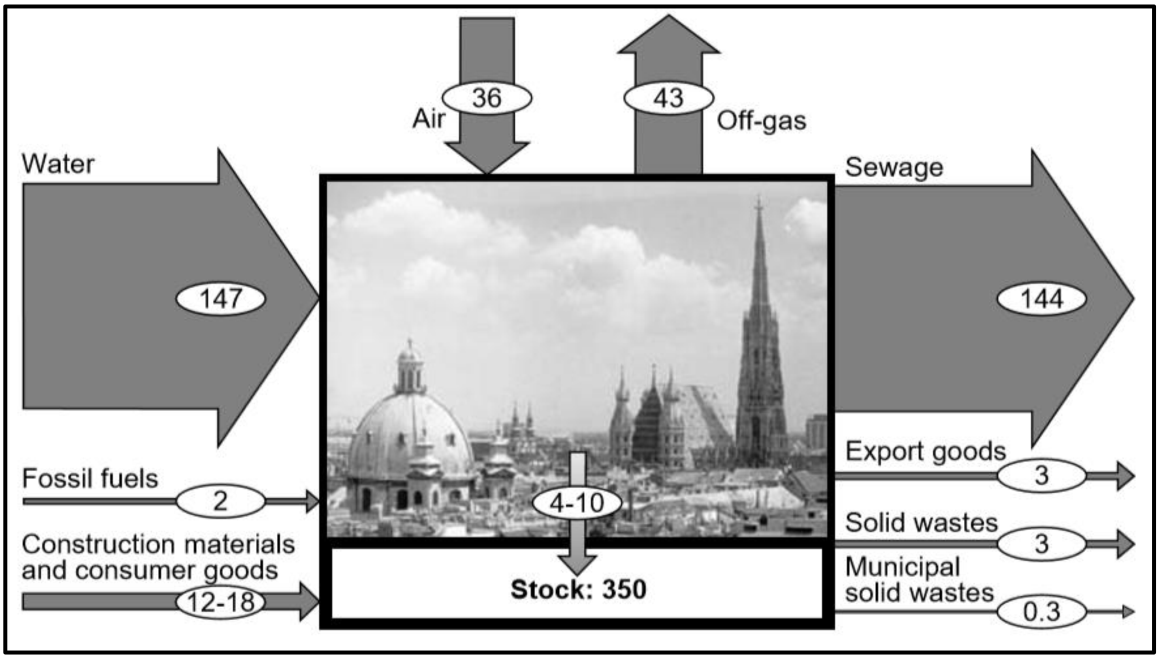

Figure 20 – Example of a basic MFA, using as boundary the city of Vienna in the 1990s. The process occurring within the boundary is anthropogenic metabolism of the city. (Units are tonnes of material per capita and year) [47].

3.1.1 Purpose

Previous chapter reviewed every REE and determined neodymium to be the most critical in the near future. This provides essential insight for following work, as with its increasing demand and Chinese social-economic issues it's expected that secondary sources will become progressively more relevant.

This MFA aims to understand the pathway of neodymium, the scale of its stock and flows and how it evolves with time. Having final objective of assessing its recovery potential from 'urban mines' by pinpointing and evaluating the most relevant secondary sources of the element.

3.2 System Definition

To be correctly implemented the MFA's system must be properly defined: which materials and processes are included, what are the spatial and temporal boundaries, what is the source of the data and how it was obtained, et cetera. Finally culminating in a simplified diagram that helps the reader understand the system defined. Moreover, MFA-specific terms must be defined [47, 48]:

- **Material –** in MFA, the term '*Material*' denotes both *goods* and *substances* [47];
- **Substance –** a single type of matter that's consisted of identical uniform units, if the units are atoms, the substance is termed '*element*', if it's molecules then it's denoted as '*chemical compounds*'. Substances are considered to be conservative, this is, they do not transform during any process (e.g. assuming no losses, if 2g of the substance 'neodymium' are processed into a 6.67g of magnet the amount of substance in the magnet is still considered to be 2 grams) [47];
- **Goods –** nomenclature given to a substance (e.g. metallic neodymium) or mixture of substances (e.g. NdFeB alloy) that's considered by markets to have economic value. This value can be positive (e.g. in-use magnet) or negative (e.g. municipal solid waste) [47];
- **Process –** any type of transport, storage or transformation (production or consumption) of materials is regarded as a process [47];
- **Storage and Stock –** the 'Storage Process' is essential for this MFA, as its purpose is to evaluate the mass and rate of change (depletion of accumulation) of stock. The quantity of materials stored within a given process is designated as 'stock'. E.g. Goods stored in households, waste in landfills or in collection points, amount of goods placed in market [47];
- **Flow and Flux –** often the terms 'flow' and 'flux' are misleadingly considered to be the same. '*Flow*' refers to the ratio of mass per time that flows through a conductor, like the rate of water passing through a pipe, usually given in tonnes/year or kilogram/second. Example: oil consumption rate of Switzerland (in tonne per year). '*Flux*' refers to the flow per cross section of a system, using the 'water in pipe' analogy flux would be a flow in a cross section of the pipe, with the units of kg/(sec.m^2). Example: oil consumption rate per capita in Switzerland (in kg per inhabitant per year), in this case an inhabitant is a cross section of the country (Fig. 21) [47];
- **System and Boundaries –** the object of study of a MFA is the *System*, this is, a group of components that are connected or related, acting as a single element, evaluating its interactions and boundaries between them in space and time. A system can be 'Open' and interact with its surroundings (i.e. having material/energy exports and/or imports) or 'Closed'. The area in which processes occur is regularly considered as the '*Spatial boundaries'*, depending on the system it can range from biological bodies, industrial plants, cities, regions, nations to even an entire planet. Typical MFAs that models metal stocks and flows are open systems comprised of a nation over the period of a year [47].

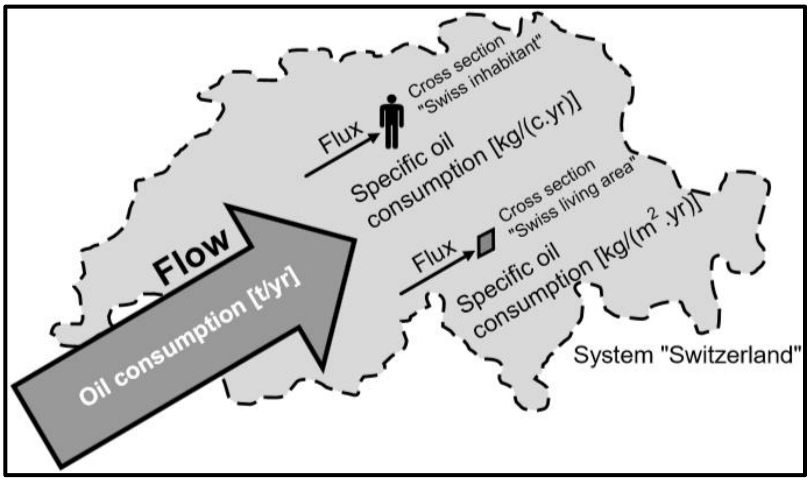

Figure 21 – Comparison of flow and flux using the example of oil consumption within the system 'Switzerland' [45].

3.2.1 Spatial and Temporal Scale

Spatial boundary is commonly set by the scope of the project. For MFA that assesses stocks and flows of metal, the typical boundary is nations, as most databases available are regarding them. Since the author's university is in Portugal, and there are repositories with reliable and updated datasets for the aforesaid, the chosen spatial boundary is Portugal.

Temporal boundaries are also highly dependent on the available data and its nature. In anthropogenic systems, like nations, reports are often written on an annual basis covering the period of previous years or estimating following ones, therefore much of the data is regarding yearly periods. For the chosen spatial boundary, there're sound data available that allows assessment of neodymium flows and stocks between 2000-2015 and 2016-2020, the latter period using projections. To provide a recent view on consumption, demand and EOL, the year of choice is 2015. The choice comes from the fact that 2015 is the most recent year with sound records available [2, 49, 50].

3.2.2 Materials

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, the wind turbine technology (permanent magnet generators) that employs Nd does not exist in the chosen system. Moreover, the percentage of vehicles with magnet-based electrical motors within the system is still negligible, and since it's placement on the market is very recent (less than a decade) there's still no information regarding its end-of-life or waste flows. For the aforementioned reasons, EEE is the focus of this investigation. This growing, yet slightly mature market has the necessary abundance of reasonably accurate data regarding stocks, flows and end-of-life that allows the conception of a satisfactory and informative analysis.

This work complies with 2012/19/EU (recast) directive on WEEE, in effect since August 15th, 2018 it considers 6 categories instead of the previous 10. Besides EU's directive, UNU-Keys are applied, this classification was created by the United Nations University and condenses EEE that have similar function, compositions, weight, lifespan and end-of-life, into 54 'product groups' (UNU-keys). More information in Appendix A [2, 51, 52].

Not every equipment possesses Nd within its components, thus the scope is reduced to the 'potential neodymium-containing equipment'. The equipment with a higher chance of containing Nd is the ones containing magnets, the main application of the substance in EEE (Table 9).

Table 9 – Neodymium bearing equipment considered in the analysis [2, 49, 50, 53, 54].

Category		UNU-Keys	Nd-bearing components
I	Temperature exchange equipment (TEE)	0108 – Fridges, 0109 – Freezers, 0113 – Air conditioners	Compressors, motor, magnets (unspecified)
II	Screen, monitors and equipment containing screens w/ surface greater than $100cm^2$	0303 – Laptops and tablets, 0408 – Flat display TVs	Speakers, hard drive, optical drivers, magnets (unspecified)
III	Lamps	--	
IV	Large equipment (any external dimension more than 50 cm)	0104 - Washing machines, 0105 - Dryers	Motors, magnets (unspecified)
V	Small equipment (no external dimension more than 50 cm)	0114 – Microwaves, 0204 – Vacuum cleaners, 0205 – Personal care Eq., 0404 – Video and projectors	Motor, hard drives, optical drivers, magnets (unspecified)
VI	Small IT and telecommunication equipment (no external dimension more than 50 cm)	0302 – Desktop PCs, 0306 – Mobile phones, 0702 – Game consoles	Speakers, hard drive, optical drivers, motors, magnet (unspecified)

3.2.3 Processes

Metal stock and flow analysis usually consider solely three processes, 'Put on Market' (POM for short), 'In Stock' and 'Waste Generated', yet this work also includes an additional stage regarding the management of the waste produced. Production, manufacture and transportation are usually not considered, as the main goal is to follow the flows of the chosen metal within a certain economy, since they enter the market until being discarded [2].

- **Put on Market (POM)** - as the name suggests, it refers to the neodymium that penetrate the systems spatial borders in the year chosen, specifically it considers the amount of neodymium that enters Portuguese economy for the selected year [2];
- **In-use Stock –** denotes the amount of Nd that's present inside in-use products (and its components) in Portugal during the year that's being evaluated [2];

- **Waste Generated -** amount of neodymium existent in products (and its components) that reach end-of-life and are disposed in Portugal for the year being analysed [2];
- **Waste Management –** composed of the different 'sub-processes' that represent the different destinations for the Nd within the WEEE. It includes the amount that is collected and consequentially Reuse\Recycle\Recovery but also the disposal to municipal landfills and the percentage of neodymium that's in an unknown location, denoted 'not-collected'.

3.2.4 System Overview

Having the spatial & temporal boundaries, materials and processes established, the system boundary can be determined. The system boundary diagram functions as an overlook into the entire system, this allows the reader to understand the specific part of the substantial value chain that's being diagnosed.

The scope englobes market penetration, consumption (and stocking) by end-users, end-of-life and waste management for EEEs that contain neodymium in Portugal for the year of 2015 (Fig 22). This analysis acknowledges but does not consider any primary production or manufacturing steps in its modelling (the remaining boundaries in figure 22 represent steps the substance has undergone before arriving to the chosen system - Primary Production, Magnet manufacturing, and product assembly). Furthermore, it considers that all manufacturing is performed outside of the nation, even if there are a small percentage of products being assembled in Portugal.

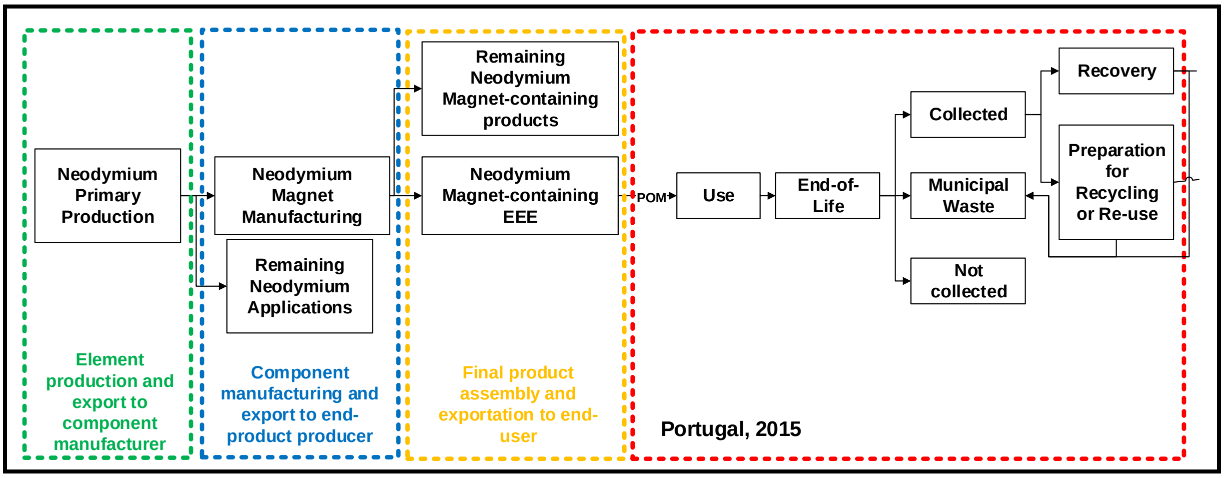

Figure 22 – System boundary where the neodymium flow & stock analysis will be performed (in Red).

Nonetheless, most of manufacturing occur outside of Portugal (and European Union), with the totality of primary production being held outside of European borders. One can consider that the '*end-user market in 2015 Portugal*' is the actual boundary of the system that's modelled, since it only comprises of the products Put-On-Market for the consumer, it's consumption and end-of-life.

Currently there's no Nd recycling being performed in the nation; therefore, the recycling chain is not considered entirely since all neodymium present within the EEE being processed is not extracted being potentially landfilled. Yet, it's of chief importance to consider the amount of Nd that's currently entering recycling facilities precisely to understand the quantity that's being left unprocessed and ultimately lost.

With the main goal of assessing neodymium's recycling potential being left untapped in Portugal, the early stages of the waste management are considered and modelled. Moreover, there's also the neodymium-containing components (e.g. electric motors, speakers, et cetera) that are being recovered or reused to be considered, yet while some amount do probably get recovered to some extent, there's not enough data to sustain this hypothesis.

3.3 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 (*POM*), that entered in previous years being already in use by the end-user (*Stock*), 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 is required to depict flows and stocks in 'kg of neodymium' instead of 'number of units'. The following chapter will describe procedures and methodologies used to obtain the results.

3.3.1 Data Quality

The following steps require data that's not easily available and sometimes non-existent in reliable reports such as the ones of the European Commission. A thorough research was enforced in order to get data, several sources were found, rarely the results were consensual.

A 'data quality 1 to 4 scale' is proposed to select among several data the most reliable, this scale is based on critical assessments on the several sources used. Table 10 presents the criteria chosen for the classification.

Table 10 – Data quality 1-4 scale used to critically assess the sources for the data used.

Level of data quality	*Description*	*Examples*
1: Good	Data from empirical projects with substantial numbers of representative samples; full *in-situ* data collections	National census; laboratories analysis of a magnet composition
2: Medium	Big scale statistics from reputable entities; empirical analysis with few representative samples from a very disperse and broad pool	Results from a European Commission report; measured average magnet weight per device
3: Medium-low	Opinions from experts; data provided verbally by producers and manufacturers	Average magnet weight per device provided by 'Sector leading Manufacturer'
4: Low	Data provided without any source or reasoning for its obtention	Guessing the market share of NdFeB magnets

3.3.2 Put on market (POM)

POM data were obtained directly from an open-source online script named *Waste over Time Results* (Fig. 23). Programmed by *Statistics Netherlands* is part of a European Commission study on *Collection rates of WEEE* which provides POM data regarding each UNU-key for all EU from 1980 to 2021 [50, 54]. Calculated using confidential data from the European Database *PRODCOM* (*Production Communautaire*), POM was computed by the group using the following expression [50, 54]:

$$POM = Domestic\ production + Import - Export$$

The group further corrected the results from previous steps as some data were missing or the results were unrealistic, using data from similar EU member-states for example [50, 54].

Being part of a report commissioned by a reliable entity (European Commission), the computed POM is considered accurate to a data quality level of '2: Medium'. Considering the current statistical tools, procedures and resources, this report provides, probably, the highest quality possibly attainable.

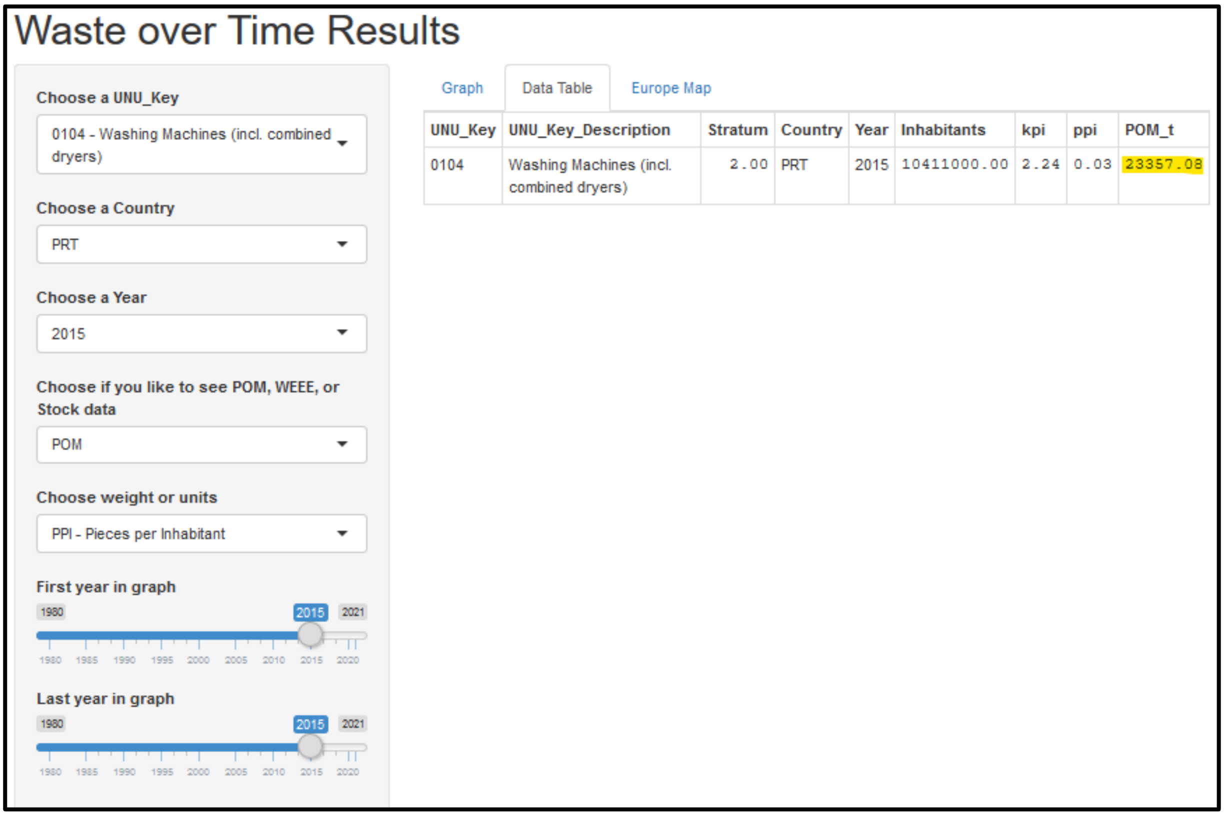

Figure 23 – User interface of the 'waste over time' software script, the desired POM data for this example is highlighted in yellow [54].

POM data for the 14 selected UNU-keys between the period of 1995 and 2015 are extracted to model the flows, stock and waste generated. This period was chosen based on the average lifespan of each EEE, i.e. to be sure that the big majority of devices with long lifespans entering the market in the first modelled year (1995) reach its EOL before the target year (2015) guaranteeing that, even the oldest devices that are still in stock, are considered [50, 54].

Waste over Time Results script provides POM in 'tonnes of equipment', since the average magnet weight is available in 'kg of magnet per unit' there's the need to convert the POM from 'weight of equipment' (in tonnes) to the 'number of equipment' (in units). For that purpose, a conversion factor is employed, in this case the 'average weight per UNU-key'. The same European report provides this factor, measured on 1995, 2000, 2005, 2010, 2011 and 2012 to account the evolution through the years. Considering the proximity between 2012 and 2015 it's reasonable to adopt those values for the entire period of 2012-2015. Having the required data collected and using the expression shown below, POM was calculated for all UNU-keys in the desired format [50, 54]:

$$POM\ (in\ units) = \frac{POM_{year\ X}\ (in\ tonnes) \times 1000}{Average\ Weight_{Year\ X}(in\ Kg/unit)}$$

Table 11 provides the POM values (in kg), the average equipment weight for the period of 2012-2015 and the desired POM (in units) for each selected UNU-key in the target year of 2015.

Table 11 – POM (in Kg), average weight and POM (in Units) for the selected UNU-keys for 2015 [50, 54].

UNU Key	2015 POM (in kg)	Average weight* in 2012-2015 (kg/unit)	2015 POM (in units)
0104 – Washing machines	23357080	71.5	326 672
0105 – Dryers	1995470	43.5	45 873
0108 – Fridges	15064110	54.1	278 449
0109 – Freezers	3859640	43.3	89 137
0111 – Air conditioners	5727700	25.2	227 290
0114 – Microwaves	6871370	22.2	309 521
0204 – Vacuum cleaners	3645740	5.8	628 576
0205 – Personal care equipment	649290	0.5	1 298 580
0302 – Desktop PCs	2661470	8.8	302 440
0303 – Laptops (incl. tablets)	1111880	3	370 627
0306 – Mobile phones	349130	0.1	3 491 300
0404 – Video and projectors	2621670	2.7	970 989
0408 – Flat display TVs	4990700	14.3	349 000
0702 – Game consoles	560900	1.9	295 211

*Note that the first year modelled is 1995, therefore the conversion factors from all the relevant years are used through the calculations (e.g. when modelling a given UNU-key for the year 2000, its average weight measured in 2000 is applied), information the remaining years average equipment weight is available in Appendix B.

3.3.3 Neodymium Magnets Market Share

It would yield very inaccurate results considering that for every UNU-key, the percentage of equipment that uses Nd magnets is 100%, since there are alternative magnet technologies that can be applied in cases where cost or temperature is the driving force or NdFeB magnets are simply not necessary.

For that reason, the next modelling stage focused on obtaining the market share of neodymium magnets for each UNU-key. Since there aren't any large-scale statistical surveys regarding this specific indicator, all data obtained is based on potentially inaccurate data from experts or manufacturers input. Four sources are used in this step, often the results are conflicting, therefore each source must be critically evaluated in order to choose the most fitting percentage. Since most information available comes from potentially imprecise sources, there's an effort to (when possible) combine multiple sources and use median figures that are potentially closer to reality. The chosen market percentage is shown in Table 12 and 13 and using those values the POM is adjusted to account only the percentage of equipment that in fact contain Nd [53, 55-57].

Table 12 represents the used sources and its assessed quality, apart from one, all sources are considered to have medium-low quality, nonetheless it's expected that the output will be more realistic when compared with a scenario where the market share is considered 100% for all UNU-key. In the cases where one of the sources had better quality, that value was considered the more accurate, therefore chosen.

Table 12 – Quality of the sources used to obtain the market share of the neodymium magnets [53, 55-57].

Authors of source	*Origin of the source proposed value*	*Quality of the source*
Habib et al. [53]	Market leading manufacturers & experts in the field	Level 3: Medium-low
Seo et al. [55]	JEITA, 2009. Japan Permanent Magnet Index.	Level 2: Medium
Sekine et al. [56]	Manufacturers	Level 3: Medium-low
Lixandru et al. [57]	Expert in the field	Level 3: Medium-low

Note that, in the case of air conditioners, some sources pointed to an constant increase in the share as a trend, thus the chosen value for 2015 reflected this trend and is slightly larger than the ones proposed by the sources [53, 55-57].

Table 13 – Neodymium market share for each selected UNU-Keys and corrected POM [53, 55-57].

UNU-key	**Source**	**Market share according to the sources**	**Chosen value**	**Adjusted POM (units)**
0104 – Washing machines	*Habib et al.*	25%	24.5%	80 035
	Seo et al.	24%		
	Sekine et al.	24%		
0105 – Dryers	*Habib et al.*	25%	25%	11 468
0108 – Fridges	*Habib et al.*	30% (from 2003 onwards)	15%	41 767
	Seo et al.	13% (from 2010 onwards)		
	Sekine et al.	14% (from 2010 onwards)		
0109 – Freezers	*Habib et al.*	30% (from 2003 onwards)	75%	66 853
0111 – Air conditioners	*Habib et al.*	30% (from 2003 onwards)	80%	181 832
	Seo et al.	75% (2010)		
	Sekine et al.	45% (2004), 60% (2007), 75% (2010)		
0114 – Microwaves	*Habib et al.*	30% (from 2013 onwards)	30%	92 856
0204 – Vacuum cleaners	*Habib et al.*	30% (from 2013 onwards)	30%	188 573
0205 – Personal care eq	*Habib et al.*	25% (from 2007 onwards)	30%	389 574
0302 – Desktop PCs	*Habib et al.*	100%	100%	302 440
	Sekine et al.	100%		
0303 – Laptops (incl. tablets)	*Habib et al.*	100%	100%	370 627
	Sekine et al.	100%		
0306 – Mobile phones	*Habib et al.*	100%	100%	3 491 300
0404 – Video and projectors	*Sekine et al.*	100%	100%	970 989
0408 – Flat display TVs	*Lixandru et al.*	66%	66%	230 340
0702 – Game consoles	*Habib et al.*	100%	100%	295 211
	Sekine et al.	100%		

3.3.4 Stock and Waste Generated

Waste generated is computed using the '*Sales-Lifespan*' model. This method uses historical POM data and lifespan distribution to calculate the quantity of waste generated on a selected year, the following formula is used to compute the model [50]:

$$W(n) = \sum_{t=t_0}^{n} POM\ (t) \times L^{(p)}(t,n)$$

- $w(n)$ – is the amount of waste generated on the selected year 'n';
- $POM(t)$ – is the quantity of products that penetrate the market in an historical year 't' prior to 'n';
- t_0 - is the initial year to be modelled or the year the equipment first entered the market;
- $L^{(p)}(t,n)$ – is a Weibull distribution-based parameter that models the lifespan of a given equipment and predicts the percentage of equipment that entered the market on the historical year t and is discarded in the selected year n.

The lifespan distribution is modelled using time-dependent shape 'α' and scale parameter 'β' and is represented with the following simplified formula [50]:

$$L^{(p)}(t,n) = \frac{\alpha}{\beta^{\alpha}}(n-t)^{\alpha-1}e^{-[n-t/\beta]^{\alpha}}$$

It is extremely difficult to obtain the time-variant parameters [i.e. α(t) and β(t)], therefore it's common to assume the same distribution parameters through the years, simplifying the formula, while losing some precision this formula still attains better results than just using the average lifespan value directly [50].

For instance, analysing the case of washing machines (Fig. 24), out of the devices that entered in 2014, around 0.5% reached its EOL at 2015, for the equipment that were put on market in 2005 almost 7% of them will reach EOL and those that entered in 1995 around 2.5% are discarded in 2015. In fact, having an average lifespan of 11.96 years it's understandable that, of the devices that entered the market in 2005 (10 years before), a large percentage of them are discarded in 2015 [58].

A device lifetime is not a fixed number and depends on several factors, e.g. some devices can be discarded prematurely due to an early malfunction, where others are well preserved and last longer. Hence lifespan distribution is applied rather than just assuming the average lifetime value, note that the average lifespan is still a useful indicator of the end-user consuming habits [50].

In a nutshell, the '*Sale-Lifespan*' model receives the amount of equipment that entered in each historical year and multiplies it by the chance of it being discarded on the selected year, thus giving the percentage of devices from that historical year which were discarded on the evaluation year. The amount of waste generated on the selected year is thus a cumulative sum of all obsolete equipment that entered the market through all historical years prior to the one being evaluated [50].

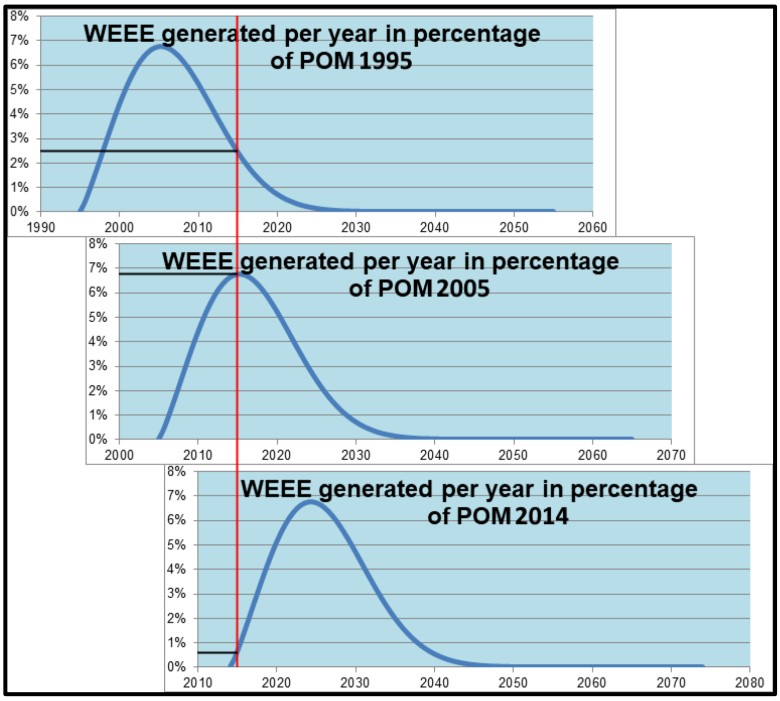

Figure 24 – Lifespan distributions for washing machines that entered the market on 1995, 2005 and 2014 respectively, with the representation of the percentage that were discarded in 2015 (red line) [50, 58].

The same research group that created the POM database script, also developed a digital tool named '*WEEE Calculation Tool'* (Fig. 25). The tool has different versions available for each European Union member to account different consumption habits hence different lifespan distributions. Evidently, the Portuguese scenario calculation tool for was chosen to carry the Waste Generation calculation [50, 58].

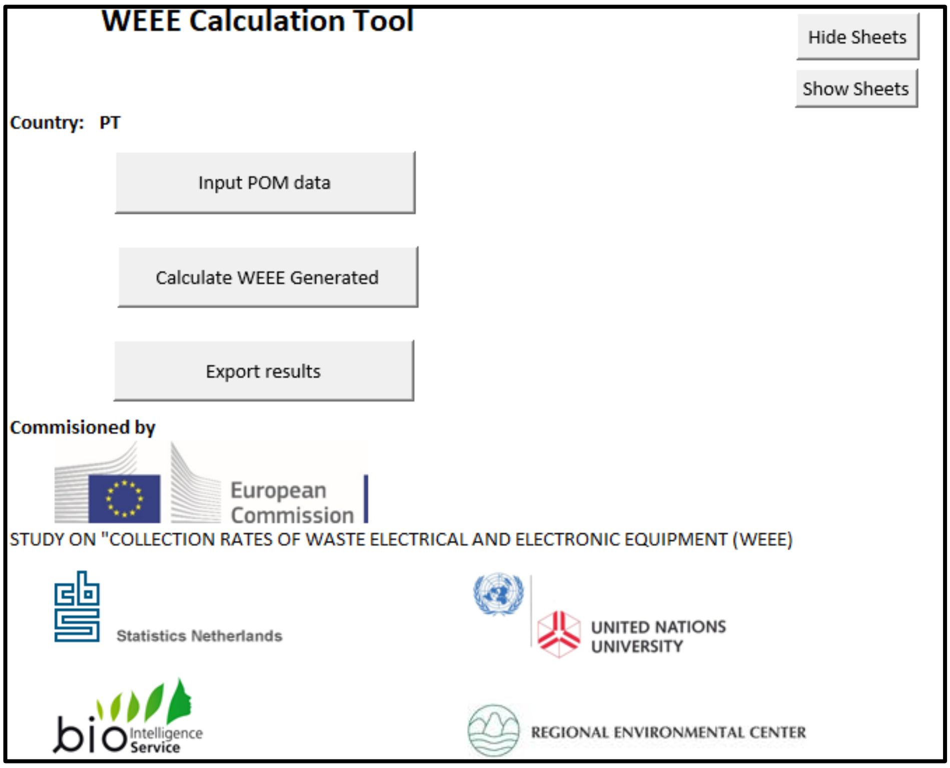

Figure 25 – User interface of the WEEE calculation tool [58].

The tool simplified the process by automatizing the Waste Generation iterations using the same 'S*ale-Lifespan'* model described before, all the Weibull parameters are already set, there's just the need to input the POM and extract the output. The calculation tool already comes with the Portuguese POM up to 2014 pre-inputted, however since this report aims to analyse just the equipment that carries Nd in its components, POM had to be adjusted. The pre-inputted POM was removed and replaced with the adjusted one for all the 14 UNU-keys being studied, the calculation was carried, and the results exported. The stock is then calculated using the following formula [50, 58]:

$$S(t) = S(t-1) + POM(t) - W(t)$$

- $S(t)$ – Stock on a given year, t;
- $S(t-1)$ – Stock from the year prior to t (for the first modelled year $S(t-1) = 0$);
- $POM(t)$ – Equipment that entered the market on the year t;
- $W(t)$ – the amount of waste generated on the selected year t.

By iterating POM, Waste and Stock for a 20 years range starting from 1995 using the procedures presented before, the result is a screenshot of the neodymium-containing EEE scenario in Portugal for the year of 2015, which is presented in Table 14.

Table 14 – POM, waste generated (WG) and stock of neodymium-containing EEE for Portugal in 2015 [50, 58].

UNU Key	Average Lifespan (in years)	POM (units)	WG (units)	Stock (units)
0104 – Washing machines	11.96	80 035	51 829	815 904
0105 – Dryers	13.97	11 468	6 680	142 527
0108 – Fridges	16.4	41 767	16 735	489 616
0109 – Freezers	17.2	66 853	34 288	730 166
0111 – Air conditioners	7.4	181 832	185 241	1 273 310
0114 – Microwaves	8.33	92 856	101 427	823 928
0204 – Vacuum cleaners	9.92	188 573	136 493	1 383 045
0205 – Personal care equipment	7.62	389 574	474 461	3 414 425
0302 – Desktop PCs	8	302 440	256 319	1 965 684
0303 – Laptops (incl. tablets)	6.08	370 627	589 240	3 018 696
0306 – Mobile phones	5.07	3 491 300	3 842 958	16 975 104
0404 – Video and projectors	7.95	970 989	717 477	5 566 386
0408 – Flat display TVs	10.41	230 340	256 301	3 585 621
0702 – Game consoles	4.56	295 211	297 138	1 144 903

3.3.5 Waste Management

The following step's concerning WEEE, regarding its fate in Portugal there's currently 3 possible ends: collection (and consequent recovery), disposal at a municipal waste landfill, or none of the previous (i.e. uncollected, its location is unknown).

Collection rates are attained from an online database named "*Urban Mine Platform"* part of *"Prospecting Secondary raw materials in the Urban mine and Mining waste*", *ProSUM*, an EU-sponsored (Horizon 2020) project. Among others, the database provides collection rates within every EU state member for each EU-6 EEE categories in the period of 2010-2015. The same database also provides the percentage of WEEE that is disposed in municipal landfills and uncollected [2].

The database meta-data states that the lack of harmonization between members states in reporting collection rates lead to discrepancies and high uncertainties, thus the database is evaluated to have a data quality level of '3 Medium-low'. However, provided rates are plausible considering the current knowledge of the Portuguese scenario, depicting reasonable results aligned with the expectations [2].

Regarding the recovery rate and the percentage of WEEE prepared for reuse and recycling these are available from the Portuguese Environmental Agency (APA – Agência Portuguesa do Ambiente) yearly WEEE report. This data is considered to have a quality level of '2 – Medium', as it comes from a national agency report. APA's report also provides the tonnage of WEEE collected (in the EU-10 EEE categories). Yet it doesn't provide the projected amount of Waste Generated neither the historical POM this information cannot be used to compute the collection rates [59].

To calculate the amount of WEEE collected for each individual UNU-key the collection rate is required, consequently the ProSUM source is the preferred since it provides the required information in the desired format (Table 15) [2, 59].

Table 15 – WEEE rates per category (WEEE EU-6) [2, 59].

	Collected				
WEEE category	***Collected***	**Recovery**	**Prepared for reuse and recycling**	***Municipal waste***	***Not collected***
Category I	37%	94%	80%	0%	63%
Category II	22%	92%	82%	2%	76%
Category IV	41%	94%	80%	2%	57%
Category V	34%	94%	80%	23%	43%
Category VI	41%	92%	82%	23%	36%

To compute the WEEE figures, each UNU-keys adopts the rates of its category (conversion between UNU-keys and EU-6 categories system is available at Appendix C) and multiplies it by the amount of waste generated. The recovery rate and the percentage of equipment that's prepared for recycling and reuse are calculated using the amount of waste 'collected and reported' as basis and not the overall waste generated (Table 16) [2, 59].

Table 16 – Amount of WEEE collected, recovered, prepared for reuse and recycling), disposed in municipal waste and not collected. All data below are presented in units [2, 59].

		Collected			
UNU-Keys	***Collected***	**Recovery**	**Prepared for reuse and recycling**	***Municipal waste***	***Not collected***
0104 – Washing machines	21 250	19 975	17 000	1 037	29 543
0105 – Dryers	2 739	2 575	2 191	134	3 808
0108 – Fridges	6 192	5 821	4 954	0	10 543
0109 – Freezers	12 687	11 925	10 149	0	21 602
0111 – Air conditioners	68 539	64 427	54 831	0	116 702
0114 – Microwaves	34 485	32 416	27 588	23 328	43 613
0204 – Vacuum cleaners	46 407	43 159	37 126	31 393	58 692
0205 – Personal care eq.	161 317	150 025	12 9053	109 126	204 018
0302 – Desktop PCs	105 091	96 684	86 175	58 953	92 275
0303 – Laptops (incl. tablets)	129 633	119 262	106 299	11 785	447 823
0306 – Mobile phones	1 575 613	1 449 564	1 292 002	883 880	1 383 465
0404 – Video and projectors	243 942	212 230	197 593	165 020	308 515
0408 – Flat display TVs	56 386	49 056	45 673	5 126	194 789
0702 – Game consoles	121 826	112 080	96 243	68 342	106 970

3.3.6 Average Neodymium Content

Up to this point all data has been processed using as unit of reference 'numbers of equipment' (i.e. units), however, as the objective is to study the mass of Nd present and flowing within the system, the last step is to convert all the previous results to the desired format: 'kg of neodymium'. The required specifications are the 'average magnet weight per equipment' (AMW) and the 'average magnet composition' (AMC). These allow to calculate the conversion factor 'Average Neodymium Content' (ANC) (Table 17). The procedure to obtain these values is like the 'Neodymium Magnets Market Share' sub-chapter where several sources are collected, and the definitive value is chosen afterwards. Like the aforementioned case, sources do not provide homogenous input, hence they must be critically evaluated (Table 18), and the final value obtained by choosing a representative and reasonable choice.

Table 17 – Quality of the sources used to obtain the AMW and AMC [53, 55-57, 60].

Authors of source	*Origin of the source proposed value*	*Quality of the source*	
		AMW	AMC
Habib et al. [53]	Laboratorial analysis for four UNU keys, low sample size	Level 2: Medium	Level 1: Good
	Manufacturers and experts input for the remaining	Level 3: Medium-low	Level 2: Medium
Seo et al. [55]	JEITA, 2009. Japan permanent magnet Index.	Level 3: Medium-low	NA
Sekine et al. [56]	Manufacturers input	Level 3: Medium-low	Level 2: Medium
Lixandru et al. [57]	Laboratorial analysis for one UNU key, median sample size	Level 2: Medium	Level 1: Good
Schulze et al [60]	Expert input	Level 3: Medium-low	NA

1. **Average Magnet Weight per equipment (AMW)**

It is difficult to acquire accurate figures for the 'average magnet weight' as there's a multitude of factors that can vary within the same UNU-key (different brand, different models, et cetera). Some sources provide empirical measures of the AMW, however with an unrepresentative low sample size, thus the results can potentially be inaccurate, nonetheless the precision of those empirical values is assumed to be superior when compared with the assumptions.

2. **Average Magnet Composition per equipment (AMC)**

Since the UNU-keys being studied do not have particularly unusual working conditions, it is expected that their magnet compositions are probably close to the typical NdFeB magnets and do not vary much between brands and models. For these cases the empirical sources (even with low sample size) are considered accurate, also the values obtained from experts and manufacturers input are trusted.

AMC and AMW are selected based on a critical analysis of the multiple sources with the main criteria being the source quality and the consistency between the multiple sources. In cases where every source does not have high quality, the difficulty is to select a reasonable value that's representative of the multiple sources. In the cases where the different sources provide very distinct numbers, there's an effort to select the median values in the range between the highest and lowest values presented by the sources [53, 55-57, 60].

Table 18 – Average magnet weight (AMW, g magnet/unit) and average magnet composition (AMC, Nd wt%/magnet) for each UNU key being evaluated and the resulting average neodymium content per equipment (ANC) [53, 55-57, 60].

UNU-key	Source	AMW (gr/unit)	AMC (wt%)	Chosen values		ANC (kg/unit)
				AMW (kg/unit)	AMC (wt%)	
0104 – Washing machines	Habib et al.	1004	29	0.5	28.5	0.1425
	Seo et al.	80-180	NA			
	Sekine et al.	100-250	28			
0105 – Dryers	Habib et al.	540	29	0.5	29	0.145
0108 – Fridges	Habib et al.	260	29	0.2	28.5	0.057
	Seo et al.	40-60	NA			
	Sekine et al.	100-250	28			
0109 – Freezers	Habib et al.	490	29	0.4	29	0.116
0111 – Air conditioners	Habib et al.	500	29	0.25	28.5	0.07125
	Seo et al.	60-400	NA			
	Sekine et al.	100-240	28			
	Schulze et al	250	NA			
0114 – Microwaves	Habib et al.	110	29	0.11	29	0.0319
0204 – Vacuum cleaners	Habib et al.	90	29	0.09	29	0.0261
0205 – Personal care equipment	Habib et al.	1	30	0.001	30	0.00029
0302 – Desktop PCs	Habib et al.	12.5	30.8	0.0125	30	0.0037
	Sekine et al.	10	29.5			
0303 – Laptops (incl. tablets)	Habib et al.	3.4	30.4	0.004	30	0.0012
	Sekine et al.	2	29.5			
	Lixandru et al.	2.6-10.3	NA			
0306 – Mobile phones	Habib et al.	0.7	27.5	0.0007	27.5	0.0001925
0404 – Video and projectors	Habib et al.	1.4	35.10	0.0014	33	0.000462
	Sekine et al.	1	31			
0408 – Flat display TVs	Lixandru et al.	3.0-33	19.87	0.012	19.87	0.0024
0702 – Game consoles	Habib et al.	12.5	30.8	0.0125	30	0.0037
	Sekine et al.	10	29.5			

Some sources provide values considered unreasonable when compared with the remaining sources and (if its data quality is in the same level as other sources) are excluded. This is particularly noticeable in the case of washing machines, where one of the sources claims AMW of 1 kg where the remaining sources state it to be around 200 gr [53, 55, 56, 57, 60].

Inflated results are undesired, thus there's a small degree of underestimation when selecting, this is to prevent unrealistic overestimated results that could potentially generate wrong conclusions. By underestimating, one can guarantee that if the undervalued modulation provides already a meaningful result, the real amount is larger, therefore even more meaningful [53, 55-57, 60].

Having the AMW and AMC selected is then possible to calculate the conversion factor 'Average neodymium Content per equipment' (ANC, in kg/unit) by using the following formula:

$$ANC = AMC \times AMW$$

Using the conversion factor ANC for each UNU-key and multiply it by the values obtained previously (POM, Waste Generated, Stock, Waste Managed) the result is the desired modulation of the neodymium stocks and flows (in kg of neodymium) within the system.

3.3.7 Other Assumptions

In order to successfully compute the neodymium flows several assumptions had to be made, mainly due to the inexistence of relevant data. Most assumptions have already been clarified, however there are some that aren't as trivial and require additional elucidation.

1. **Data regarding game consoles**

Besides POM and waste generated, which are truly correlated to the game consoles numbers, the remaining information was taken from data concerning desktop PCs. The assumption is made upon the fact that, especially in recent years, the constitution of videogames consoles is extremely similar to those of desktop computers, with modern devices being essentially slightly modified computers.

2. **Permanent Magnet Motors share**

Several UNU-keys have electrical motors in its components, there are two main varieties of electrical motors, 'induction' and 'permanent magnet', as the name suggests, only the latter employs magnets. Both technologies are widely used, yet to avoid hard-to-obtain assumptions regarding market share of motors type it's assumed that permanent magnet motors are exclusively used.

4. Results and Discussion

The following chapter's concerning the results and its interpretation. It's structured into 3 sections: (1) urban mine prospection to assess potential element recovery; (2) an assessment on collection rate improvements and (3) an investigation regarding the feasibility to perform large scale Nd recycling of EOL magnets.

4.1 I-O Results

Material Flow Analysis is essentially an Input-Output (I-O) simulation of a selected substance within a given system. Table 19 and Sankey diagram portray the studied I-O scenario (Fig. 26).

Table 19 – Neodymium flows 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

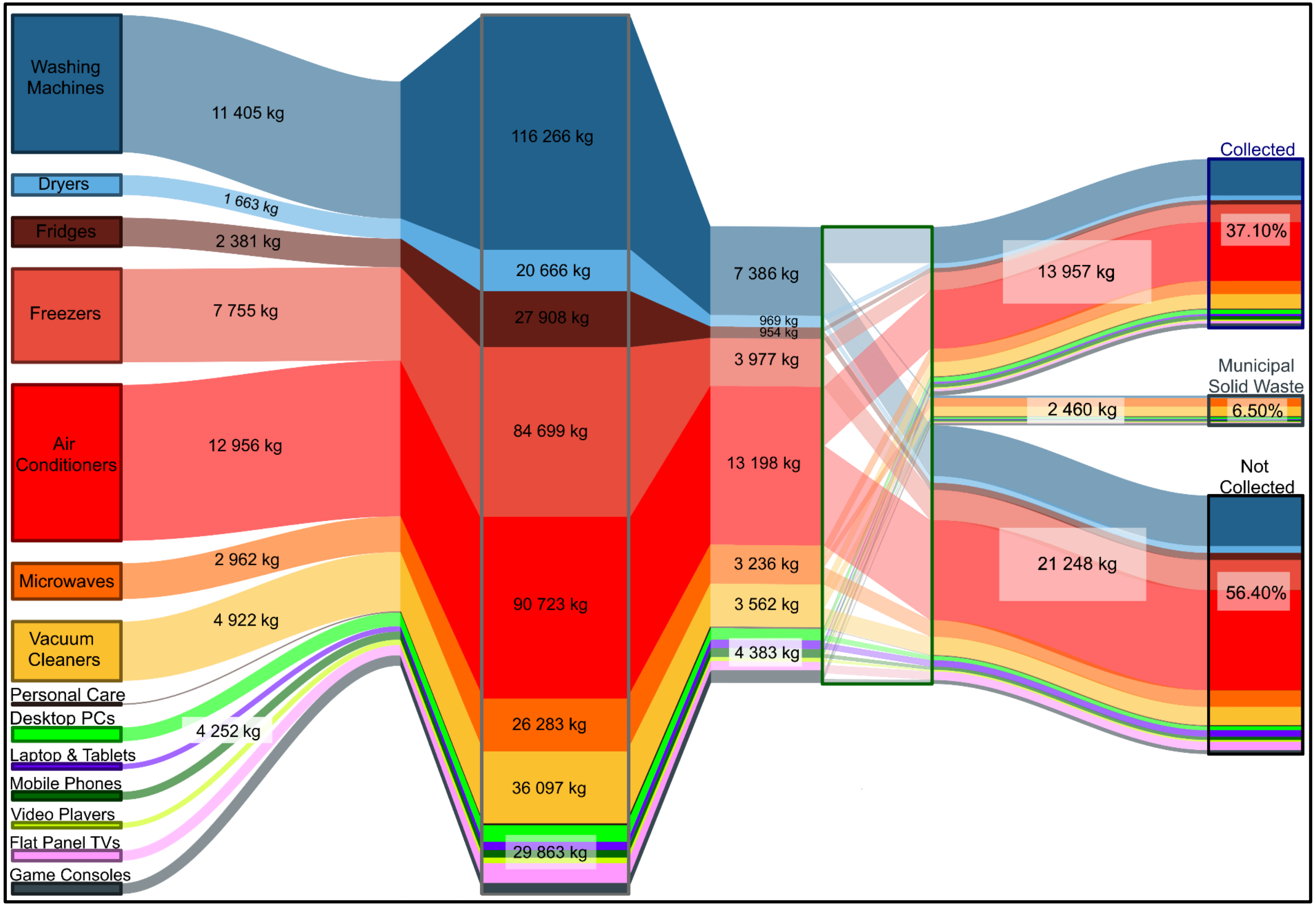

Figure 26 – Sankey diagram depicting the neodymium flow and stock (in kg of neodymium) in Portugal within selected EEE for the year of 2015. Totals: POM = 48 296 kg; stock = 432 505 kg; waste generated = 37 665 kg.

4.2 Urban-Mine Prospection and ‘Exploitation’

The following section aims to assess the amount of neodymium existent within the system that could be potentially recovered and pinpoint its main sources.

4.2.1 At a Glance – Stock Analysis

Upon an initial view, the most emphasized feature (particularly noticeable in the Sankey diagram) is the proportions. Effortlessly, the 14 UNU-keys can be split into 3 different tiers (Table 20) according to the amount of neodymium present within them, easing the process of pinpointing the most potential sources within the system. This classification is based on the neodymium present in stock (Fig.27).

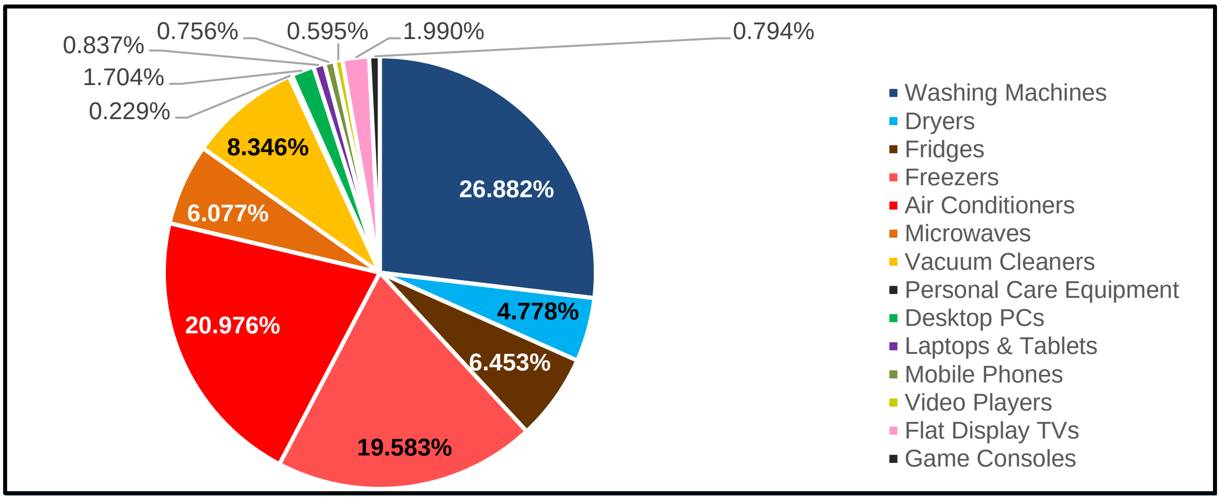

Figure 27 – Pie chart depicting the percentage (per UNU-key) of the total neodymium within stock (432 505 kg).

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.

Table 20 – Classification of UNU-keys 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

Above 90% of the total neodymium present within the system is within Tier I and Tier II, meaning that the remaining seven (Tier III) - personal care equipment, desktop PCs, laptops & tablets, mobile phones, video players, flat TV displays and game consoles, contains minute amounts. Tier III holds collectively less than 10% of the total amount of 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.

4.2.1 POM Analysis - Trends & Outlook

All previous interpretations were based on stock data, i.e. it regards the in-use equipment that was acquired in historical years. Consuming habits can mutate rapidly due to technological developments, society trends or global events. Yet, stock is a slow-changing process, it can take multiple years (depending on the equipment lifetime) until it reflects newer consuming habits.

Ultimately, all results are dependent on POM (Fig.28), processing it helps forecasting consuming trends, stock changes and consequently, waste generation thus predicting future waste generation scenarios. There are two possible methods to approach this forecasting exercise:

1. future POM is simulated, and the flow analysis is iterated for a period beyond the evaluated year, producing forthcoming waste flows;
2. using historical POM data and average equipment lifetime it's possible to roughly predict future stock and waste flows trends and the year range to which those trends are expected to perpetuate.

The first option produces more precise results, however, its execution would require additional computing to generate results that are useful, but not the research focus. Being auxiliary information, it's a reasonable option to use a less accurate procedure.

Fluctuations in historical POM are noticeable, and some are expected, i.e. due to events such as 2008 global crisis and 2011 Portugal's financial aid request to the IMF (International Monetary Fund). Noteworthy equipment with very unstable values is the air conditioner, it's considered a premium possession and not essential for daily life, thus its POM is highly susceptible to the nation's economic status.

Other dispensable premium devices, such as flat display TVs or game consoles are also affected by this phenomenon. If any affected equipment is part of the Tier I, as it is in the case of air conditioners, it can pose a risk if a proposed secondary production would solely rely on the collection of instable equipment.

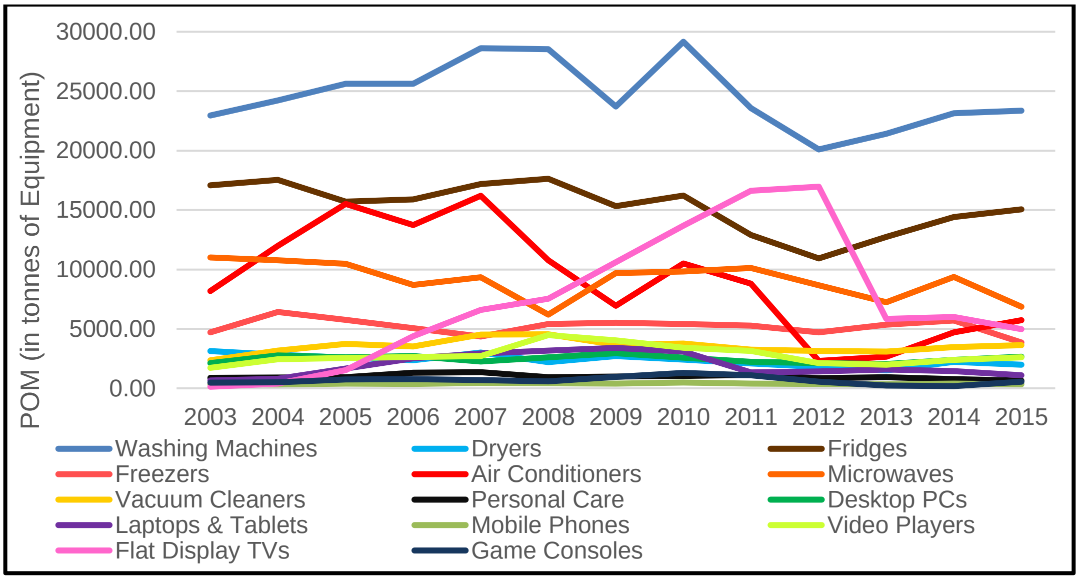

Figure 28 – Evolution of the selected UNU-Keys POM in Portugal between 2003 and 2015 [50, 54].

Nonetheless, POM and stock data points out that most UNU-keys either stabilised or increased in years before 2015. Furthermore, comparing stock between 2010 and 2015, there's an average increase of 17.7% (Fig. 29). Does this imply that it will continue to increase in the following years?

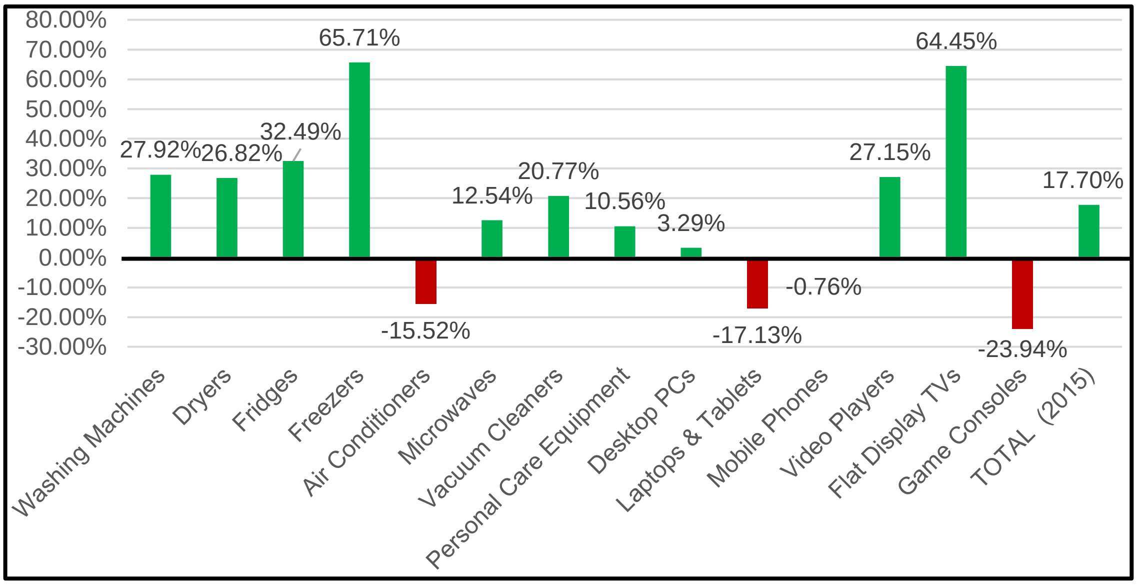

Figure 29 – Percentual change of neodymium in stock within Portugal between 2010 and 2015.

Between 2014 and 2015 the neodymium content within the system increased 2.52% on average, some equipment (mainly Tier III) even decreased, inferring that an increase is poised to continue, but possibly at a slower pace. Knowing the importance of NdFeB magnets for current technologies and the difficulty in finding equally performing substitutes, it's reasonable to assume that Nd demand is set to continue its increase in following years. If the current scenario (where almost no critical elements waste management is enforced) continues the system will become progressively more unsustainable and further away from the goal of achieving a circular economy regarding this specific highly critical element.

Considering the average lifespan of the studied UNU-keys (Table 21), it can be expected that the 2015 POM will stay in stock for an average of 9.3 years before reaching end-of-life (if only Tier I and II are considered, the average rises to 12.16).

Table 21 – Average lifetime of the selected UNU-Keys and the chosen tiers.

UNU Key	Average lifespan	UNU Key	Average lifespan
0104 – Washing machines	11.96	**0205 – Personal care equipment**	7.62
0105 – Dryers	13.97	**0302 – Desktop PCs**	8
0108 – Fridges	16.4	**0303 – Laptops (incl. tablets)**	6.08
0109 – Freezers	17.2	**0306 – Mobile phones**	5.07
0111 – Air conditioners	7.4	**0404 – Video and projectors**	7.95
0114 – Microwaves	8.33	**0408 – Flat display TVs**	10.41
0204 – Vacuum cleaners	9.92	**0702 – Game consoles**	4.56
Average lifetime of tier I and II	12.16	**Average lifetime of tier III**	7.09
Overall average lifetime			9.30

Even if neodymium POM would be null for subsequent years, there's already over 430 tonnes within the system, considerable amounts of Nd-containing WEEE would continue to be generated each year, at least until 2024. Since neodymium POM from 2015 onwards will probably continue to surge, by consequence the amount of waste generated will increase as well, an ever-growing urban mine containing tonnes of highly demanded critical elements is being left unexploited.

4.2.2 Waste Generated – Does it Correlate with POM & Stock?

The waste generated each year echoes past POM figures, thus waste generation proportions (i.e. the amount of neodymium present per UNU-key) can differ from recent POM and stock results. Yet, if neodymium recovery would be performed considering 2015 waste generated, the equipments that yield the largest quantity are the same as previously proposed (Fig. 30).

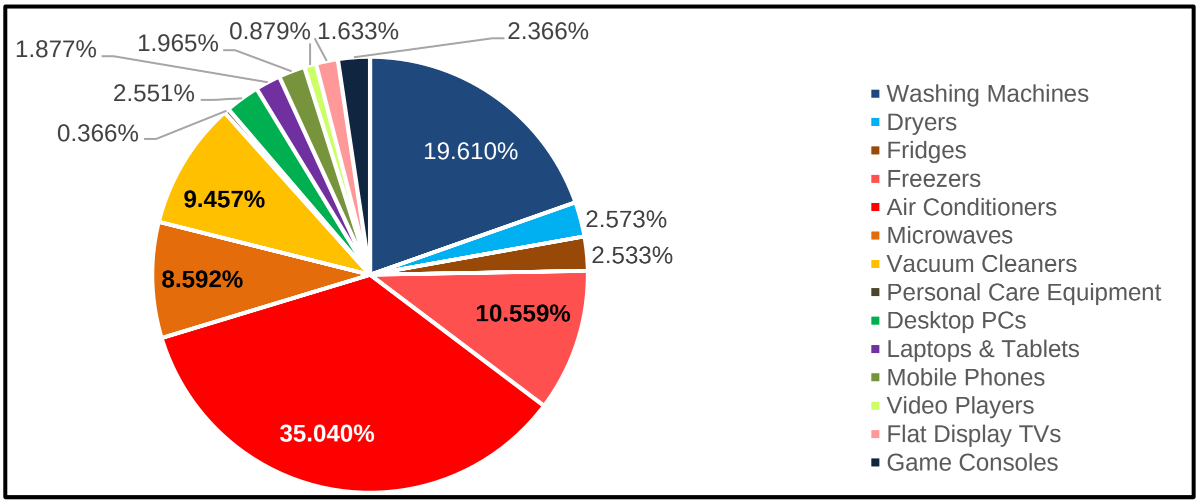

Figure 30 – Pie chart depicting the percentage (per UNU-key) of the total neodymium present in the waste generated (37 665 kg) at 2015.

The previously created 3-Tier classification is valid and applies to not only to POM and stock but to current WEEE data as well. Since the proposed classification is valid across the three main processes it can be concluded that, on average, 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 neodymium (Tier I and II).

4.2.3 WEEE Management & Potential Recovery by Recycling

Although POM and stock are excellent indicators for the urban mine status in forthcoming years, it's the waste generation that defines the present urban mine. By analysing 2015 (and historical years) waste generation it is possible to describe the state of the urban mine in that year (Table 22 and Fig. 31). Additionally, by analysing the collection and recovery rates it is also possible to appraise the waste management effectiveness towards achieving a circular economy.

It should be reminded that performing substance flow analysis on Waste Management processes with limited information available will not deliver accurate results. Firstly, the "not collected" indicator is very difficult to interpret as it's mainly based on the difference between projected (waste generated) and reported (collected) data. It can have innumerable interpretations: over or under-projections, lower or longer lifetimes than expected, hibernating stocks, officious collection of junk yards, et cetera. Reality is probably an immeasurable incorporation of all the factors referred above.

Moreover, the method used to appraise waste management is entirely independent from the previous records. E.g. if a given quantity of WEEE is considered 'Not Collected' in one year, but is collected in the ensuing, this method will identify it as waste generated and collected on the collection year, rather than the generation year. The "Not Collected" data from the previous year remains unchanged even though a part of it was eventually collected. This can greatly influence the 'Unexplored Urban Mine' prospection, as it considered as a cumulative sum of uncollected WEEE from the past until the evaluation year.

Also, during Recovery, equipments are usually disassembled and its components separated into different post-processes. Since there isn't any data regarding where each specific component starts and terminates, it's not possible to accurately follow the recovery path of neodymium in a way that's possible to trace it back to its equipment of origin (a necessary requirement to perform a flow analysis). The chosen solution is a simulation of all recovery processes considering that no disassembly is done during any of the processes. In short, instead of considering as an 'accurate depiction', all Waste Management results should be treated as a useful presumption (with a high level of uncertainty) for the amount of neodymium that can potentially be present within each waste-related process.

Table 22 – Neodymium present within WEEE management processes (in kg of neodymium), percentages depicted are relative to waste generated.

UNU Key	Waste generated	Municipal waste	Not collected	Collected	Landfilled	Recovered	Other reco. methods	Prep. for recy. and reuse
	Waste generated							
				Collected				
						Recovered		
0104 –Washing machines	**7 386**	148 (2%)	4 210 (57%)	3 028 (41%)	182 (2.46%)	2 846 (38.5%)	424 (5.74%)	2 422 (32.8%)
0105 –Dryers	**969**	19 (2%)	553 (57%)	397 (41%)	24 (2.46%)	373 (38.5%)	56 (5.74%)	318 (32.8%)
0108 –Fridges	**954**	0 (0%)	601 (63%)	353 (37%)	21 (2.22%)	332 (34.8%)	49 (5.18%)	282 (29.6%)
0109 –Freezers	**3 977**	0 (0%)	2 505 (63%)	1 472 (37%)	88 (2.22%)	1 384 (34.8%)	206 (5.18%)	1 178 (29.6%)
0111 –Air conditioners	**13 198**	0 (0%)	8 315 (63%)	4 883 (37%)	293 (2.22%)	4 590 (34.8%)	684 (5.18%)	3 906 (29.6%)
0114 –Microwaves	**3 236**	744 (23%)	1 392 (43%)	1 100 (34%)	66 (2.04%)	1 034 (32%)	154 (4.76%)	880 (27.2%)
0204 –Vacuum cleaners	**3 562**	819 (23%)	1 532 (43%)	1 211 (34%)	85 (2.38%)	1 126 (31.6%)	157(4.42%)	969 (27.2%)
0205 –Personal care eq.	**138**	32 (23%)	59 (43%)	47 (34%)	3 (2.38%)	44 (31.7%)	6 (4.43%)	38 (27.2%)
0302 –Desktop PCs	**961**	221 (23%)	346 (36%)	394 (41%)	32 (3.33%)	362 (37.7%)	39 (4.06%)	323 (33.6%)
0303 –Laptops & tablets	**707**	14 (2%)	537 (76%)	156 (22%)	12 (1.77%)	144 (20.3%)	16 (2.21%)	128 (18.1%)
0306 –Mobile phones	**740**	170 (23%)	267 (36%)	303 (41%)	24 (3.28%)	279 (37.7%)	30 (4.09%)	248 (33.6%)
0404 –Video	**331**	76 (2%)	142 (43%)	113 (34%)	15 (4.44%)	98 (29.7%)	7 (2.05%)	92 (27.7%)
0408 –Flat display TVs	**615**	12 (2%)	468 (76%)	135 (22%)	18 (2.85%)	117 (19.1%)	8 (1.32%)	109 (17.8%)
0702 –Game consoles	**891**	205 (23%)	321 (36%)	365 (41%)	29 (3.28%)	336 (37.7%)	37 (4.10%)	299 (33.6%)
TOTAL	**37 665**	2 460 (6.5%)	21 248 (56.4%)	13 957 (37.1%)	892 (2.4%)	13 065 (34.7%)	1872 (5%)	11 192 (29.7%)

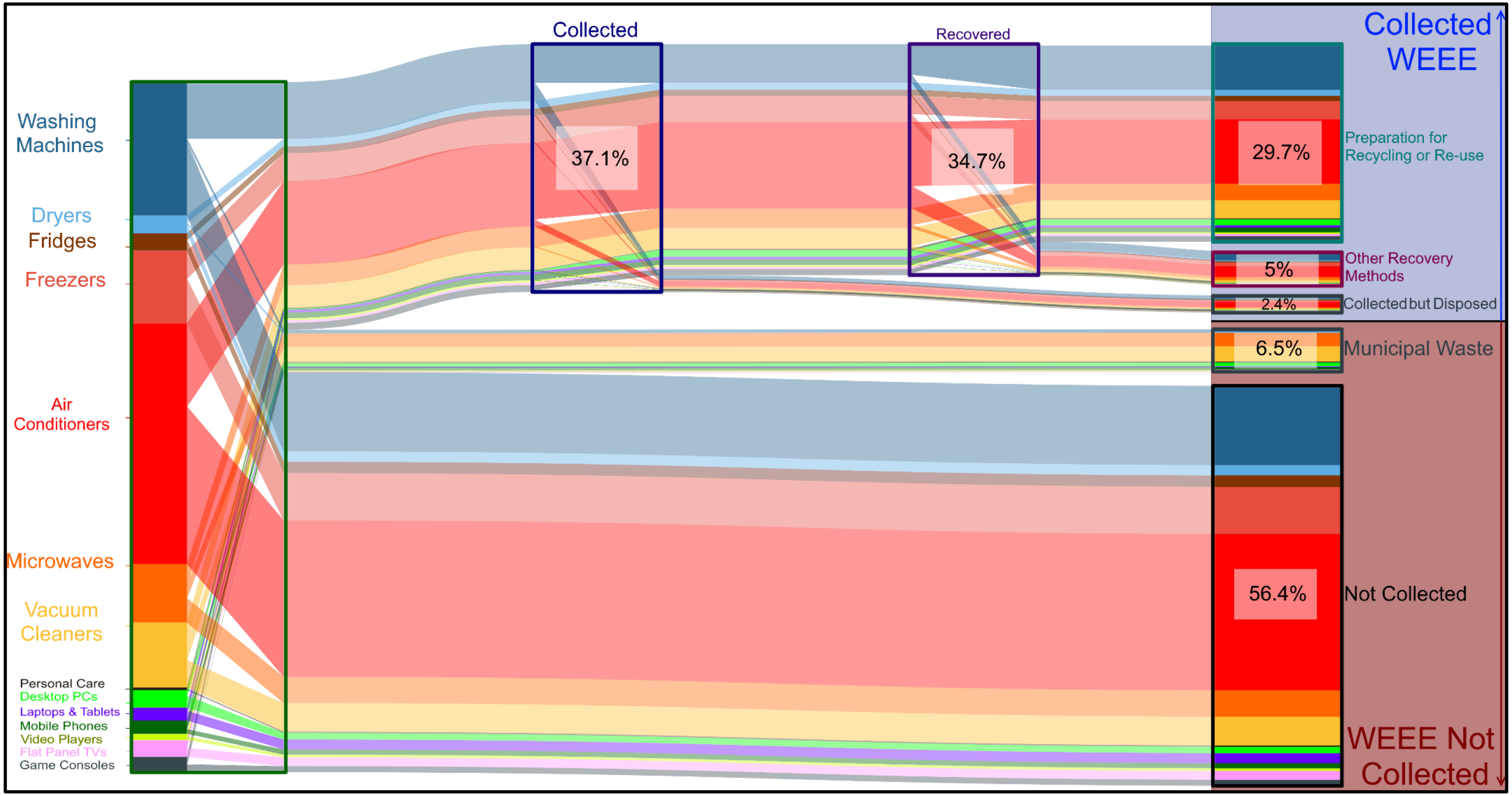

Figure 31 – Sankey diagram representing WEEE flows of the selected UNU-keys in percentage of neodymium out of the total present in WEEE generated in 2015 (37 665 kg).

According to the results (Fig. 32 and 33), in 2015 over 37 tonnes of neodymium were present within WEEE, out of it only 14 (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.

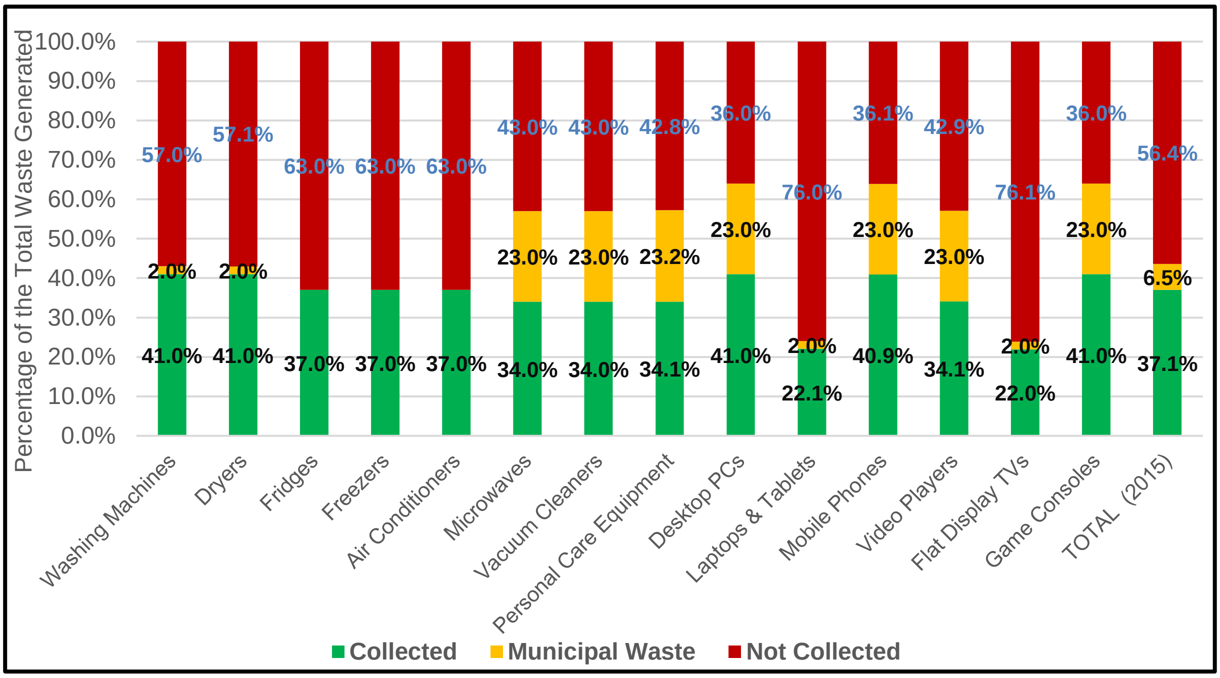

Figure 32 – Portuguese WEEE rates (collected, municipal waste and not collected) in 2015.

A total of ~23 tonnes out of all neodymium within WEEE are in an unknown situation or were disposed in landfills (or around 49% of the same year's POM). Tier I and Tier II contain around 20 of the uncollected tonnes (or 43% of the total POM). Large 'not collected' figures are decidedly undesirable, as it not only signifies that the location of high amounts of WEEE are unknown, but also that vast quantities of recoverable elements are being left unexploited in a world where its demand is increasing, and primary production can hardly cover it.

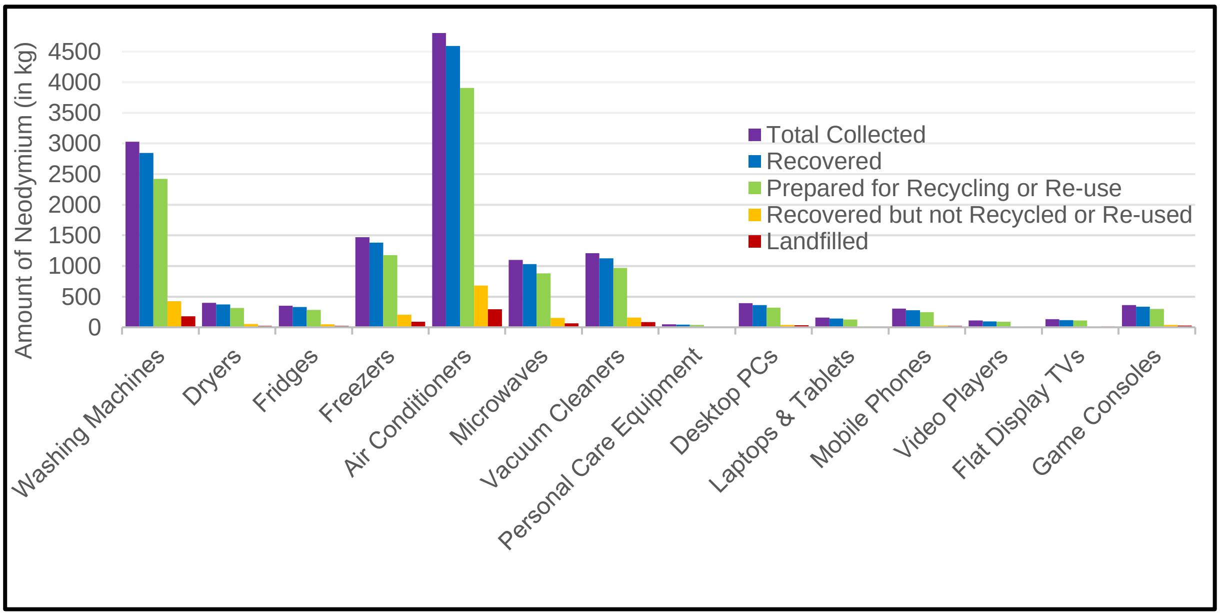

Figure 33 - Neodymium present within WEEE in recovery routes.

From 14 tonnes of neodymium within ‘collected WEEE’, an estimated 13 tonnes enters in recovery paths. Out of those 13 tonnes an estimated 11 tonnes are within WEEE being prepared for Reuse and Recycling. Note that, the recycling rate of neodymium is below 1% worldwide and currently there aren’t economically viable recycling procedures, so even if element could be traced further, the secondary metal output would be null. Still, there’s inherent amounts of neodymium present within the equipments going through those recovery steps, by measuring that value it’s possible to determine the amount of neodymium that could be potentially recycled if there were effective recycling methods.

Assuming no reuse and considering 2015 rates an estimated maximum of 11.2 tonnes could have potentially been recovered if Nd recycling was performed, this is around 23% of 2015 demand for neodymium in Portugal (POM).

4.2.4 Neodymium Recovery by Reuse

As known, no neodymium recycling is performed, however 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 to reuse in new or refurbished devices (Table 23).

Table 23 – Components within Tier I and II UNU-Keys that employ neodymium magnets [2].

UNU Key	Usual components that contain NdFeB magnets
0104 – Washing machines	Electrical Motor
0105 – Dryers	Electrical Motor
0108 – Fridges	Compressor
0109 – Freezers	Compressor
0111 – Air conditioners	Electrical Motor, Compressor
0114 – Microwaves	Magnetron, Electrical Motor
0204 – Vacuum cleaners	Electrical Motor

It’s highly plausible that large amounts of Nd from WEEE are being recovered and re-introduced in the system through the reuse of components in refurbished or new equipments. Considering a best--case scenario, where recovery is highly efficient, all components are effectively separated and disassembled, it can be assumed that those 11 tonnes of Nd could have been recovered and re-introduced in the market through reuse. And the ‘not collected’ fraction that ends in scrapyards also counts for the amount of neodymium being recovered by reuse.

Unfortunately, there’re no data available indicating the amount of Nd being recovered through components reuse, thus it’s not possible to appraise and quantify it. Nevertheless, it is acknowledged that an unknown, yet substantial, amount of Nd is being recovered through reuse.

4.2.5 Neodymium’s Unexploited Urban Mine

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. The ‘unexploited’ fraction of an urban mine can be described as the sum of the waste generated through the years, that’s considered ‘not collected’ or ends landfill.

During the period of 2010-2015 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 (POM) for the element in the same year (Table 24). 64 tonnes were reported as collected, out of it 51.6 tonnes could have been potentially recovered (knowing that around 80% of the amount collected is prepared for reuse and recycling), a little over 2015 demands (around 48 tons) [59].

However, over 141 tonnes of the waste generated did not even enter recovery facilities (17.8 were presumably landfilled and over 123 tonnes are in an unknown situation). 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 24).

Table 24 – Waste generation statistics between 2010 and 2015 [2].

Year	*2010*	*2011*	*2012**	*2013*	*2014*	*2015*	*2010-2015*
Total waste generated (kg)	30 187	33 020	33 899	34 695	36 089	37 665	205 555
Collected %	28%	35%	25%	28%	34%	37.1%	31.2%
Not collected %	62%	56%	66%	63%	58%	56.4%	60.2%
Municipal waste %	10%	9%	9%	9%	9%	6.5%	8.8%
Collected (kg of Nd)	8 452	11 557	8 475	9 715	12 270	13 957	64 426
Not collected (kg of Nd)	18 716	18 491	22 373	21 858	20 931	21 248	123 618
Municipal waste (kg of Nd)	3 019	2 972	3 051	3 123	3 248	2 460	17 872

*Note that the collection rate abrupt reduction in 2012 is due to Portugal’s 2011 financial crisis.

Note that, this evaluation only covers waste generation during a period of five years, whereas neodymium-bearing equipments have been entering in the market for longer, the effective amount of the element existing within uncollected waste could be considerably larger. At the same time considering the “not collected” data unreliability, claims regarding the unrecovered amount of neodymium within the system cannot be considered as accurate depictions, nevertheless it indorses that considerable amounts are available within uncollected WEEE.

4.2.6 The System in a Nutshell

Considering solely the evaluation year, it's estimated that the amount of neodymium within WEEE generated could potentially cover around 71% of its national demand (Fig. 34). But the total amount of Nd that entered the market still exceeds the waste generated in about 10 tonnes (48 POM vs 38 WG), meaning that there is more element present within equipments entering the market than leaving it, i.e. the neodymium stock is growing in the system.

However, as previously referred, an urban mine is defined by the waste generated through historical years and its future is determined by stock and POM, and considering these factors, the amount present in uncollected waste can potentially exceed the demand multiple times. For instance, the waste generated in the period of 2010-2015 could potentially sustain 2015 Portugal 4.25 times (Table 24).

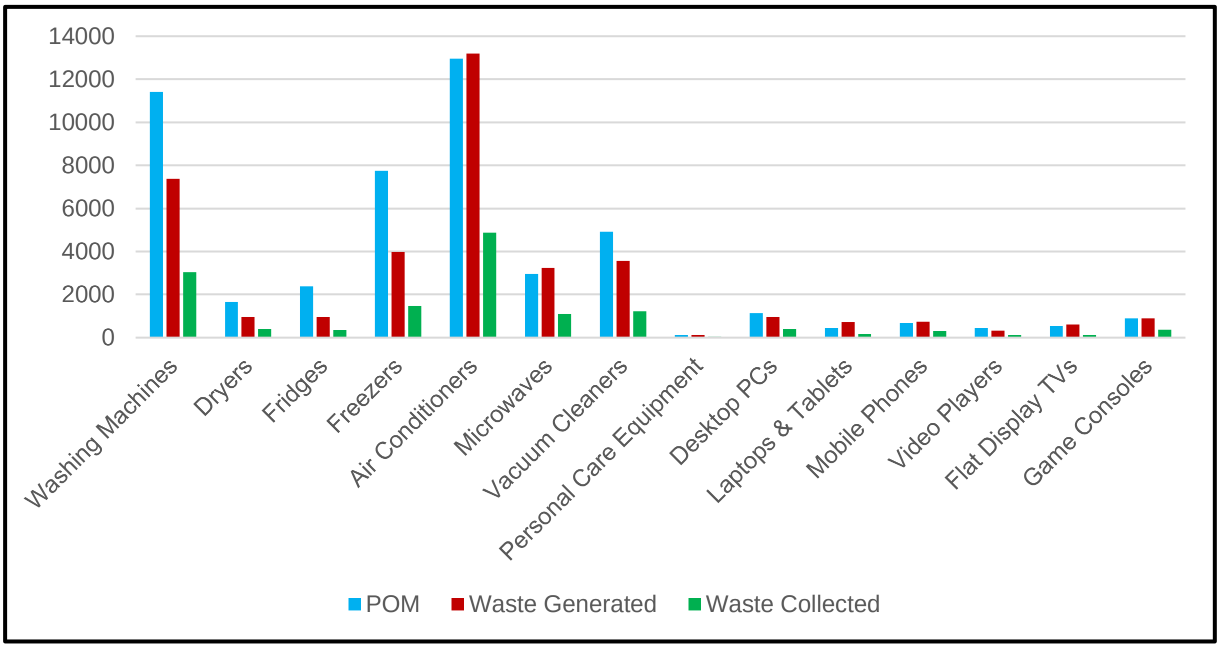

Figure 34 – Comparison of POM with waste generated and collected in 2015.

With the Portuguese modest collection rate (only around 37% of the waste generated is collected), the amount of neodymium that could have been potentially recovered drops to about 29% of its national demand (up to 56% of the waste generated, or 43% of POM, is in an unknown location). This value further decreases to 23% (of POM), assuming that, just ~80% of the waste collected eventually enters on the final recovery routes (the rest being presumably disposed).

Since it is known that no neodymium recycling is performed, the only way the element can currently be recovered is through reuse, however there's no information available regarding magnets reuse in Portugal. Yet it is credible that a substantial amount is being recovered through reuse in recovery facilities and officious scrapyards. Table 25 depicts Portugal neodymium WEEE urban mine prospection results for the year of 2015.

Table 25 – 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	~14 (29%)	Unknown
Recycling (2015)	~11.2 (23%)	None
Reuse (2015)	>11.2* (>23%)	Unknown, but substantial
POM 2015	~48	NA
Stock 2015	~432	NA

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

4.3 Improving Collection Rates

Analysing Tier I and II WEEE (Table 26), besides vacuum cleaners, all equipments are large with high Nd content and relatively low number of units, thus its management and collection should not be troublesome to control. It should not be difficult to track and avoid its disposal in incorrect locations and increase its collection rate, by promoting good practices and improving the collection efficiency.

Table 26 – Table depicting Tier I and II equipment and its general waste characteristics.

UNU Key	**2015 WG (in units)**	**Average weight in 2012-2015 (kg/unit)**	**Nd content per device (kg/unit)**	**Amount of Nd in not collected devices (kg)**	**Amount of Nd in collected devices (kg)**
0104 – Washing machines	51 829	71.5	0.1425	4 358	3 028
0105 – Dryers	6 680	43.5	0.145	572	397
0108 – Fridges	16 735	54.1	0.057	601	353
0109 – Freezers	34 288	43.3	0.116	2 505	1 472
0111 – Air conditioners	185 241	25.2	0.07125	8 315	4 883
0114 – Microwaves	101 427	22.2	0.0319	2 136	1 100
0204 – Vacuum cleaners	136 493	5.8	0.0261	2 351	1 211
Total / average	532 694	37.9	0.084	20 838	12 444

Knowing that a 100% collection rate is utopian, two European nations (Belgium and Sweden) were used to benchmark Portuguese rates. These scenarios are used to appraise how much an improved collection would affect a hypothetical recovery considering the same amounts of waste generated as 2015. Belgium values represent a rate that can be plausibly achieved by Portugal with minor improvements, whereas Sweden rates represent a more optimistic scenario, yet not impossible to achieve with appropriate policies (Fig. 35).

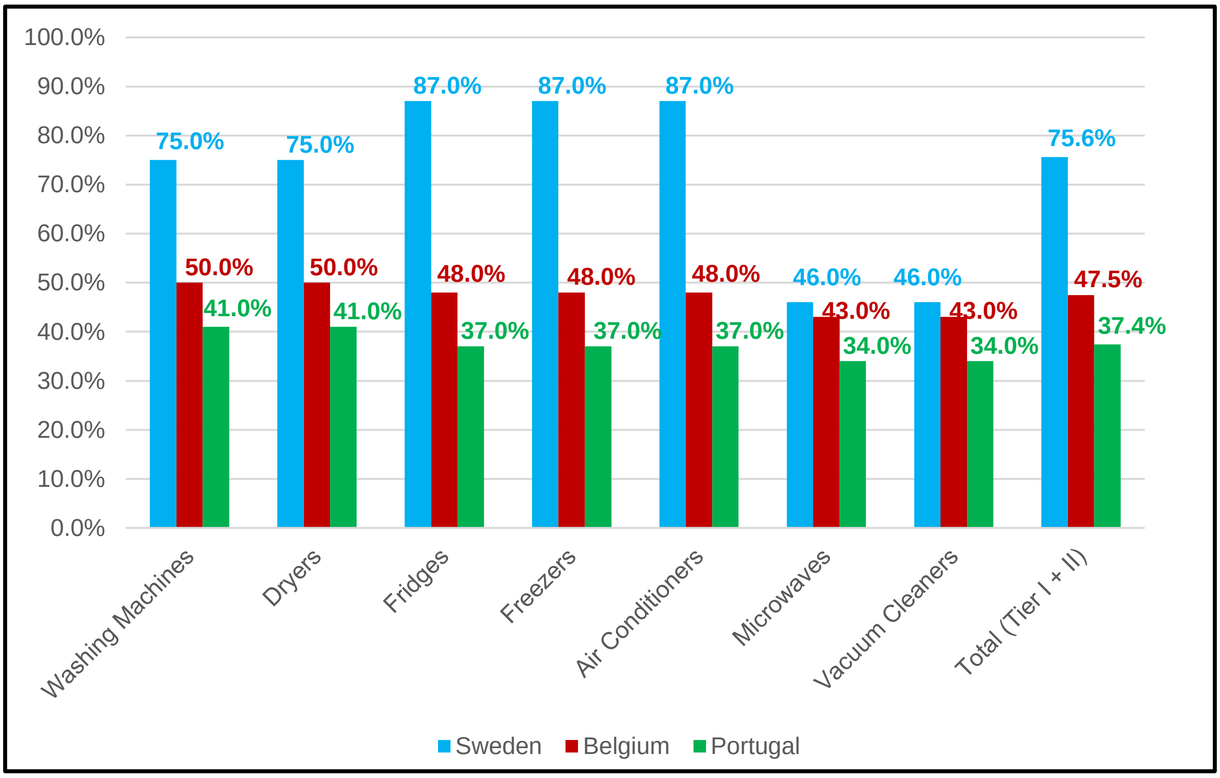

Figure 35 – Collection rates for tier I + II UNU-keys in Portugal, Belgium and Sweden in 2015.

Considering that the improvements are only applied to Tier I and II equipments (leaving Tier III rates unchanged) the amount of neodymium collected would rise to around 15.8 tonnes (from 12.4), if Portugal would achieve Belgium rates (an 13% increase on average).

Achieving Belgian rates just for Tier I and II would allow Portugal to potentially cover 35% its neodymium demand (assuming all collected amount could be recovered). If Portugal would achieve the Swedish rates, the recovery could theoretically climb to around 55% of its POM, this means that more than half of the Portuguese neodymium demand could be supplied by secondary sources (Table 27).

Note that, category I (temperature exchange equipments) and IV (large equipments) have very high rates in nations with good collection policies (e.g. Sweden), this endorses the claim that it is possible for Portugal to achieve much higher collection rates for Tier I and II equipments. And since, these are also the categories that have the potential to hold most of the neodymium within a given system, a targeted collection improvement just on these specific devices could increase the yield greatly.

Table 27 - Comparing tier I and II combined average collection rates and potential neodymium yield (considering the Portuguese waste generated) between Portugal, Belgium and Sweden in 2015 [2].

Average collection rate for tier I and II (2015)	**Neodymium in Recovery Facilities (kg)**	**Percentage of POM covered**
Portugal – 34.5%	12 444	29%
Belgium – 47.5%	15 803	35%
Sweden – 75.6 %	25 166	55%

4.4 Neodymium Recycling Viability

Neodymium recycling endeavours are currently driven by academia rather than industrial or governmental entities, mostly because the element is still not exceedingly expensive, so recycling is not economically feasible. Yet, remembering the example of Solv*ay's REE* recycling plant at La Rochelle, it is known that external stimuli (i.e. sharp price increase) can force an industry to invest in recycling.

Neodymium's demand is expected to increase due to the rapid dissemination of technologies that depend on NdFeB magnets, it is reasonable to assume that primary production would not be able to sustain such high demands and the price will rise, favouring large-scale recycling endeavours (Fig 36). It's suggested that the price of neodymium will continue to increase through the years, by 2021 it will become the most expensive REE, reaching a projected price of 152€ per kg in 2025 (a 116% increase comparing with 2015's 70€/kg) [61].

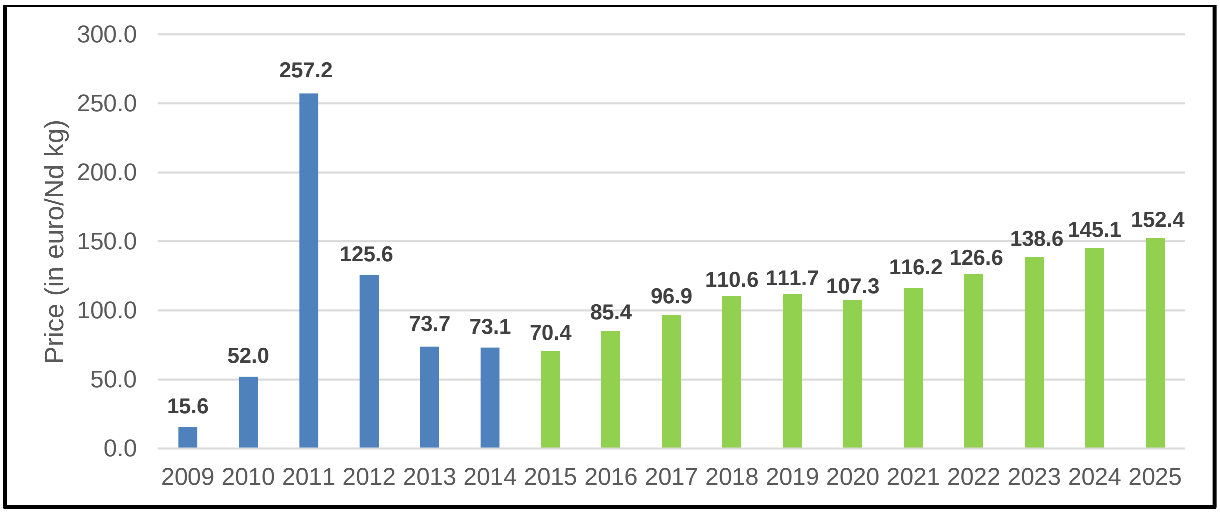

Figure 36 – Worldwide elemental neodymium price in eur/kg. (Colour green represents projections) [61]

A 2016 report simulated a large-scale Nd magnet recycling plant using the 'RE salt synthesis' method and concluded that such recycling endeavour would be unviable, at least considering the conditions in 2016. It stated that a recycling plant in New Mexico, USA, could produce 296 kg of neodymium per day, with a production cost of 385€ per kg at 90% plant capacity. The high manufacture cost is due to the necessary raw materials (H_3TriN_Ox and $K[N(SiMe_3)$ for the 'RE salt synthesis' method (the same report claims that 99% of the production cost come from raw materials acquisition).

In order to Nd recycling to be economically feasible, the metal price per kg would have to continue its increase and the raw materials price must decrease (or alternatively a novel inexpensive method created) [62].

If the expected 2025 neodymium price of 152€ per kg would be reached, only if the raw material cost would decrease to 100€ it would be possible to achieve an internal rate of return (IRR) of around 45% and the recycling would be feasible. Otherwise the price of Nd would have to surpass the 385€/kg production cost (a 450% increase from 2015 values) for an industrial recycling effort to produce a positive cash flow. Even with skyrocketing demand, only a large geopolitical event similar to China's 2011 embargoes could trigger such drastic rise [62].

Assuming recycling costs computed for 2016, Portuguese collection and prices from 2015 a potential neodymium recycling endeavour could give a loss up to 4.3 million euros. Whereas the most 'recycling favourable' scenario (2025 price of 152€, raw material cost of 100€ and Swedish collection rates), the income rough estimation would be around positive 1.3 million €, possibly low value that could not attract potential investors [62] (Table 28).

Table 28 – Neodymium recycling feasibility and potential profit or losses depending on the conditions [62].

Neodymium price (2015)	70.4 €/kg
Neodymium price (2025)	152.4 €/kg
Raw material for recycling (RM) Cost (2016)	385 €/kg
Raw material for recycling (RM) Cost (lower)	100 €/kg
Neodymium collected in 2015 (assuming PT rates)	13 957 kg
Neodymium collected in 2015 (assuming SW rates)	26 679 kg
Recycling cash flow (price 2015, PT rates, RM 2016) *	-4 390 872 €
Recycling cash flow (price 2025, SW rates, RM 45% ICC) *	+1 397 979 €

*Assuming the recycling process is 100% efficient, using the entire amount collected in 2015, and excluding collection costs.

Therefore, the most sensible solution for making neodymium recycling feasible, is to either reduce the price of the raw materials necessary to perform it or to work on a novel method that could reach much lower production costs [62].

And since the demand for Nd is almost entirely due to magnet manufacturing, therefore there could be a recovery alternative, whereas instead of recycling the element from EOL magnets, the magnet alloys could be re-melted. However, this alternative requires a careful selection of the source material, because neodymium magnets have large varieties of compositions depending on application. A direct magnet recycling approach would require a tight input composition control to ensure the recycled magnet has the correct composition, therefore requiring a more thorough collection and preparation.

4.5 Final Remarks

The whole interpretation was made assuming a semi-isolated system, but Portugal is an open nation within a political and economic union (European Union) and part of a globalized world. Conjecturing the results as a percentage of a nation's demand is a good exercise to study the recovery potential outcome, however most magnets (and EEE) industry is mostly produced outside of it.

Even if Portugal could recover those theoretical amounts, it would still lack the industrial power to manufacture and sustain the whole EEE demand using the recovered element. Neodymium recovery must be an international effort of collecting, recovery, and manufacturing of goods using secondary sources. It is in the European Union interests to reduce its critical elements reliance on unsafe sources such as China, lacking natural resources, the solution is secondary production.

These results are confidently analogous to the remaining European nations and confirm that there is an untapped urban mine waiting to be explored and transformed into usable raw materials freer of environmental hazards and geopolitical issues. Although results indicate that it is not possible to fully sustain a nation solely based on secondary neodymium sources indefinitely, it can ease the strain on primary production, reduce its supply risk by decreasing the reliability on unstable sources and promote a regenerative economy.

5. Conclusions

The main objective of this dissertation was to evaluate strategic metals envisaging the sustainable management. Key questions were then placed and answered throughout the document, being herein described the main conclusions achieved.

Objective 1 - Investigate Rare Earth Elements in a detailed manner to understand its criticality.

Rare Earth Elements are a group of elements that have unique atomic configurations which provides them peculiar properties. Some of these properties are extremely useful in applications such as Catalysts, Battery Alloys, Phosphors and Permanent Magnets (Research Question 1a).

REE atomic configuration also explains its complex production procedures. Rare Earth Oxides can easily substitute each other's within crystal lattices, making extremely difficult and expensive to refine. Moreover, despite being used in 'green technologies', REE extraction and refining have large environmental footprints, especially in regions surrounding production facilities as hazardous chemical compounds are required for its refining. Nevertheless, the biggest issue regarding REE is its supply risk. Over 80% of the world reserves and 95% of its primary production are in China. Other nations attempted primary production endeavours, but almost all went bankrupt since it is not possible to compete with the Chinese low-cost production due to cheap labour, illegal mines and lack of environmental policies. It effectively means that the Asian behemoth holds a quasi-monopoly of Rare Earths and that its supply chain is almost entirely determined by the nation's exportation policies. This was particularly evident in 2011 where the Chinese government enforced an export embargo to promote internal consumption, prompting worldwide REE prices to rise steeply. (Research Question 1b)

By consequence of the embargo, the European Commission, created entities like EuRare and ERECON to tackle REE criticality and study solutions to reduce the reliance on China. Three mainly suggested response strategies are:

- To reduce the REE content in its applications (e.g. fluorescent lights are being replaced by LED lighting which uses only fraction of RE);
- To use alternative RE-free technologies (e.g. RE-bearing NiMH batteries are currently being replaced with RE-free Lithium based batteries);
- To recover REE from EOL goods (e.g. in response to 2011 prices rise *Solvay* created a Fluorescent Lamp recycling plant to recover REE). (Research Question 1c).

Objective 2 - Analyse the demand for REE and identify which element is the most critical and will remain critical.

Reduction and substitution efforts are being successfully implemented in most REE applications. It is expected that in the near future almost every REE can be either fully replaced or just required in minute contents, effectively reducing its critical status and dependence on unstable supply chains.

However, there's one particular application that requires additional attention: neodymium Magnets. These magnets can achieve high-performance levels allowing technological breakthroughs such as miniaturization. There are alternatives such as ferrite, samarium-cobalt or praseodymium magnets, but none can achieve the same performance levels and some even use other critical elements. Even in state-of-the-art magnet research there's no equivalent RE-free alternative to neodymium, in conclusion, Nd is to be the most critical REE. (Research Question 2a)

Neodymium magnets are used in a variety of applications in the main being: turbines, EEE and EVs. Only considering the latter is estimated that by 2050 the demand for neodymium just for electrical/hybrid vehicles will be larger than the current worldwide demand for all REE collectively. In a nutshell, the demand for neodymium magnets is set to continue its increase through the years indefinitely until an effective alternative is encountered. (Research Question 2b)

Objective 3 - To study the anthropogenic incidence neodymium in Portugal, during 2015, using the method 'Material Flow Analysis' in order to prospect its potential recovery by urban mining.

The urban mines of Nd (and other critical elements) are being left unexplored, tonnes of waste containing strategical elements are not used, yet the demand for those elements remains high. With neodymium's demand expected to sharply increase and no valid alternative available, the only remaining solution to reduce its criticality and dependence on unreliable primary production is to invest in secondary production.

In order to study the potential that secondary production of a critical element could have in a nation's economic system (i.e. moving from a linear to a circular economy), this dissertation proposed to prospect the incidence of neodymium in Portugal for the year of 2015. Material Flow Analysis, a tool used to assess flows and stock of materials within a system, was the method chosen for this prospection. Firstly, the system boundaries were established, based on the data available it was determined that analysing the presence of the substance within magnets in Electric and Electronic Equipment in 2015 would provide the best setup for prospection, delivering the most meaningful results. Secondly, using available data: EEE POM from historical years until 2015; the average equipment weight and its lifetime distribution; and the average magnet weight/composition per EEE, it was possible to successfully simulate the prevalence of the element. Results showed that in 2015 over 48 tonnes of neodymium entered the market, joining for a total of 432 tonnes already present in Stock. On the same year, 38 tonnes of neodymium ended in waste generated, reportedly only 14 tonnes were collected, with the remaining 24 being either disposed or in an unknown condition. In conclusion, this method proved to be simple and efficient, and the output satisfactory, revealing to be a suitable technique to prospect critical elements within nationwide urban mines (Research Question 3a, 3b).

In case of an actual attempt to recover neodymium from WEEE, the prospection concluded that the element can be essentially pinpointed to 3 types of equipment: air conditioners, washing machines and freezers (Tier I), these hold collectively 67% of the total neodymium in stock. Additionally, microwaves, vacuum cleaners, dryers and fridges (Tire II) also hold substantial amounts of neodymium within the system (having around 26% of the total Nd stock). (Research Question 3c)

But an urban mine cannot be defined by a single year, it's the cumulative result of waste being generated through time. Assuming only 2015, the Portuguese neodymium Urban Mine could potentially yield up to 38 tonnes of neodymium, but in a 5-year span (2010-2015) the potential yield would rise to 205 tonnes. Since neodymium-bearing equipment has been entering for several years, the urban mine could theoretically yield much larger amounts. (Research Question 3d)

Assuming current collection and recovery rates, an estimated 11 tonnes of neodymium could have been recovered in 2015, only a small fraction of the total tonnage of waste generated (38). WEEE collection could be largely improved especially in larger equipments such as washing machines resulting in substantial impacts. It is shown that if Portugal could achieve the Swedish collection rates just for Tier I and II equipments, the amount of Nd collected would double. However, neodymium recycling of EOL magnets is currently not economically feasible, since it has high production costs (up to 385€ per recycled kg). The only method to which Nd can be currently recovered is through the reuse of EOL components like electrical motors, probably this process is implemented to some degree, but there aren't any data available to confirm this claim. Nonetheless, it's expected that, with increasing demand (and consequent surges in price) neodymium recovery will eventually be feasible. (Research Question 3e)

Ultimately, this prospection aimed to analyse the possibilities of a nation adopting a regenerative economy regarding strategic elements. And the conclusion is that, although due inefficient collection and rapidly increasing demand, it wouldn't be possible to fully sustain a nationwide 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 primary sources by recovering its collected neodymium (this value could increase to 55% in the best-case scenario). (Research Question 3f)

5.1 Challenges, Limitations and Future work

During development, all main challenges were related with data restriction, and by consequence some results have large inherent uncertainties. The major difficulty was obtaining the 'Average Magnet Weight' and 'Average Magnet Content' per equipment as there are few trustworthy sources. And while some reports provided empirical measures, most assumed values provided by unreferenced sources that were not critically evaluated.

As future work, it would favour future prospections of critical elements within EEE to pre-emptively construct a reliable database containing accurate average compositions per equipment class, containing when possible empirical measures, otherwise using input from multiple referenced sources.

Moreover, neodymium and EEE are not the only with high economic importance, being proven that this methodology can be successfully implemented to prospect critical elements within certain goods in a nation, it would be interesting to explore alternative prospecting scenarios. For instance, the prospection of critical elements such as neodymium within vehicles in Portugal.

References

[1] V. Zepf, "Rare Earth Elements: What and Where They Are," in *Rare Earth Elements, A New Approach to the Nexus of Supply, Demand and Use: Exemplified along the Use of Neodymium in Permanent Magnets*, Berlin, Springer, Berlin, Heidelberg, 2013, pp. 12-39.

[2] J. Huisman, P. Leroy, F. Tetre, M. L. Soederman, P. Chancerel, D. Cassard, A. N. Lovik, P. Waeger, D. Kushnir, R. S. Vera, P. Maehlitz, L. Herreras, J. Emmerich, A. Hallberg, H. Habib, M. Wagner and S. Downes, "Prospecting Secondary Raw Materials in the Urban Mine and Mining Wastes (ProSUM) - Final Report," European Union Horizon 2020, Brussels, 2017.

[3] C. NG, Nomenclature of Inorganic Chemistry: IUPAC Recommendations 2005. the Red book, Cambridge: Royal Society of Chemistry, 2005.

[4] C. Allègre, . G. Manhès and É. Lewin , "Chemical Composition of the Earth and the Volatility Control on Planetary Genetics.," Earth Planet Sci Lett, 2001, p. 49–69.

[5] R. Rudnick and S. Gao, "Composition of the Continental Crust.," in *Holland HD, Turekian KK (eds)Treatise on Geochemistry*, San Diego, Science and Technology Books, 2003, pp. 1-64.

[6] S. B. Castor and J. B. Hedrick, "Rare Earth Elements," in *Industrial Minerals & Rocks*, Littleton, Colorado, USA 80127, Society for Mining, Metallurgy, and Exploration, Inc (SME), 2006, pp. 769-192.

[7] B. Skinner, "A Second Iron Age Ahead?: The Distribution of Chemical Elements in the Earth's Crust Sets Natural Limits to Man's Supply of Metals that are Much More Important to the Future Of Society than Limits on Energy.," *Am Sci,* vol. 64, no. 3, pp. 258-269, 1976.

[8] A. Walters, P. Lusty, C. Chetwyn and C. Hill, "Rare Earth Elements," British Geological Survey, Natural Enviroment Research Council, Keyworh, Nottingham, NG12 5GG, United Kingdom, 2010.

[9] B. McLellan, G. Corder, A. Golev and S. Ali, "Sustainability of the Rare Earths Industry," *Procedia Environmental Science ,* vol. 20, pp. 280-287, 2014.

[10] A. Valkov, V. Sergievskiy and V. Sofronov, "Studies in the Field of Rare Earth Elements," *Procedia Chemistry,* vol. 11, pp. 171-175, 2014.

[11] S. Liyananadirah Mat, W. I. Wan Hanisah, A. A. Badhrulhisham and D. Mohd Rizauddin, "A Review of Rare Earth Mineral Processing Technology," *Chemical Engineering Research Bulletin,* vol. 19, no. Special Issue, p. 20.35, 2017.

[12] K. Binnemans, P. Jones and T. Blanpain, "Recycling of Rare Earths: A Critical Review," *Journal of Cleaner Production,* vol. 51, pp. 1-22, 2013.

[13] D. J. Cordier, "Rare Earths [Advance Release]," in *2009 Minerals Yearbook*, U.S. Geological Survey, U.S. Department of the Interior, 2011, pp. 60.1-60.15.

[14] Deloitte Sustainability; British Geological Survey; Bureau de Recherches Géologiques et Minières; Netherlands Organisation for Applied Scientific Research, “Study on the Review of the List of Critical Raw Materials (2017),” European Comission, Brussels, June 2017.

[15] k. Binnemans, P. Jones, K. Van Acker, B. Blanpain, B. Mishra and D. Apelian, “Rare-Earth Economics: The Balance Problem,” *Journal Of the Minerals, Metals & Materials Society,* vol. 65, pp. 846-848, 2013.

[16] F. Bea, “Geochemistry of the Lanthanide Elements,” in *XXXV Reunión de la Sociedad Española de Mineralogía*, Huelva, 2015.

[17] G. Blengini, D. Blagoeva, J. Dewulf, C. Torres de Matos, V. Nita, B. Vidal-Legaz, C. Latunussa, Y. Kayam, L. Talens Peirò, C. Baranzelli, L. Mancini, Nuss, P. Nuss, A. Marmier, P. Alves-Dias, C. Pavel, E. Tzimas, F. Mathieux, D. Pennington and C. Ciupagea, “Assessment of the Methodology for Establishing the EU List of Critical Raw Materials - Background Report,” Publications Office of the European Union, Luxembourg, 2017.

[18] Deloitte Sustainability, British Geological Survey, , “Study on the Review of the List of Critical Raw Materials - Critical Raw Materials Factsheets, Bureau de Recherches Géologiques et Minières, Netherlands Organisation for Applied Scientific Research,” European Comission , B-1049 Brussels, 2017.

[19] S. Massari and M. Ruberti, “Rare Earth Elements as Critical Raw Materials: Focus on international Markers and future strategies,” *Resources Policy,* vol. 28, pp. 36-43, 2013.

[20] G. Charalampides, K. I. Vatalis, B. Apostoplos and B. Ploutarch-Nikolas, “Rare Earth Elements: Industrial Applications and Economic Dependency of Europe,” in *International Conference on Applied Economics (ICOAE)* , Kazan, Russia, 2015.

[21] European Rare Earths Competency Network (ERECON), “Strenghtening the European Rare Earths Supply-Chain Challenges and policy options,” European Commission, Brussels, 2015.

[22] EURARE, “Development of a Sustainable Exploitation Scheme for European Rare Earth Ore Deposits: European REE Market Survey - task 1.1.2,” European Commission, Brussels, 2017.

[23] E. Machacek and P. Kalvig, “Assessing Advanced Rare Earth Element-Bearing Deposits for Industrial,” *Resources Policy,* vol. 49, pp. 186-203, 2016.

[24] J. Gambogi, “2015 Minerals Yearbook: Rare Earths [Advanced Release],” USGS, 2018.

[25] USGS, “Rare Earths: Mineral Commodity Summaries 2015,” USGS, 2015.

[26] USGS, “Rare Earths: Mineral Commodity Summaries,” USGS, 2018.

[27] USGS, “Yttrium: Mineral Commodity Summaries,” USGS, 2015.

[28] USGS, “Yttrium: Mineral Commodity Summaries,” USGS, 2018.

[29] EURARE, “Research and Development for the Rare Earth Element Supply Chain in Europe,” European Commission, 2017.

[30] Z. Weng, N. Haque, G. M. Mudd and S. M. Jowitt, “Assessing the Energy Requirements and Global Warming Potential of the Production of Rare Earth Elements,” *Journal of Cleaner Production,* no. 139, pp. 1282-1297, 2016.

[31] M. Ikhlayel, “Evaluation of the Environmental Impacts of Rare Earth Elements Production,” *International Journal of Environmental Studies,* vol. 74, no. 6, pp. 939-957, 2017.

[32] Roskill, “Rare Earths Global Industrym Markets & Outlook,” Roskill, London, 2017.

[33] Adamas Intelligence, “Rare Earth Market Outlook to 2025,” Adamas Intelligence, Ontario, 2016.

[34] K. Binnemans, P. Jones, T. Mueller and L. Yurramendi, “Rare Earths and the Balance Problem: How to Deal with Changing Markets?,” *Journal of Sustainable Metallurgy ,* vol. 2018, no. 4, pp. 126-146, 2018.

[35] H. Nakamura, “The Current and Future Status of Rare Earth Permanent Magnets,” *Scripta Materialia,* 2017.

[36] J. J. Anderson, “Structural and Magnetic Properties of Neodymium-Iron-Boron clusters,” University of Nebraska, Lincoln, 2010.

[37] J. Lucas, P. Lucas, T. Le mercier, A. Rollat and W. Davenport, Rare Earths: Science, Technology, production and Use, Elsevier, 2015.

[38] A. Akah, “Application of Rare Earths in Fluid Catalytic Cracking: A review,” *JOURNAL OF RARE EARTHS,* vol. 35, no. 10, p. 941, 2017.

[39] P. J. Walsh, “Fluorescent Lighting Is Introduced.,” in *Salem Press Encyclopedia*, Salem Press, 2013.

[40] N. Wang, “Preparation of LaPO:Ce3+. Tb3+ Nanophosphors by Mixed Co-Precipitation Process and their Photoluminescence Properties,” *Ceramics International,* vol. 40, pp. 1653-16258, 2014.

[41] A. Vecht, “Preparation and Investigation of Phosphors for Emissive Displays: Final Technical report,” European research office of the US Army, London, 1996.

[42] E. Machacek, “Recycling of Rare Earths from Fluorescent Lamps: Value Analysis of Closing-The-Loop Under Demand and Supply Uncertainties.,” *Resources, Conservation and Recycling,* no. 104, pp. 76-93, 2015.

[43] P. H. L. Notten, “Nickel-Metal Hydride Batteries: From Concept to Characteristics,” *Chem. Ind.,* vol. 54, no. 3, pp. 102-115, 2000.

[44] P. Desai, *Tesla's Electric Motor Shift to Spur Demand for Rare Earth Neodymium,* Reuters, 2018.

[45] S. M. Jowitt and T. T. Werner, “Recycling of the Rare Earth Elements,” *Current Opinion in Green and Sustainable Chemistry,* 2018.

[46] D. Schueler, M. Buchert, R. Liu, S. Dittrich and C. Merz, “Study on Rare Earths and Their Recycling: Final Report for The Greens/EFA Group in the European Parliament,” Öko-Institut e.V., Darmstadt , 2011.

[47] H. P. Brunner and H. Rechberger, Pratical Handbook of Material Flows Analysis, Florida: Lewis Publishers, 2004.

[48] E. Mueller, L. M. Hilty, R. Widmer, M. Schuep and M. Faulstich, “Modelling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods,” *Enviromental Science & Technology,* 2014.

[49] J. Huisman, H. Habib, V. S. Rotter, P. Maehlitz, N. Korf, P. Chancerel, D. Kushnir, M. L. Soederman, A. Loevik, K. Baldé and V. Straalen, “Prospecting Secondary Raw Materials in the Urban Mine and Mining Waste - Historic and Current Stocks Deliverable 3.1,” European Union, 2016.

[50] F. Magalini, F. Wang, J. Huisman, R. Kuehr, K. Baldé, V. van Straalen, M. Hestin, L. Lecerf, U. Sayman and O. Akpulat, “Study On Collection Rates of Waste Electrical and Electronic Equipment (WEEE) - Possible Measures to be Initiated by the Comission as Required by Article 7 (4), 7 (5), 7 (6) and 7 (7) of Directive 2012/19/EU on Waste Electrical and Electronic Equipment,” European Comission, Brussels, 2014.

[51] BIO Intelligence Service for European Commission , “Review of the Scope of the Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE) Final report,” BIO Intelligence Service 2013, Paris Île de France, 2013.

[52] european weee registers network, “WEEE2 – Definition and Understanding of the 6 Categories (15.08.2018),” European weee registers network, Fuerth, 2017.

[53] K. Habib, P. K. Schibye, A. P. Vestbo, O. Dall and H. Wenzel, “Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach,” *Enviromental Science & Technology,* vol. 48, pp. 12229-12237, 2014.

[54] V. Van Straalen, A. Roskam and C. Baldé, “Waste Over Time Script,” Statistics Netherlands, 2017.

[55] Y. Seo and S. Morimoto, “Comparison of Dysprosium Security Strategies in Japan for 2010-2030,” *Resources Policy,* vol. 39, pp. 15-20, 2014.

[56] N. Sekine, I. Daigo and Y. Goto, “Dynamic Substance Flow Analysis of Neodymium and Dysprosium Associated with Neodymium Magnets in japan,” *Journal of Industrial Ecology,* vol. 21, no. 2, pp. 356 - 367, 2016.

[57] A. Lixandru, P. Venkatesan, C. Joesson, I. Poenaru, B. Hall, Y. Yang, A. Walton, K. Gueth, R. Gauß and O. Gutfleisch, “Identification and Recovery of Rare-Earth Permanent Magnets from Waste Electrical and Electronic Equipment,” *Waste Management,* vol. 68, pp. 482 - 489, 2017.

[58] Baldé, K.; Meeuwissen, H.; Magalini, F.; Wang, F.; Statistics Netherlands; United Nations University; Bio Inteligence Service; Regional Enviromental Center, *WEEE calculation tool,* European Comission, 2017.

[59] Agência Portuguesa do Ambiente, "[Portuguese] Resíduos de Equipamentos Elétricos e Eetrónicos (REEE)," Agência Portuguesa do Ambiente, 2016.

[60] R. Schulze and M. Buchert, "Estimates of Global REE Recycling Potentials from NdFeB Magnet Material," *Resources, Conservation and Recycling,* vol. 113, pp. 12-27, 2016.

[61] Stormcrow Capital Ltd, "Industry Report // Rare Earths: Initiating Sector Coverage - The Rare Earths Market Keeps Changing," Stormcrow Capital Ltd, Canada, 2014.

[62] A. X. Dai, C. A. Lippincott, M. E. Nissan and R. Shim, "Recycling of Neodymium and Dysprosium from Permanent Magnets," Senior Design Reports (CBE), University of Pennsylvania, Pennsylvania, 2016.

Appendix

Appendix A – EU 2012/19/EU (recast) Directive on WEEE

I. **Temperature Exchange Equipment (TEE)** – EEE with internal circuits where substances other than water are used for cooling/heating and/or dehumidifying [51, 52].
   a. **Examples**: Refrigerators, Freezers, Air-conditioning and dehumidifying equipment, oil radiators [51, 52].
   b. **Not Included**: Ventilation/infrared equipment, water radiators [51, 52].

II. **Screen, monitors and equipment containing screens w/ surface greater than 100cm^2 –** EEE that's intended to provide information on an electronic display i.e. Cathode Ray Tube (CRT), Liquid Crystal Displays (LCD), Light-emitting Diode Display (LED) [51, 52].
   a. **Examples:** Screens, Televisions, LCD photo frames, Monitors. Also, Laptops, Notebooks, Tablets and eBook Readers with screen surfaces greater than 100cm^2.
   b. **Not included:** All small IT equipment such as smartphones, GPS, telephones. Not all equipment with screen area over 100 cm^2 are eligible, the equipment usage focus must be in information displaying, thus some household appliances are not included [51, 52].

III. **Lamps –** Equipment of any size that generates light using electrical light sources and that can be installed or exchanged by the end-user [51, 52].
   a. **Examples:** tubular fluorescent lamps, fluorescent lamps, compact fluorescent lamps, high-intensity discharge lamps, low pressure sodium lamps, LED lamps [51, 52].
   b. **Not Included:** luminaries/light fixtures [51, 52].

IV. **Large Equipment (any external dimension more than 50 cm) –** Any EEE that's not allocated in category I, II or III and have any of the external dimensions (width, height, depth) larger than 50 cm. The dimensions must be measured when the equipment is assembled [51, 52].
   a. **Examples:** washing machines, clothes dryers, dish washing machines, cookers, electric stoves, light fixtures, sound/image reproducing equipment, large computers mainframes, medical devices, household appliances [51, 52].
   b. **Not Included:** Any equipment that is included in category I, II or III such as, refrigerated vending machines, large lamps, large screens [51, 52].

V. **Small Equipment (no external dimension more than 50 cm) –** Any EEE that's not in category I, II, III, IV or VI and any external dimension (width, height, depth) lower than 50 cm [51, 52].
   a. **Examples:** vacuum cleaner, light fixtures, microwaves, ventilation equipment, sound/image reproducing equipment, electrical tools, medical devices, household appliances, consumer equipment [51, 52].
   b. **Not Included:** All small IT with external dimensions lower than 50cm like smartphones, phablets, routers, printers, GPS are part of category VI not V [51, 52].

VI. **Small IT and telecommunication equipment (no external dimension more than 50 cm) –** Any EEE that's not allocated to categories I, II, III, IV or V. Equipment that can collect, transmit, process, store and show information. Telecommunication equipment that can electronically transmit/receive data over distances are also included. Dimensions are determined when the equipment is assembled and 'ready to use' [51, 52].

a. **Examples:** Smartphones, phablets, regular mobile phones, calculators, GPS, Router, small personal computers, game consoles, computer accessories, printers [51, 52].

b. **Not Included:** Small equipment that do not transmit/receive data and/or handles information. Large IT equipment like printers and desktops or IT equipment with screen surfaces larger than 100 cm^2 such as laptops and tablets [51, 52].

Appendix B – Conversion Between UNU-keys and EU's WEEE

EU WEEE	*UNU-Keys*
Category I	0108 Fridges (incl. combi-fridges)
	0109 Freezers
	0112 Other Cooling (e.g. dehumidifiers, heat pump dryer
	0113 Professional Cooling (e.g. large air conditioners, cooling displays)
	1002 Cooled Dispensers (e.g. for vending, cold drinks)
Category II	0303 Laptops and Tablets
	0308 Cathode Ray Tube (CRT) Monitors
	0309 Flat Display Panel Monitors (LCD, LED)
	0407 Cathode Ray Tube (CRT) TV´s
	0408 Flat Screens
Category III	0502 Compact Fluorescent Lamps (incl. retrofit & non-retrofit)
	0503 Straight Tube Fluorescent Lamps
	0504 Special Lamps (e.g. professional mercury, high- & low-pressure sodium)
	0505 LED Lamps (incl. retrofit LED lamps & household LED luminaires)
Category IV	0001 Central Heating (household installed)
	0002 Photovoltaic Panels (incl. inverters)
	0101 Professional Heating & Ventilation (excl. cooling equipment)
	0102 Dishwashers
	0103 Kitchen (e.g. large furnaces, ovens, cooking equipment)
	0104 Washing Machines (incl. combined dryers)
	0105 Dryers (wash dryers, centrifuges)
	0106 Household Heating & Ventilation
	0307 Professional IT (e.g. servers, routers, data storage, copiers)
	0602 Professional Tools (e.g. for welding, soldering, milling)
	0703 Leisure (e.g. large exercise, sports equipment)
	0802 Professional Medical (e.g. hospital, dentist, diagnostics)
	0902 Professional Monitoring & Control (e.g. laboratory, control panels)
	1001 Non-Cooled Dispensers (e.g. for vending, hot drinks, tickets, money)
Category V	0114 Microwaves (incl. combined, excl. grills)
	0201 Other Small Household (e.g. small ventilators, irons, clocks, adapters)
	0202 Food (e.g. toaster, grills, food processing, frying pans)
	0203 Hot Water (e.g. coffee, tea, water cookers)
	0204 Vacuum Cleaners (excl. professional)
	0205 Personal Care (e.g. tooth brushes, hair dryers, razors)
	0401 Small Consumer Electronics (e.g. headphones, remote controls)
	0402 Portable Audio & Video (e.g. MP3, e-readers, car navigation)
	0403 Music Instruments, Radio, Hi-Fi (incl. audio sets)
	0404 Video (e.g. Video recorders, DVD, Blue Ray, set-top boxes)
	0405 Speakers
	0406 Cameras (e.g. camcorders, photo & digital still cameras)
	0501 Other Lamps (e.g. pocket, Christmas, excl. LED & incandescent)
	0506 Household Luminaires (incl. household incandescent fittings)
	0507 Professional Luminaires (offices, public space, industry)
	0601 Household Tools (e.g. drills, saws, high pressure cleaners, lawn mowers)
	0701 Toys (e.g. car racing sets, electric trains, music toys, biking computers)
	0801 Household Medical (e.g. thermometers, blood pressure meters)
	0901 Household Monitoring & Control (alarm, heat, smoke, excl. screens)
Category VI	0301 Small IT (e.g. routers, mice, keyboards, external drives & accessories)
	0302 Desktop PCs (excl. monitors, accessories)
	0304 Printers (e.g. scanners, multi functionals, faxes)
	0305 Telecom (e.g. (cordless) phones, answering machines)
	0306 Mobile Phones (incl. smartphones, pagers)
	0702 Game Consoles

Appendix C – Average Equipment Weight

UNU Key	*1980-1999*	*2000-2004*	*2005-2009*	*2010*	*2011*	*2012-2015*
0104 – Washing Machines	72.6	73.1	71.4	72.4	72.4	71.5
0105 – Dryers	59.6	46.9	43.2	45.9	46	43.5
0108 – Fridges	40.2	47	52.3	55	55.2	54.1
0109 – Freezers	50.6	44.1	43.9	44.1	44.1	43.3
0111 – Air Conditioners	33.4	47.3	26.6	26.6	26.6	25.2
0114 – Microwaves	17.6	19.2	20.6	22.9	22.9	22.2
0204 – Vacuum Cleaners	5.3	5.5	5.5	5.9	5.9	5.8
0205 – Personal Care Equipment	0.7	0.6	0.5	0.5	0.5	0.5
0302 – Desktop PCs	15	10.2	9.2	8.8	8.8	8.8
0303 – Laptops (incl. tablets)	4.9	4.3	3.7	3.2	3.2	3
0306 – Mobile Phones	0.6	0.2	0.1	0.1	0.1	0.1
0404 – Video and projectors	4.9	4.2	4	2.6	2.9	2.7
0408 – Flat Display Panel TVs	0	0	12	14.7	14.7	14.3
0702 – Game Consoles	2.1	2	2	2	2	1.9