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An EU closed loop waste management system for Rare Earths – Tackling criticality with a disruptive circular economy policy

Guilherme António Ribeiro Azambuja

Applied project submitted as partial requirement for the conferral of the degree - Master in Economics and Public Policies

Supervisor:
Doctor Maria Fátima Ferreiro, Associate Professor with habilitation
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CIÊNCIAS SOCIAIS
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Abstract

The EU has recently upped its efforts to ensure a stable access to raw materials and mostly finite ones, many of which are not explored domestically. The Raw Materials Initiative launched in 2008 opened the door to a European industrial policy agenda focused on sustainable access and management of raw materials. Shortly after, the EU began publishing its list of Critical Raw Materials (CRM) every 3 years.

Among the most critical of materials are rare earths (REE), which are indispensable to the EU energy transition and a carbon neutral society. The EU challenge of ensuring both a stable access and a circular management of rare earths is an enduring conundrum. Despite the policy efforts to push for more circularity and recycling of the rare earths, the situation has not improved since 2011 – reliance on Chinese supply is about 100% and recycling has no expression for most rare earths.

The focus of this project is to provide a policy contribution to tackling this conundrum. The rare earths situation in the EU is studied carefully by considering EU's strategic interest, the demand from EU sectors and the state of global supply. Public policies targeted at CRM are critically assessed and its limitations are discussed. An alternative policy path is presented in which the EU would commit to co-creating a recycling system aimed at recovering rare earths from waste of electric and electronic equipment.

Key-words: Rare earths, WEEE, rare earths recycling, CRM, EU policies, waste management system

Resumo

Recentemente, a UE redobrou os seus esforços no sentido de assegurar um acesso estável, principalmente a recursos finitos, para os quais não há extração doméstica. A “Iniciativa matérias-primas” lançada em 2008, deu início a uma agenda europeia de política industrial centrada no acesso e na gestão sustentáveis de matérias-primas. De seguida, a EU dá início à publicação trienal da sua lista de matérias-primas críticas (MPC).

Entre as mais essenciais destas MPC estão as terras raras (TR) que são indispensáveis para transição energética e para a neutralidade carbónica da UE. O desafio da União de garantir um acesso estável e uma gestão sustentável das TR é um dilema que se arrasta no tempo. Apesar das políticas públicas para aumentar a circularidade e reciclagem de TR, a situação não melhorou desde 2011 – a dependência do fornecimento Chinês ronda os 100% e a reciclagem não tem praticamente expressão para a maioria das terras raras.

Este projeto centra-se numa contribuição de política pública para enfrentar este dilema. A situação das TR na UE é cautelosamente estudada, tendo em conta o interesse estratégico da UE nestes materiais, a procura setorial da EU bem como o estado da oferta mundial. Procede-se com uma revisão crítica das políticas que visam as MPC e as suas limitações são discutidas. Apresenta-se de seguida uma política pública alternativa, na qual a UE se compromete a co-criar um sistema de reciclagem visando a recuperação de terras raras a partir do fluxo de resíduos de equipamentos elétricos e eletrónicos.

Palavras-chave: reciclagem terras raras, TR, MPC, sistema de gestão de resíduos, política industrial europeia

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Glossary

AP-CRM - Action Plan on Critical Raw Materials

BGS – British Geological Survey

BRGM - Bureau de Recherches Géologiques et Minières

Ce - Cerium

CRM – Critical Raw Materials

DG - Directorate General

Dy – Dysprosium

EC – European Commission

EEA – European Environmental Agency

EEE - Electrical and Electronic Equipment

EIB – European Investment Bank

EIP-RM - European Innovation Partnership - Raw Materials

EIT – European Institute of Innovation and Technology

EOL - End of Life

EPR – Extended Producer Responsibility

ERECON - European Rare Earths Competency Network

Er - Erbium

ERMA – European Raw Materials Alliance

Eu - Europium

EU – European Union

EV – Electric Vehicles

FCC – Fluid Cracking Catalyst

FP7 – 7th Framework Programme of Research and Development

FP7-NMP – “Cooperation - Nanoscience, Nanotechnologies, Materials and new Production Technologies” call of FP7

Gd – Gadolinium

H2020 – Horizon 2020

HDD – Hard Disk Drive

HLSG - High-Level Steering Group

HPMS - Hydrogen Processing of Magnetic Scrap

HREE – Heavy Rare Earth Elements

JOGMEC – Japan Oil, Gas and Metals National Corporation

JRC – Joint Research Centre

KET – Key Enabling Technologies

La - Lanthanum

LCD – Liquid Crystal Display

LED - Light-Emitting Diode

LREE – Light Rare Earth Elements

MRDS - Mineral Resource Data System

MS – Member States

Nd - Neodymium

NdFeB - Neodymium Iron Boron permanent magnets

NiMH - Nickel–Metal Hydride batteries

NGO – Non-Governmental Organization

PGM – Platinum Group Metals

Pr - Praseodymium

R&D – Research and Development

REE - Rare Earth Elements

REO - Rare Earth Oxides

RIR – Recycling Input Rate

RMI – Raw Material Initiative

RMIS - Raw Materials Information System

SIP - Strategic Implementation Plan

Sm – Samarium

SME – Small and Medium Enterprises

SRM – Secondary Raw Materials

Tb - Terbium

TV - Television

USGS – United States Geological Survey

UV – Ultraviolet light

WEEE – Waste from Electrical and Electronic Equipment

WFD – Waste Framework Directive

WTO – World Trade Organization

Y - Yttrium

Introduction

The expansion of world economies in the last century has rapidly accelerated the consumption of the worlds finite resources, virtually putting at risk the very economic system which led to its depletion. In 1972, the Club of Rome concluded just that (Meadows et al, 1972) in what, for a long time, seemed to be a distant and unpleasant world scenario (or rather a range of scenarios) to consider. This concern has continuously captured more attention from both governments, the academia, NGOs and private organizations in Europe. In the last decade, the EU has upped its efforts to ensure a stable access to raw materials and mostly finite ones, many of which are not explored domestically.

The Raw Materials Initiative launched in 2008 opened the door to a European industrial policy agenda focused on sustainable access and management of raw materials (COM/2008/699). In 2011, the EU published its first List of Critical Raw Materials, in which it assessed the dynamics of demand and supply for different raw materials, defining the most crucial ones to the EU economy (COM/2011/25). The most critical among these materials are rare earths and a decarbonized economy can hardly happen without some of them (Bauer et al, 2010; Ait Abderrahim and Monnet, 2018; Kooroshy et al, 2015; Zhou, Li and Chen, 2017; Machacek and Kalvig, 2017; Binnemans, 2015; Espinoza et al, 2019). With the roadmap set out in the European Green Deal and the ambitions to become a Circular Economy, a fundamental piece does not fit the puzzle – How will Europe guarantee a stable and environmentally sustainable supply of Rare Earths? Moreover, what is the role of closing the loop on these materials given the EU import reliance and what difficulties persist in setting up recycling activities?

“The need for primary materials, such as ores and concentrates, and also for processed and refined materials is huge and crucial for the wealth -even the survival- of the European industries and their associated jobs and economy.” (Deloitte Sustainability et al, 2017: 23 b.). These declarations summarize the importance of REE to protect the EU economy as it is and, in a sense, as it projects itself into the future, namely to ensure a steady transition to a climate neutral circular economy by 2050 (COM/2019/640, COM/2018/773). The way in which the EU pursues these objectives and where it places more policy emphasis will bare consequences to the EU’s strategic positioning in the rare earths value chains but also to the very industries and jobs it aims to protect.

The EU is dependent on CRM like rare earths and components containing them for value-added activities (Deetman et al, 2017: 20-24) as well as for exports (Tukker, 2014). Rare earths represent the ultimate challenge for EU policy, as the economic block is entirely reliant on external supply and has only a marginal capacity to process these materials. The vision for a circular and environmentally sound Europe may risk being just a vision if EU policy is inadequate to simultaneously provide an answer to rare earths supply uncertainties while closing the loop for these materials. The combination of environmental and strategic aspects of this rare earths conundrum enhances the limitations and weaknesses of a free-market approach followed by EU policymakers. The policies adopted delegate to industrial players the development of resilient value chains anchored on principles of circular economy.

By carefully studying the European conundrum of rare earths and the policies devised to resolve it, this project points to the insufficiency of the latter. Given the loopholes in the European rare earths value chains and the current outlook of Rare earths markets, closing the loop on rare earths emerges as the only environmentally sound long-term strategy to ensure resilience and growth in EU’s REE sectors. To do that, disruptive policies are needed along with a stronger role of the EU in the co-creation of an industrial solution to the REE conundrum. Other policy paths have been favoured by the EU, and key aspects of this EU CRM strategy must be maintained, namely its focus on innovation and R&D.

Underpinned by the EU environmental principles, its industrial and circular economy strategies, an alternative policy path is suggested. One that places circularity at the forefront of tackling criticality and building a resilient value chain for REE in the EU. Favouring a rapid boost in rare earths recovery through collection, dismantling, sorting, and recycling capacity from post-consumer scrap, while improving processing along the recycling chain.

The first chapter provides a background to the EU conundrum of rare earths. It begins by introducing the criticality dilemma in the EU, followed by a brief overview of rare earths, reserves and recent history, as to provide a context of the rising importance of these elements. The remainder of this chapter addresses the state of supply and demand for rare earths from a European perspective. The aim of this section is to answer – Why are rare earths critical to the EU and what is the market context in this domain?

Chapter two provides a critical summary of EU policies relevant to REE in chronological order with a focus on circularity and recycling. Policies covered in this chapter range from the Raw Materials Initiative in 2008 to the CRM Action Plan published in 2020. A broad selection of EU-funded projects related to REE is presented, while again emphasizing the ones focusing on waste management solutions. This chapter aims to build a consistent and comprehensive account of EU policies, thereby informing on the strategy to tackle rare earth criticality as well as on the kind of projects being funded by EU programmes.

The third chapter proposes an alternative policy path to solve rare earth criticality in the EU. The limitations of a free-market-oriented policy approach are discussed along with the

contradictions raised by this conundrum. An overview of the desirable institutional architecture and operational objectives for a waste management system are provided. A public-private collaboration is suggested to correct a market gap in rare earths recovery, thereby boosting the existing recycling chain and setting the standard for practices in the field. Policy recommendations are presented based on 3 pillars guiding the intervention suggested.

1. What is the rare earths challenge in the European Union?

1.1 Introduction to the EU's environmental conundrum with Rare Earth Elements

The EU has a long legacy of environmental policy, having approved its first environmental action programme in 1972 and its first waste framework directive in 1975. It has systematically participated in international conventions and conferences on environmental topics like climate change, sustainable development, and waste, namely the Basel Convention in 1989, the Earth Summit in 1992 the Kyoto Protocol in 1997 among many others. In recent years EU Member States have taken further measures to pursue environmental goals namely by implementing more demanding waste regulation and pollution controls, besides adopting concepts like energy efficiency and energy transition (focusing on renewable sources), ecodesign, climate neutrality and circular economy.

The EU environmental policy has recently been marked by the most ambitious goals of transforming the EU economy. The European Green Deal (COM/2019/640) sets a renewed commitment to a sustainable and circular economy transition, making use of virtually all policy areas of EU competence and incorporating environmental considerations into funding and investment mechanisms. The various elements of the European Green Deal are presented in **Figure 1**.

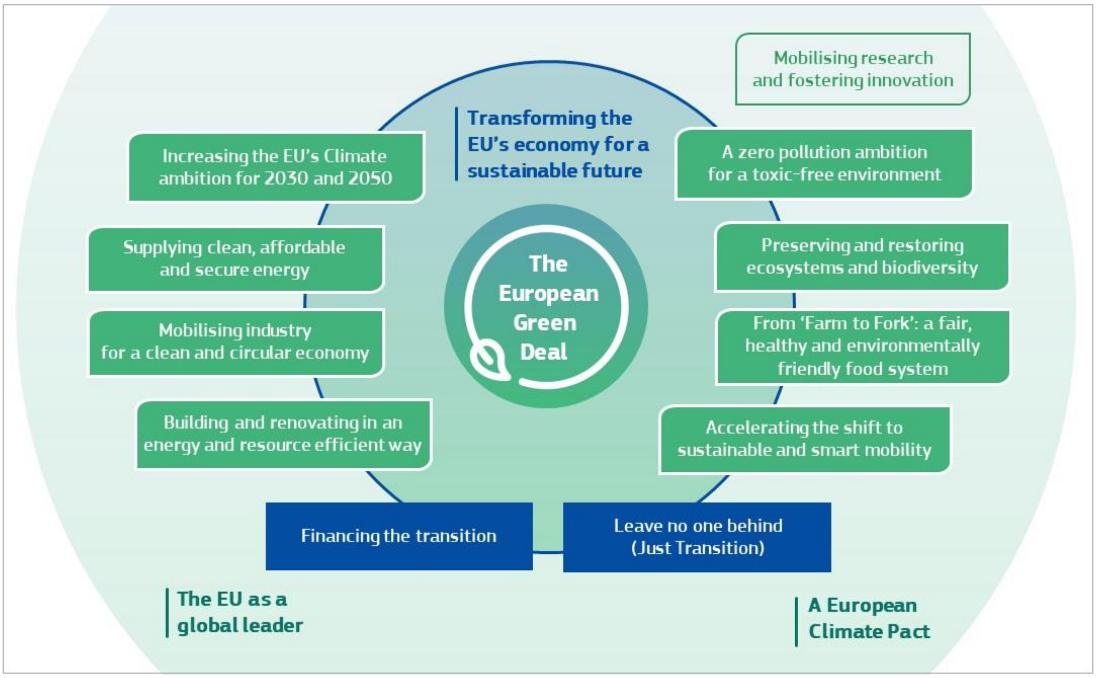

Figure 1- Elements of the EU Green Deal (extracted from COM/2019/640)

"Ensuring the supply of sustainable raw materials, in particular of critical raw materials (…) is therefore one of the pre-requisites to make this transition happen." (COM/2019/640). Achieving climate neutrality is inseparable from energy and raw material security (EEA, 2020: 57). The EU institutions have admitted both the EU's reliance on access to virgin raw materials to sustain domestic industries as well its need to close the loop on raw materials. In 2011, the EU released its first List of Critical Raw Materials (CRM), in which it assessed the criticality of several elements and formally adopted 14 of these as CRM for the EU (COM/2011/25).

Material Criticality is a theoretical concept used to assess the supply risk and economic importance[1] of a given material. It evaluates the degree of exposure to potentially destabilizing events in the supply chain of a specific material and the resulting impacts to the economy through i.e. industrial output and jobs. The factors used in criticality assessments differ significantly within the literature (Achzet and Helbig, 2013, Graedel et al 2012, Blengini et al, 2017: 33-82). Some of the most used dimensions in material criticality studies are presented in **table 1.**[2]
The methodological framework used to study criticality varies substantially, namely by differences in factors included in the assessment. Materials can be ranked according to their criticality and thus inform the policy-making process. To better demonstrate how these factors are organized in a material criticality study, an example of the EU overall structure of the revised criticality methodology is provided in figure 2 (Deloitte Sustainability et al, 2017b).

Several authors have pointed out that a sustainable transition will require an increased use of critical raw materials such as rare earths in key applications, namely wind turbines, electric vehicles and industrial motors[3]. Additionally, the upstream part of the value chain is underdeveloped in Europe (Bartekóva and Kemp, 2016) making the EU manufacturing sector heavily reliant on foreign supply of these materials (BIO by Deloitte, 2015). Rare Earth Elements are among the most critical minerals in the EU, given that they score the highest in terms of supply risk and above most materials in terms of economic importance[4].

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[1] Terminology used to refer to economic importance is vast ranging from importance in use, through impact of supply restriction, to vulnerability to disruptions in the supply. The term chosen is based on the policy documents of the EU, namely the EU CRM lists of 2011, 2014, 2017 and 2020 (COM/2011/0025, COM/2014/0297, COM/2017/0490, COM/2020/474) and the reports which informed policy making (i.e. Blengini et al, 2017, Deloitte Sustainability et al ,2017b.

[2] This table is not an extensive account of all indicators, while the categories to which the indicators pertain are far from being consensual across publications (Erdmann and Graedel, 2011).
[3] For more information on this topic see: Haxel, 2002; Binnemans, 2015; Kooroshy et al, 2015; Zhou, Li and Chen, 2017; Abderrahim and Monnet, 2018; Espinoza et al, 2019, European Commission, 2020 a.)
[4] There is significant variation when assessing rare earth individually.

Table 1- Dimensions and indicators commonly used in Criticality Studies, adapted from Erdmann and Graedel, 2011.

SUPPLY RISKS	ECONOMIC IMPORTANCE
Concentration of production at country and company level	Demand growth and emerging technologies
Country risk (production)	Consumption share of sectors
Future supply to demand ratio	Gross value added of sectors
Geological availability	Specific impact on sectors
Substitutability	Industrial policy (production)
Recycling rate	
Regulatory risk (i.e. import prices and quotas)	
Price volatility	
Environmental considerations	

Without appropriate policy action and in the current market conditions, a resilient and competitive supply chain of rare earths in Europe may never flourish (Kooroshy, 2015:72). Even considering possible mining output within the European continent (which has high legal costs and barriers to entry), reliability on China will persist given its near monopoly of upstream processing capacity. Besides, some REE value chains are not well established in the Union, leading to substantial imports of REE-embodied components for EU final product sectors.

This summarizes the EU's environmental conundrum of rare earths. It represents a confrontation between the environmental ambitions and the reality constraining it. A structural dilemma of emancipation and sustainability within EU industrial policy which uncovers an incompatibility between the EU political ambitions and its free market orientation.

The central question is: How will REE reliant industries in the EU become competitive and sustainable without a reliable supply and an integrated domestic value chain of these materials? Moreover, important questions are raised about the type of policy intervention which would be simultaneously adequate to kickstart and assists upstream activities in Europe without creating inefficient operations dependent on state protectionism. (Kooroshy et al, 2015: 76). The remainder of part 1 will focus on clarifying the rare earth situation in Europe.

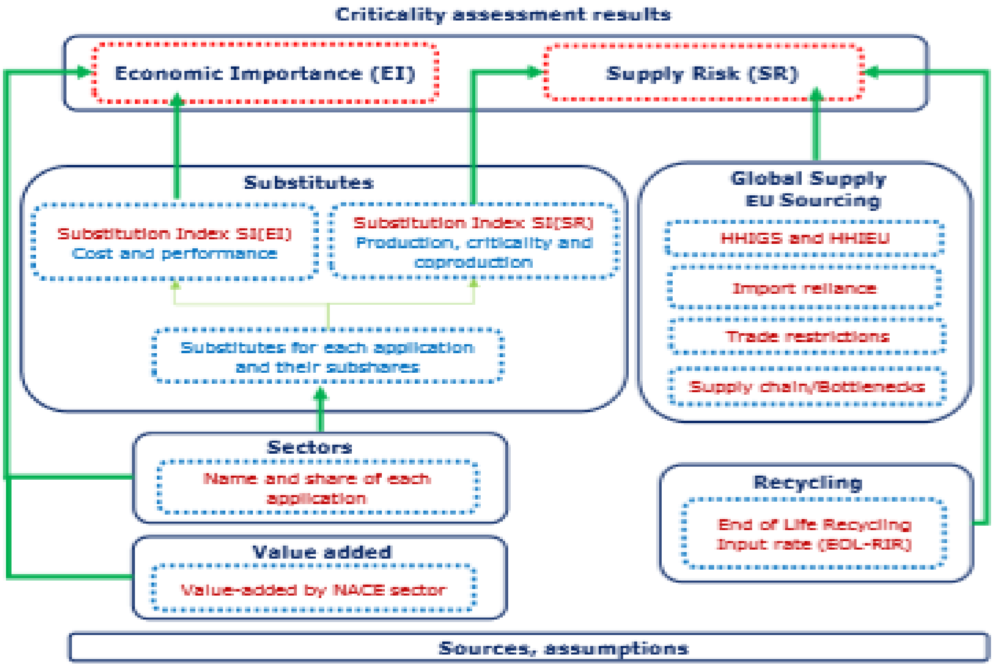

Figure 2 - Overall structure of EU criticality methodology[5]*; extracted from "Study on the review of the list of Critical Raw Materials (Deloitte Sustainability et al, 2017b)"*

1.1.2 Rare Earths – What are they?

Rare earth elements (REE) are a set of metallic elements which have gained traction in industrial uses and its characteristics are increasingly recognized in different sectors. Their economic importance has become unquestionable, as their uses multiply in applications such domestic appliances, technological gadgets, electric and hybrid vehicles, wind turbines, solar panels, fighter jets or ballistic missiles. REE are known for their electric conductivity and are used for their catalytic, optical, and magnetic properties, making them highly demanded.

Rare earths include 17 elements as can be seen highlighted in the periodic table in **figure 3**. Some authors and publications distinguish between the 15 lanthanides and Scandium and Yttrium, given the atomic numbers which range from 57 to 71 for lanthanides and 21 for Scandium and 39 for Yttrium. Other useful although not consensual distinctions, are between Heavy Rare Earths Elements (HREE) with higher atomic numbers, including Scandium and

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[5] HHIGS and HHIEU mean Herfindahl–Hirschman Index for both Global and EU supply

Yttrium and Light Rare Earth Elements (LREE), with lower atomic numbers. Some institutions also use a third classification – medium REE (Machacek and Kalvig, 2017,18-19)

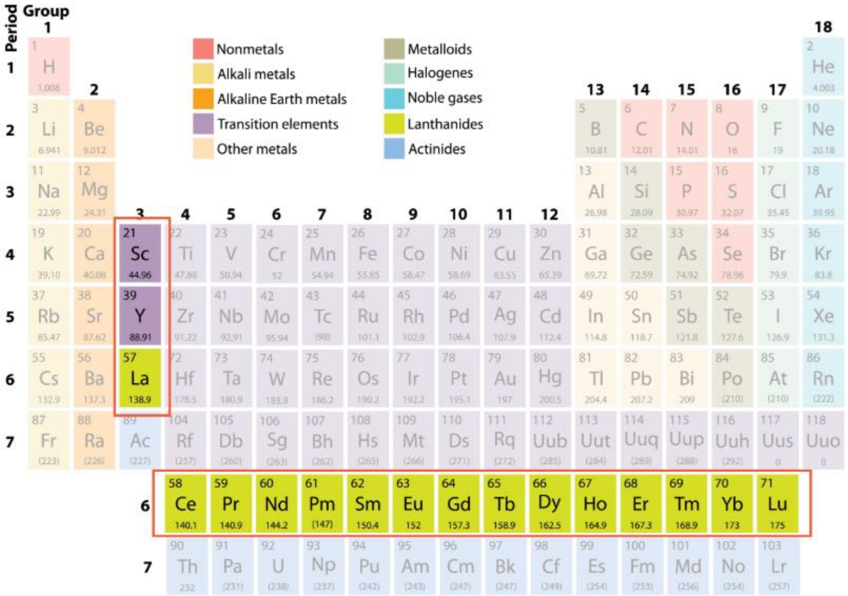

Figure 3- Periodic table with rare earth elements highlighted.

Most REE are not actually rare. In fact, some of these elements are quite abundant, which is the case of cerium, lanthanum, neodymium and yttrium. Rare earths are not found as metals in nature but rather mixed in over 200 different minerals commonly containing thorium and uranium. Most reserves consist of ores with low gradients of Rare Earth Oxides (REO), which are not economically viable to mine. Their chemical properties make them hard to extract and isolate into individual elements at a profitable margin.

According to the BRGM these reserves amount to 81 230 000 tonnes scattered on the earth's crust in different types of minerals (BRGM, 2015). Nonetheless USGS estimates are more optimistic at 120 million tonnes in the Mineral Commodities Summaries of 2020, although they were reported a 130 million tonnes just 4 years prior (USGS, 2020: 132; USGS, 2016:134). (Extensive mapping has been done by the USGS in a platform named Mineral Resource Data System (MRDS)[6].

Despites these figures it should be noted that reserves and their REE are subject to different assessments, based on the quantity and quality of information gathered. Hence, most mine estimates of total world reserves of rare earth oxides (REO) vary significantly among reporting authorities and scientific papers (Machacek and Kalvig, 2017: 21). Besides the permanent advance of prospection and exploration data in different sites across the globe,

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[6] Open and accessible online with geographical interactive maps of operating mines with the grade and minerals present in different reserves: Mrdata.usgs.gov

REE reserves are found in ores which mostly contain other elements while bearing different concentrations and distribution of rare earths, contributing to additional uncertainty.

The main sources of REE are minerals like Bastnäsite, Loparite, Monazite, Rare-earth laterite, Carbonatite, Pegmatite and Xenotime where REO occur in complex mixtures rather than individually.[7] This means that in order to extract any rare earths, other elements (including REE) are inevitably extracted too. In other words, the exploration of the primary source minerals, whether for REEs or any other elements, always generates by-products.

Most mining operations of HREE take place in China, while LREE extraction is more widespread[8]. The recent expansion of mining operations outside of China, has contributed to a less concentration in mining sectors of REE. However, challenges will persist in terms of meeting global demand for HREE from explorations outside of China.

No REE mining currently takes place in Europe, despite the recent efforts for determining the geological potential within Europe (Goodenough et al 2016 and EU-funded projects like ProMine, Minerals4EU and EURARE). Several projects are under exploration to determine their viability, but advanced exploration stage was reached only in Greenland (Kvanefjeld and Kringlerne) and Sweden (Norra Kärr) both of which are being explored by foreign companies – Greenland Minerals Energy ltd (Australia), Tanbreez Mining Greenland A/S (Australia) and Leading Edge Materials[9] (Canada), respectively. REE exploration from these deposits could significantly contribute to the European demand for both HREE and LREE in quantitative terms, satisfying more than the EU demand. (Kooroshy et al, 2014: 36; Machacek et al, 2017:33; Jones, 2017:5) However, until licensing of mining operations is granted a few challenges remain, namely the funding necessity for separating facilities as well as the predominance of China in rare earth consuming markets. As Commissioner Breton declared in the launch of European Raw Materials Alliance – "(…) we also need to look at loopholes in the value chain. It is not sufficient to have the raw materials if we do not have the processing facilities in Europe"[10]. Without resolving these open questions, reliance on China's separation capacity will remain unchallenged and so will European import reliance.

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[7] for further information on geological characterization of REE primary sources see Machacek and Kalvig, 2017; Goodenough et al 2016; and Minerals4EU final report.

[8] This can be explained by the distribution of ores found in the deposits in China being significantly higher than in most other deposits mined worldwide.

[9] Subsidiary of Tasman Metals Ltd

[10] Quote from Commissioner Thierry Breton's speech at the launch of the ERMA. The integral speech can be seen in - https://www.youtube.com/watch?v=G-TdcFTgX7o&ab_channel=EITRawMaterials

1.1.3 Brief History of the rise of Rare Earth Elements

The demand for these materials has seen significant increases in the past. The evolution of the REO world mine production can be seen in figure 4. The graph resorts to data from the U.S. geological Survey (USGS) Mineral Commodity Summaries from the year 1996 onwards. It should also be noted that the data on world production statistic cannot account for the production resulting from illegal mining activities (Binnemans et al, 2018: 131). In the space of 15 years from 1994 to 2009, extraction more than doubled and in the decade following 2009, it grew by over 50% according to the latest estimates of the USGS. And since 2017, there has been a spike in production to over 200 000 t.

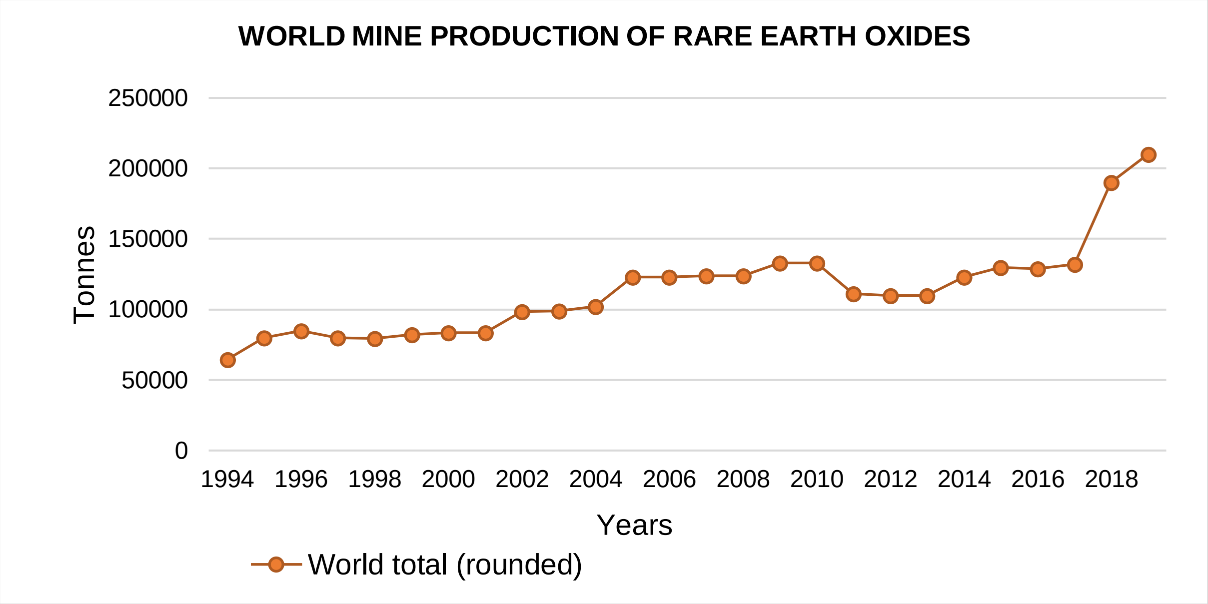

Figure 4- World mine production of rare earth oxides (compiled according to USGS data)

From when they were first discovered in 1787 in Sweden to their first commercial application in 1884 and well onto the mid XX century, REE were largely a novelty under exploration with a few niche markets such as incandescent gas mantles, mischmetal or glass (Mancheri et al, 2013). Starting from the 1960s uses for REE became pervasive. Lanthanum and cerium started being used in catalyst for petroleum crude processing, Europium was used for cathode ray colour televisions, Neodymium and Yttrium started being used in lasers for defence purposes before the end of the 60s. The 60s and decades that followed brought rare earth containing innovations which have resisted the test of time. Things like Terfenol-D, a Terbium and Dysprosium containing alloy which is used for speakers and fuel injection in diesel cars. Another example is magnets, where rare earths still play a major role - first with the rise of Samarium Cobalt magnets in the 1970 and later in the 90s with the commercialization of Neodymium Iron Boron (NdFeB) magnets (Constantinides, 2012).

According to Mancheri et al (2013), the 90s and 00s decade was marked by a lack of technological breakthroughs in terms of REE uses and a shift in research efforts towards incremental improvements in products and technologies. However, it is hard to characterize innovation in such broad scale of different value chains. It should also be noted that each sector and market is subject to different innovation processes, hence when looking at specific product markets, one can see all kind of trends. Some technologies like samarium cobalt magnets and Nickel–metal hydride (NiMH) battery, containing Samarium and, Lanthanum and Neodymium respectively, have been leading technologies in their associated applications but are being surpassed by other emerging or consolidated technologies (Mancheri et al, 2013: 40; Espinoza et al, 2019: 52-53; Constantinides, 2012; Constantinides, 2013). Technologic innovation is inherent to the use of REE and while new uses and ways of using REE are being researched, the volatility in the markets has fuelled a wave of innovations aimed at reducing and substituting REE in certain applications.

1.2 Demand - Current and Future Market Drivers

Understanding demand and supply dynamics of the rare earths market is essential to decipher the current and future EU reliance on these materials and its dependence on foreign sources of supply. Devising policy initiatives to tackle criticality of rare earths can only be done through an informed policy-making process where the EU industry’s needs, and bottlenecks are well identified to protect it from disruption in global markets. We look at current and future sectoral demand at the EU level, after briefly explaining the different roles that REE can play in processes and products as well as providing a structure of the general value chain observed for rare earths.

1.2.1 REE value chain and usefulness in products and processes

Determining the driving forces of Rare earths markets is a complicated issue. Most emphasis is usually given to demand arising from downstream steps of the value chain and, implicitly, authors assume that the upstream activities function as supply to feed the different downstream steps. Technological advances and innovations which make use of REE’s properties for product or process enablers create demand pushes for those REE. Nonetheless the exact opposite forces also play a part, when technological innovations absent of REE become widespread, companies may refrain from using REE in their production processes, thus slowing down demand for the elements being substituted. It should be noted that the latter phenomenon has been pursued by companies and governments to avoid dependence of REE.

Many experts recognize that in face of complex commodity markets, there is a mix of additional factors affecting demand and supply aspects of the market namely institutional factors such as industrial policy and environmental regulation on mining activities. (Kooroshy et al, 2015; COM/2011/25 : 2-3 ; Abderrahim and Monnet, 2019 :9-11; , Espinoza et al, 2020 :7-10).

Rare earths are applied to enhance processes or products efficiency or properties, providing them with improved performance which can be hard to achieve using different materials. Hence the applications for REE can be grouped within two categories – process enablers and product enablers (Hatch**,** 2011; Kooroshy et al, 2015; Eggert et al, 2016). Process enablers are REE whose use serves to improve some sort of production process without being included/contained in the final product sold. Examples of process enablers can be found in the polishing or the catalyst industry, where polishing agents containing Cerium are applied to things like hard disk drives (HDD) or in the latter case, REE are useful in fluid catalytic crackers for breaking up molecules into lighter or smaller chains. In this later case, cerium, lanthanum and yttrium are added to zeolite catalysts in petrochemical, water treatment or ion exchange processes making catalysts more efficient at breaking up the molecular binds and granting more resilience to temperature and to dealumination.

Product enablers on the other hand are integrated in products whether in specific components or embedded in the actual final product, either way granting the product desirable properties. REE are used for phosphors, glass, magnets, batteries and other industries, which make use of rare earths. In glass for instance, lanthanum is used as an enabler in infrared transmission useful for night vision and optic fibre equipment, whereas Cerium is used to provide colour or to decolourize glass, allowing it to absorb UV light when added to some kinds of glass. In phosphors, REE enable light emission in different waves. Cerium, terbium, europium and yttrium can be contained in phosphor coatings used in things like plasma TVs and LCD displays, fluorescent and LED lights.

It is important to bear in mind that process enablers require different procedures to account for REE contents than in product enablers. When REE is contained in products it is easier to collect data on the use of a given element in that product type or category, because all products placed on the market can be subjected to chemical examination to assess its rare earth content. However, fuels for example will not contain the REE that was used to produce them, because REE were used in its production process but are absent from the product itself, or rather omitted. Additionally, it has been reported that even the manufacturers or retailers of these final products may not possess information on the contents of the imported goods retailed or used in production. (Machacek and Kalvig, 2017: 83)

A commonly used distinction is made between upstream and downstream activities, which refer to the steps of the REE value chain. Upstream activities are associated with the initial processing steps necessary to isolate the REE, which are then used for all production activities. On the other hand, downstream activities refer to the manufacturing steps where rare earths are incorporated in materials (like powders, metals and alloys), components and final products. In this section we will analyse downstream activities while the following section on supply deals with the upstream activities.

A generic value chain for rare earths can be structured according to extraction, processing, manufacturing, use phase and waste management, as demonstrated in figure 5.

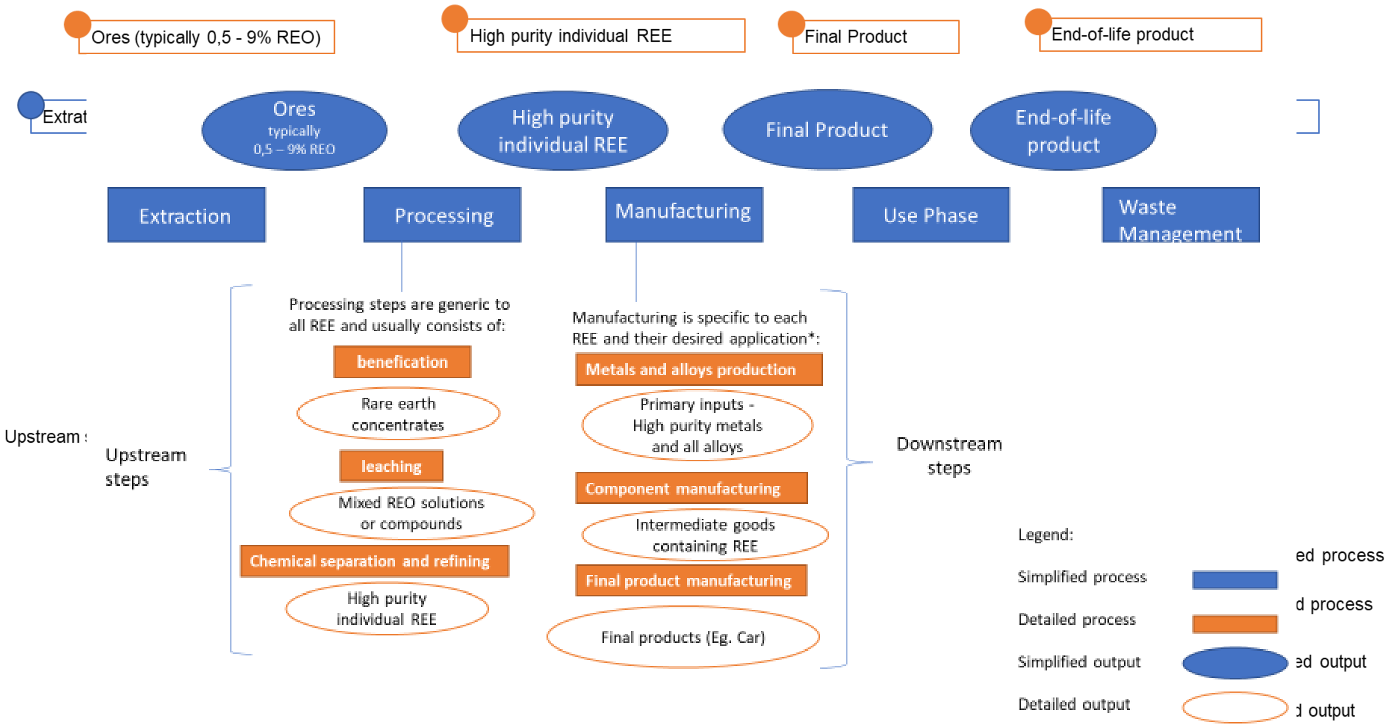

Figure 5 - Simplified Rare Earths Value Chain, elaborated by the author.

Rare earths feed numerous industries and applications. REE value chains are deeply interconnected given the geological morphology of the reserves and the similarity in most upstream steps. Additionally, REE may be combined along the value chain for intermediate products like phosphor powders used in lights or for final products like NiMH batteries. Figure 6, extracted from Mancheri et al (2013), was coined “the rare earth economic network”. It illustrates the complexity and connectivity between sectors, industries, intermediate goods and final products. Individual value chains of each element are interconnected and intertwined among each other, making it hard to monitor. A Chevrolet Volt for example, can contain REE in over 10 different components, from its approximately 25 electric motors, through UV cut glass (or UV resistant) and headlight lamps to glass and mirror polishing powders (Constantinides, 2013: 6-7). Other authors point out that a car may contain up to 200 permanent magnets, depending on its class (Mahacek and Kalvig, 2017).

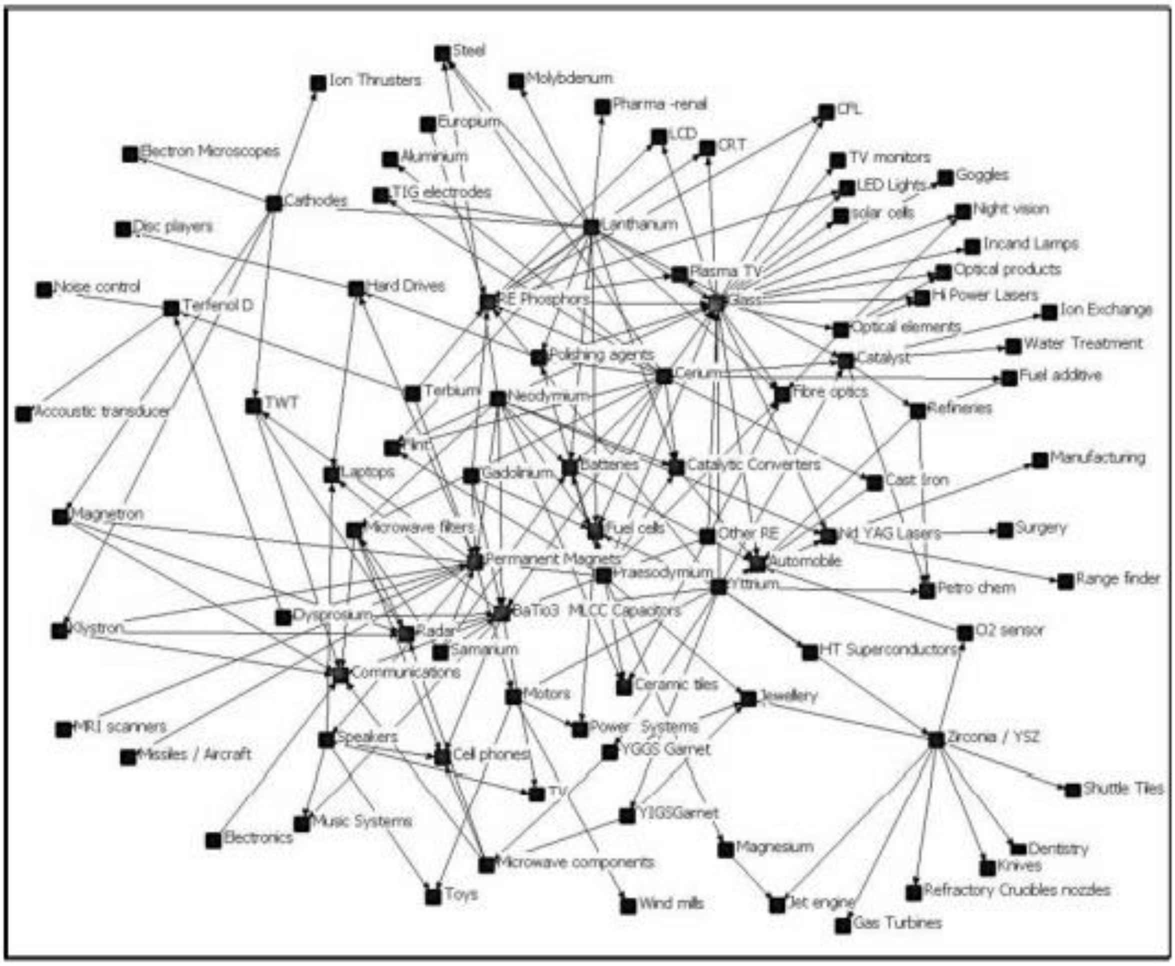

Figure 7 - The rare earth economic network (extracted from Mancheri et al (2013) with permission from the authors)

1.2.2 A sectoral approach to demand

A few clarifications are relevant for this section. From herein the term **REE sector** refers to the different manufacturing activities of either primary inputs or intermediate goods which make use of rare earths and the term **final product sector** refer to the activities using rare earth compounds to manufacture consumer goods at the end of the value chain, whereas **applications** is used for all kind of product including primary inputs, intermediate products or final products.

These REE sectors use rare earths supplied by upstream industries to manufacture goods which can be intermediate products or primary inputs for other manufacturing sectors. This implies that the scope of this analysis captures only a segment of the REE value chains. To exemplify this, we briefly explain what is meant by the “phosphors” sector in the text box to the right.[11]

There are no comprehensive datasets covering the whole “rare earth economic network”. In this case the most relevant limitation is that these REE sector will capture demand from an early step of downstream activities, leaving out the large volumes of rare earths imported in intermediate and final products.

To illustrate the current and future state of demand a sectoral approach is adopted. Given that publications vary widely in their definition of sectors, official EU reports are used, where variations exist in a weaker degree.[12] In no particular order, the REE sectors considered are – permanent magnets, fluid cracking catalyst, automotive catalyst, polishing agents, phosphors, glass additives, ceramics, metallurgy, while the remaining pertain to the group “others”. Figure 7 shows the share of production by industrial applications using REO both in the EU and in the world for 2010 [13]. Magnet production accounts for just 3% of total rare earth used in the EU compared to 22% in the rest of the world. In the EU 18% of REE serve to produce additives for the glass industry whereas only 7% of REE worldwide feed similar production. It is also noteworthy to highlight that the largest share of REE inside and outside of the EU are used for catalysts, 42% and 23% respectively. In the category “catalysts” 2 types stand out – fluid catalytic

THE CASE OF PHOSPHORS

Phosphors are a wide range of intermediate goods used for lighting applications. These are mainly phosphors for Light Emitting Diodes (LED), fluorescent lamps, optical and thermal measurement instruments and serve as dopants for crystals in solid-state lasers, besides a big and diverse group of phosphors used in displays like Flat Panel Displays (FPD) (Song et al, 2013: 1276-1279). LED and fluorescent phosphors can feed lamps applications of both these types, but they can also be used complementarily for FPD like liquid crystal displays (LCD) and field emission displays (FED). These electronic displays may be final products such as televisions, monitors or projectors but it is also common that they serve as components for final products like cars, aeroplane cockpits or even digital watches and cameras. Thus, the sector categories reflect the phosphors containing REE but not whether it feeds the automotive or the electric or electronic equipment sectors for example.

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[11] For detailed explanations of each of the sectors mentioned herein, please see Machacek and Kalvig, 2017: 42-62.

[12] Looking at these publications, the clarification made in the previous paragraph becomes clear. The Aster project calls the sectors “applications” and the critical raw material factsheets refers to them as “end-uses” of REES which further the confusion on the terminology.

[13] Besides being hard to gather sector specific data on REE use, estimations are often used when data is unavailable.

cracking (FCC), used to break up long chains of hydrocarbons; automotive catalyst used in vehicle exhaust systems to control emissions. And in the EU, FCCs accounted for about 16% and auto catalyst accounted for roughly 27% of total REE use. (Kooroshy et al, 2015:21)

Figure 8 – Production of Industrial applications using REO in the EU and in the World as a percentage (adapted from Deloitte Sustainability et al, 2017a)[14]

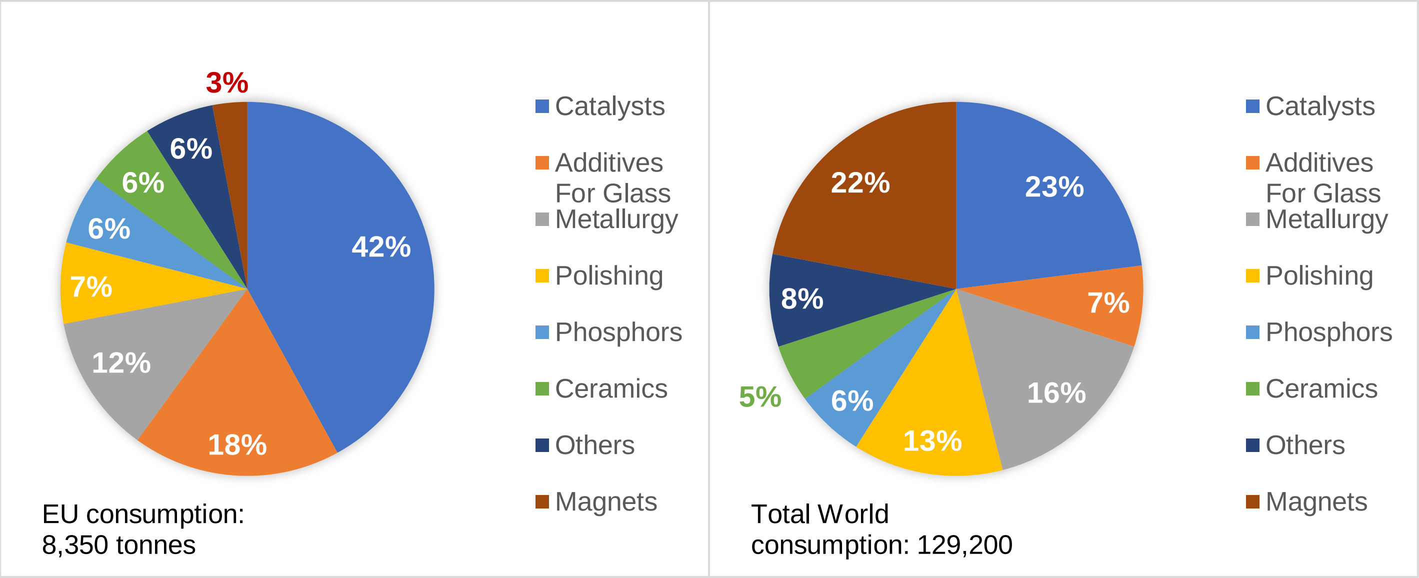

Table 2 shows the distribution of individual REE use among the different economic sectors in Europe.[15] Final product sectors are included in this publication, thus economic sectors included are broader and the classification changes accordingly.[16] The most relevant category is the mechanical and electrical sectors, which includes magnets and phosphors. These sectors represent the largest share of most rare earths, including Praseodymium, Neodymium, Samarium, Europium, Yttrium, Gadolinium, Terbium and Dysprosium.

Table 3 provides data on rare earth use as a percentage of the total REE used in each EU REE sector for the year 2010. Neodymium (Nd), one of the most critical raw materials is the dominant element only in the magnet sector. Other interesting cases are Samarium (Sm) and Dysprosium (Dy) which are used only in Other sectors and in Magnets, respectively. Most

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[14] The data presented by the original authors did not refer to a specific year.

[15] Deetman et al (2017) used a compilation of sources with data from 2013-2014 and the authors do not assign a specific date to this data.

[16] To make REE secotrs correspond to the economic sectors in table … consider that – automotive catalysts are included in the transport sector; polishing and FCCs are included in the chemical sector; phosphors and magnets are included in the mechanical and electrical sector.

sectors tend to use a combination of rare earths and within the EU no sector relies entirely on one rare earth.

Table 2 - Distribution of individual REE use by economic sector in Europe as a percentage (compiled by the author with data from Deetman et al, 2017).

ECONOMIC SECTOR / REE	La	Ce	Pr	Nd	Sm	Eu	Y	Gd	Tb	Dy	Er
Metals	5,5	4,8	4,0	3,0	-	-	-	-	-	-	-
Transport	4,2	48,4	-	1,0	-	-	1,0	-	-	17,0	-
Chemical	3,0	6,4	2,0	-	-	-	-	-	-	-	-
Petro chemical and Energy	50,0	-	14,1	-	-	-	-	-	-	4,0	-
Ceramics and Glass	16,8	27,4	7,0	7,5	-	-	-	-	-	-	86,0
Mechanical and Electrical	14,2	8,0	70,8	87,3	80,0	85,5	78,0	60,0	100,0	66,0	12,5
Heavy Industry and Construction	0,0	-	-	-	-	-	-	-	-	-	-
Other consumer goods	0,0	-	-	-	-	-	-	-	-	-	-
Others	6,4	4,8	2,0	1,3	20,0	14,5	21,0	40,0	-	13,0	1,5
Total	100	100	100	100	100	100	100	100	100	100	100

Table 3 - Individual REE use as a percentage of total REE used by REE sector in the EU (compiled by the author with data from Guyonnet et al, 2015).

REE SECTOR / REE	La	Ce	Pr	Nd	Sm	Eu	Y	Gd	Tb	Dy	OTHER	TOTAL
Magnets	-	-	16,1	64,5	-	-	-	3,2	16,1	-	-	100
Battery Alloys	52,5	31,0	4,0	11,0	-	-	-	-	-	1,5	-	100
Metal Alloys	25,4	53,1	5,5	16,0	-	-	-	-	-	-	-	100
Automotive Catalysts	4,8	90,4	2,0	2,9	-	-	-	-	-	-	-	100
Petroleum refining	89,6	10,4	-	-	-	-	-	-	-	-	-	100
Polishing powders	30,5	66,0	3,5	-	-	-	-	-	-	-	-	100
Glass Additives	23,4	67,3	1,0	2,9	-	-	-	-	-	2,1	3,3	100
Phosphors	10,3	7,9	-	-	-	6,1	-	4,0	-	71,6	-	100
Ceramics	16,2	12,0	5,9	11,4	-	-	-	-	-	54,6	-	100
Others	18,4	39,5	4,0	14,4	1,9	-	0,9	-	-	20,9	-	100

The REE global market is small both in value and in quantitative terms when compared to other materials (Kooroshy et al, 2015:16). Besides, it is considered a specialty market where trade is generally done on a business-to-business basis and prices are not determined in international markets (Machacek and Kalvig, 2017: 63).

The EUs REE sectors used roughly 8350 tonnes of REO in 2010, which accounts for just 6,5% of the world's total use – 129200 tonnes (Deloitte Sustainability et al, 2017b). EU imports of rare earth metals and alloys has continuously dropped from about 27000 tonnes in 2000 to less than half that weight in 2015. Whereas total EU rare earth imports contracted significantly in the first decade of 2000 before stabilizing at roughly 11 000 tonnes per year from 2010 to 2014, followed by substantial increases in 2015 and 2016 to almost 16 000 tonnes. (Machacek and Kalvig, 2017: 75-80). The explanation for the recent hike in rare earths imports has yet to be determined, but imports are still below 2000's levels. Nonetheless, final product manufacturers and consumers in the EU are still heavily reliant on imported REE-embedded applications (Deloitte Sustainability et al, 2017a: 338). Reliance on Chinese rare earth imports went from 90% to 32% from 2000 to 2015 (Machacek and Kalvig, 2017: 77), while peaking above 90% and reaching 98% for many elements in 2020 (European Commission, 2020: 8 b.).

Final product sectors are far more developed than REE sectors in the EU, meaning that there are important gaps in EU rare earths value chains. (Deloitte Sustainability et al, 2017b: 336-339) REE sector outputs are neither diversified nor sufficient to meet demand from downstream activities in the EU, which end up importing large amounts of rare earths further down the value chain. For instance, in 2013 the EU was almost self-sufficient in coloured glass production (containing erbium), given that it imported only 4 tonnes out of the total 35 tonnes consumed internally. However, 36 tonnes of imported glass additives were used in coloured glass production, implying a total reliance on foreign suppliers to satisfy EU's glass manufacturing.

Given this asymmetrically developed value chain (predominantly downstream activities), knowledge and skills are concentrated on final product sectors and few REE sectors. This means that important intellectual capital may be missing from the European industrial eco-system, and that includes important skills related to REE separation which are essential for recycling activities.

Two conclusions can be drawn from EU's import dependence. The first is that this dependence will most likely last, given the current state of the EU upstream segment of the rare earth value chain and the growing competition it faces. The second conclusion is that final product manufacturers face significant exposure to price fluctuations in their imported inputs and are in a clear disadvantage with competitors like China who benefit from state controlled and integrated REE industries. Unlike in the EU, rare earth industries are strategic for countries China and Japan, both of which are committed to supporting domestic companies.

Besides, the EU's objectives to develop secondary raw materials markets are far from completion in the case of REE. Urban mining of rare earths in practically inexistent and end of life recycling input rate (EOL-RIR)[17] is still persistently low for most REE, ranging from 0 and 1% for the overwhelming majority of elements to 38% for europium[18] (European Commission, 2020b). In use stocks in the EU are substantial, and potential for recycling rare earths from some end-of-life products has been recognized (Guyonnet et al, 2015; Kooroshy et al, 2015; Guenter and Murguía, 2019; Binnemans et al 2013; Rademaker et al, 2013; Sprecher et al, 2014, Yang et al, 2017). The potential contribution of secondary raw materials to meet EU needs is significant, but policy actions have not yet capitalized on these findings.

Future Demand

The EU's Green Deal ambitions are set to bring about structural change to the EU economy. Namely by channelling resources to renew capital stocks in various sectors, to allow a transition to a low carbon economy while designing out waste and closing the loop on materials. The EU will become increasingly reliant on Critical Raw Materials, and rare earths in general are not an exception. The specific needs depend on the individual requirements of future applications and the precise timing and speed of the technology shift.

In the current state of technological and industrial development, REE will be necessary in the foreseeable future. Some authors point to the dependence on rare earths for the future of specific sectors, such as Dysprosium, Praseodymium and Neodymium for electric vehicles or Neodymium for domestic appliances (Abderrahim and Monnet, 2018). Others have affirmed that green technologies are dependent on rare earths in the energy and transport sectors (Haxel (2002), Kooroshy et al (2015), Zhou, Li and Chen (2017)). Binnemans (2015), points out that critical application for a "green transition" like NdFeB magnets, NiMH batteries and lamp phosphors all require rare earths. Hence the transition to low carbon economies strongly depend on the availability of REE. Additionally, a recent report by the EC, shows that REE are also required in drones, robotics, and fuel cells (European Commission, 2020 a.)

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[17] An indicator developed by the EC aiming to translate the share of the material input resulting from recycling. In other words, the EOL-RIR tells how much of the total material needs is being met by recycled material, which essentially translates a measure of circularity in material supply.
[18] The reason for europium EOL-RIR being substantially higher than that of other REE is because recycling from end of life fluorescent lamps was done by Solvay in France from 2011 to 2016.

Discussion about future trends in Rare earths markets are common since authors do not always agree on which technologies and applications will prevail and how fast transitions will occur within each sector. This is the case for lithium ion batteries and LED lamps which will eventually replace REE application in phosphors and NiMH batteries, weighing negatively on demand for Terbium (Tb) and Europium (Eu) from phosphors and La and Nd from batteries (although Nd demand is more than compensated through demand of permanent magnets). Despite the debate over technicalities some trends are clear in the EU, namely electric mobility, resource efficient lightning and renewable energy. Electric mobility is expected to increase demand for Nd, Praseodymium (Pr) and Dy 250%, 350% and 420% respectively by 2035. For wind power, which predominantly resorts to NdFeB permanent magnets, increased use of Nd, Pr and Dy of about 80%, 110% and 30%, respectively are expected by 2035. (Abderrahim and Monnet, 2018). Zhou, Li and Chen (2017) predict REE demand from clean technologies to reach 33.3, 33.6 and 51.9 kt in 2020, 2025 and 2030.

The USGS predicts global demand for rare earths to grow close to 5% for 2020 as well as eventual price rises for the near future anchored in 4 main factors – increased demand, stringent enforcement of environmental protection practices, industry consolidation in China and a fall in illegal mining (USGS, 2019). Other predictions consider growth rates of total REO demand of between 3 and 5% yearly until 2030 (Zhou, Li and Chen 2017).

It is also noteworthy that substantial efforts of substituting REE in major applications are currently underway. Governments and companies are investing in finding alternatives to the use of rare earths. Despite the possible success of these efforts, it is difficult to assess whether these novelty technologies will have market penetration and to determine the implications to Rare earths markets.

REE are likely to remain critical for the next 10 years. Furthermore, reliability of supply and price volatility will be the main sources of uncertainty (Deloitte Sustainability et al, 2017: 345 b.). Given its total reliance on foreign supply and a foreseeable need of this material, the EU is concerned with the evolution of global supply. Fulfilling the needs of its industry and ensuring the materials for a sustainable future are among the most pressing issues for the EU.

1.3 Supply – An EU perspective

"The EU will not master the shift towards sustainable production and environmental-friendly products without such high-tech metals"[19] – (European Commission, COM/2008/699: 3) This quote from the Raw Materials Initiative points to the problem at the heart of this project - A group of materials which are necessary for the future of the Union but whose supply is uncertain and largely escapes the control of EU institutions. The focus is then to guarantee the stable flow of rare earths to the EU industries which need them. But why does this stable supply represent a challenge for the EU? This section attempts to provide an answer to this question. Starting with a general introduction to how rare earths are supplied, in line with what was done for demand. Focus is drawn to supply dynamics in world markets, firstly by briefly summarizing the role of the main market player – China - followed by a short overview of the EU's role in rare earths value chains.

1.3.1 General Supply Considerations

Supply of rare earths refers to all the upstream steps of the generic REE value chain from mining to refining as illustrated in figure 5. Upstream steps of supply present some degree of variation, depending on the type of deposit. Upstream steps are summarized in the text box below.

UPSTREAM STEPS

Mining: excavation, drilling, blasting of ores with REO contents up to 9%.

Beneficiation: beneficiation essentially removes unwanted minerals (gangue), resulting in a rare earth concentrate with REO grade of 30-70%. The ore may initially be crushed and milled then subjected to mineral separation through physical (magnetic separation) and chemical (flotation) processes.

Leaching and cracking: RE concentrates are then subjected to cracking for hard-rock ores in order to dissolve the concentrate and extract the REE into mixed compounds like REE carbonates. Alternatively, leaching can be performed for ion-adsorption clays, resorting to alkaline or acid solutions, leading to mixed REE compounds.

Chemical separation and refining: break up REO into different smaller compounds progressively isolating the individual elements using basicity differentials (only solvent extraction is used in industrial scale, thus far). These steps can result in individual rare earth compounds with purities ranging from 99% to 99,999%, depending on the application.

REE can be found in several minerals, often divided between primary and secondary deposits, depending on the types of geological morphology of the formations. These deposits, scattered across the globe, have distinct REE grades, tonnage and individual rare earths distributions. Thus, the economic potential for REE production varies significantly across mining sites. Nonetheless most of the extraction of LREE takes

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[19] High tech metals is term used in this communication to refer to minerals like cobalt, platinum, rare earths and titanium.

places in carbonatite mineral formations, which are primary deposits, while main HREE mines are Ion-adsorption clay deposits (Van Gosen et al, 2017: 7).

It is worth noting that, REE mines are open-cast and usually undertake beneficiation activities on-site or close to the mine, producing rare earth concentrates. Most rare earths are exploited as by-products of other materials. Thus, the mining and beneficiation steps tend to vary accordingly (Royen and Fortkamp, 2016: 7-13). REE can be sold at different stages of processing, although an increasing share of REO are being processed in vertically integrated companies possessing the necessary knowledge and technology to separate and refine each individual REE. (Deloitte Sustainability, 2017b: 333-334)

Besides being complex, and hence knowledge intensive, processing of ores containing REE is costly, energy intensive, environmentally hazardous and heavily reliant on the use of chemicals (Capucha, 2019: 34, Royen and Fortkamp, 2016: 17, Schüler et al, 2011: 43-59, Machacek and Kalvig, 2017: 35-41). The outputs of REE separation and refining are tailored to match each sector's needs, whereby purity levels are the crucial factor. Additionally, as REE are often found together with uranium and thorium, it means that wastes and emissions have potential radioactive contents.

Negative externalities along the rare earths value chain are well documented and represent an important burden and source of hazard to the surrounding environment of the sites where upstream activities take place, while local pollution persists after mining activities are halted (BGS, 2011:17; Schüler et al, 2011: 45; Pagano et al, 2015). Environmental impacts may include air emissions of hazardous gases and dusts, tailings which are stored in ponds or dams, solid wastes, solvent and corrosive waters containing heavy metals, acids, ammonium, and fluorides. Near mining sites, accumulation of REE in the human body and in the surrounding environment have been found, as well as potential health risks to living organisms. (Pagano et al, 2015; Li et al 2013)

Environmental requirements are among the main factors affecting global REE supply chains. Environmental regulations and compliance vary between countries meaning that mining operations are faced with different operational costs. This institutional factor is recognized as playing in favour of upstream activities taking place in countries with less stringent environmental laws in general (BGS, 2011: 17; Tukker, 2014).

1.3.2 Balance Problem – A permanently unstable market?

One of the central challenges to the rare earth industry is the balance problem. It essentially consists in choosing the adequate supply quantities to meet demand, without creating supply surpluses for any of the REE (Binnemans et al, 2018). The rare earths market has a systemic issue with balancing demand and supply, given that mining one rare earth implies also extracting other materials. An estimated 85% of rare earth deposits contain REO concentrations of <3% (Zhou, Li and Chen, 2017: 12). This means that mining activities may have difficulties in responding to rapid demand changes.

The balance problem affects mostly LREE, whose demand is driven by Nd. Thus, supplying adequate quantities of Nd will result in excess production of more abundant and less demanded elements like Sm and Ce, since Nd contents in ores are low. In such cases, companies may be forced to stockpile less demanded elements thus incurring in additional costs.

The balance problem is related to the most demanded elements, corresponding to the large volume applications for rare earths which are driven by technological developments (Binnemans, 2015). Europium was once the most critical rare earth in the 1960s and 70s, widely used in cathode ray tube (CRT) televisions for its optical properties. In the 1980s, Samarium gained prominence due to its use in permanent magnets yet none of these two elements are among the most demanded today. Technological developments can take in short time spans and can be profoundly transformative, making it virtually impossible for mining companies to respond accordingly.
Dy and Nd will likely be in shortage for the coming decade, while surpluses are expected for the remaining REE (Zhou, Li and Chen 2017 pp. 10-12). Although accurately forecasting how applications that require rare earths will evolve is tricky. The main trends have been identified and include an increase in demand from alloys, catalysts, and magnets. Meanwhile NiMH batteries and lamp phosphors are decreasing and applications for ceramics, polishing agents and glass will stabilize (Binnemans et al 2018).

Adjusting supply to meet demand and avoid supply excesses under these conditions is challenging and contributes to the enduring risks in rare earth markets. The EU will likely remain a price-taker in Rare earths markets for the foreseeable future, continuously exposed to unstable market conditions. Dealing with uncertainty is not an easy task, but policy responses to the balance problem can promote a more resilient position for the EU in the long term. These policies include diversifying the sources of REEs in favour of secondary resources (industrial wastes) and waste containing rare earths (like WEEE) as well as substituting rare earths in products and finding uses for the elements which are oversupplied (Binnemans and Jones, 2015: 32-36).

1.3.3 The State of Global Supply

“The new technologies have led to swiftly expanding markets for REE products, in which China has achieved a monopolistic role in all segments of the REE value chains” (from Kalvig and Mahacek (2017 p. 87)).

All world mine production statistics converge on the fact that China is the largest producer of rare earths, in all its forms. In 2019, China produced 132 000 tonnes of REO, about 63% of total mine output, followed by the USA, Burma and Australia representing 12%, 10% an 10%, respectively. (USGS, 2020). The main suppliers of REO in the early 90s were China and the USA with identical production volumes. From 1993 to 1997, the picture changed radically, with most producing countries, including the USA, ceasing production while Chinese output spurred. By the early 2000s, China attained a quasi-monopoly status which went undisputed until 2011.
Figure 8 shows mine and oxide production by country in 2010 and 2018 (extracted from Schmid, 2019: 6). It should be noted that the REO production from Malaysia is done with minerals mined in Australia. The factory is owned by Lynas and has been funded by JOGMEC (Japan Oil, Gas and Metals National Corporation) through its JARE venture.

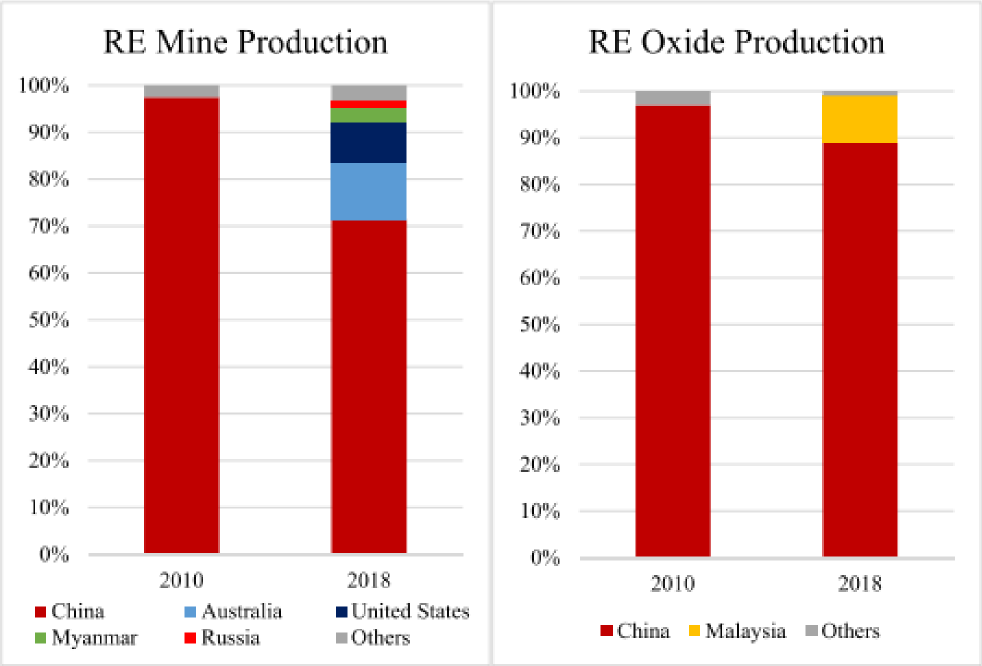

Figure 9 - Developments in the RE mine production and in the RE oxide production compared (image extracted from Schmid, 2019)

When dealing with supply concentration metrics, it is important to go beyond general market concentration statistics (Kooroshy, Korteweg and Ridder, 2010: 9)) to understand concentration at each supply chain step. The Chinese industrial policy played a

quintessential role in consolidating China's position as the main rare earth supplier across all levels of the rare earths value chains. Authorities were concerned with developing downstream steps of domestic value chains for diverse rare earth applications, favouring exports of high value-added products rather than the exportation of raw materials (Mancheri et al, 2013: 17-21; Mancheri, 2015; Schmid, 2019).
As a result, China went from exporting mainly components containing REE, such as magnets, phosphors and polishing powders before 2000, to increasingly exporting advanced REE-containing final consumer products such as batteries, mobile phones and LCDs. Implicitly this indicates that China began consuming growing quantities of REO to feed its REE and final product sectors. By 2015, China was the main consumer of REO, accounting for about 75% to 80% of total demand (Machacek and Kalvig, 2017: 64, Mancheri et al, 2019).

Table 4 shows Chinese percentage of world production at each stage of the supply chain for NdFeB permanent magnets both in 2010 and in 2015 (Eggert et al, 2016: 204). This table shows us the unwavering Chinese domination of rare earth markets even after the supply crunch of 2010-2011. Besides its dominance of REO mine production, China also possesses the major share of rare earth processing capacity along with components and final product manufacturing (Mancheri et al, 2013: 7). Despite separation of LREE being substantially easier than that of HREE (Leveque, 2014), most individual rare earth compounds and high purity REE are produced in China while only one Japanese company and Solvay were capable of separating HREE in 2014. (Machacek and Kalvig, 2017). Interestingly, both mining and separation outside of China increased from 2010 to 2015, meanwhile China consolidated its position in downstream manufacturing as well as magnet alloy and powder production (Eggert et al, 2016: 204).
China has become the only country with a rare earth supply chain which is vertically integrated (Bartekova and Kemp, 2016: 28). REE production in China is largely controlled by 'The Big Six', six large state-owned enterprises: Chinalco Rare Earth Corporation; China Minmetals Rare Earth Corporation; Xiamen Tungsten Corporation; Baogang Group (province-owned; under the umbrella China North Rare Earth High Tech); Guanschen-Guangdong Rising Nonferrous; Ganzhou Rare Earth Group (city owned) (Binnemans et al, 2018)

Table 4 – China's supply role in the supply chain for Neodymium- Iron- Boron magnets (NdFeB) (adapted from Eggert et al, 2016: 204)

SUPPLY CHAIN ACTIVITIES	CHINESE PERCENTAGE OF WORLD PRODUCTION AT EACH STAGE IN 2010[1]	CHINESE PERCENTAGE OF WORLD PRODUCTION AT EACH STAGE IN 2015
Mining and concentration	97%	80-85%
Separations	97%	80-85%
Metal refining	~100%	>95%
Alloying and magnet powders	90%	>95%
Manufacturing	75%	>80%
Components	NA	NA
Recycling	NA	NA

[1] Abbreviation: NA, not available

Resource protectionism was also extensively used by China through resource taxes, mining quotas as well as smelting and separation quotas. Export quotas, taxes and limited licenses were also imposed, the latter fell from 47 licenses granted to domestic firms in 2006 to 22 in 2011. While Chinese firms were not assigned product specific export quotas, joint ventures with sino-foreign firms were faced with exports restrictions of processed rare earths (oxides, salts and metals) from around 2004 to mid-2010. (Tse, 2011: 5-7)

Chinese rare earths policies have had a profound effect on rare earths market conditions. (Mancheri et al, 2019) Thus, the reliance on Chinese supply of rare earth related products is a source of concern for other countries, whose industries are dependent on China. This situation became evident when China's export quota policies began disrupting global Rare earths markets which motivated several countries to file complaints to the World Trade Organization in 2009 and 2012, claiming a violation of free trade rules by China.

Since this supply crunch, prices dropped abruptly, industrial processes became more efficient in material use, and supply sources are now more diverse given new mining operations outside of China (most of which extract only light rare earths) (Kooroshy et al, 2015). The abrupt price drop following the dispute, placed a burden on financial viability of new mining projects. Price uncertainty dissuades investment into new mining projects, thereby restricting diversification of supply (Mancheri et al, 2019: 111).

Besides, China and Japan are also investing heavily in mining projects abroad and raising their presence in foreign REE companies and projects (Schmid, 2019: 5-6). For China, this entails an increasingly widespread control of the global supply chain and further integration of Chinese Companies in foreign markets. Chinese companies have acquired important mines, namely Mountain Pass through the acquisition of *Molycorp* but also hold rights to important exploration projects like the Kvanefjeld in Greenland (Mancheri, 2015:107).

Acquiring foreign REE assets is a long-term strategy for China, which has been used in the past to acquire important knowhow from foreign firms like US's *Magnequench* in the late 90s, Canadian AMR technologies in mid-2000 (Mancheri et al, 2013: 19) Considering the current state of the global rare earth supply, Chinese dominance in the rare earth market is likely to continue. Besides, China can maintain its competitive advantage by allowing less stringent environmental regulation, at the cost of environmental degradation and increased health hazards.

Naturally, Chinese dominance influences the EU rare earths supply chain. Devising policies to support EU domestic supply chain will inevitably touch on the matter of Chinese dominance.

1.3.4. Supply of Rare Earths in the EU

The supply chain of rare earths in Europe is underdeveloped, namely because no mining of REE takes place in Europe but also because other upstream rare earths processing activities are missing from the European industrial ecosystem (Bartekova and Kemp, 2016; European Commission, 2020b: 16) Thus, achieving a stable and reliable supply of rare earths is essential to the EU and requires not only a thorough understanding of demand from different EU sectors but also a clear notion of the limitations in Europe's value chain.

Import dependence in the EU is absolute, which means a total reliance on foreign trade partners to obtain Rare earth concentrates and mixed REO (European Commission, 2020 b). Even if mining begins in Europe's most promising deposits, the rare earths output might well be processed in China. Hence there is no guarantee that REE import dependence in the EU would be reduced if mining were to take place in Europe (Kooroshy et al, 2015: 73).

EU upstream activities consist of services related to mineral deposits exploration and technical consultation on solvent extraction methods, and separation of mixed REO into individual REO. Few companies can separate mixed REO in large quantities. Perhaps the two largest separators are NPM Silmet[20] and Solvay, both of which source their concentrates from abroad and export part of their products (REE, rare earth compounds)[21]. Hence, both these companies are particularly vulnerable to import barriers, namely on mineral concentrates with radioactive content on one hand, and increased price competition from China (Machacek and Kalvig, 2017: 82).

The rare earths supply challenge in the EU is not exclusive to concentrates and mixed oxides but also to individual REE and primary inputs. There is a diversified set of REE sectors and final product sectors, which require rare earths in different forms and purities to meet specific industrial needs. Currently there is insufficient capacity in the EU to meet the demands from these sectors. All the glass additives containing erbium used in the EU are imported, while roughly 58% of Nd primary inputs (alloys, mischmetal, nitrates, oxides) are also imported (BIO by Deloitte, 2015).

Despite significant gaps in the rare earths value chains, relevant players operate in the EU like separators, metal and alloy manufacturers including companies like Vacuumschmelze and Treibacher. At the heart of these companies there is valuable know-how and expertise on REE which is strategic to the EU's future. For instance, according to Golev et al (2014), Solvay was the only company capable of separating both LREE and HREE outside of China in 2013. This technical knowledge and skills which need to be nurtured, without which a vibrant high-tec rare earths supply chain cannot emerge (Kooroshy et al, 2015: 80).

Despite there being strong EU actors in specific sectors, the EU supply chain as a whole is incomplete and somewhere along the value chain, rare earths or the application containing them will have to leave the EU for further processing and eventually return to the EU. Hence, the challenge cannot be overcome simply by flooding the EU with concentrates and oxides, because the EU does not hold enough capacity in its value chain to process the rare earths.

The EU rare earth challenge must be considered in the context of current global supply outlook and the EU's own supply. Recycling input rates for most REE[22] are consistently low and import dependence is likely to continue if upstream steps do not develop extensively in the EU in the upcoming years. Given the EU's strong demand for high value-added rare earths inputs and its competitive disadvantage with China, closing the loop on rare earths emerges as the only environmentally coherent option to nurture the EU's industrial landscape

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[20] An Estonian-based rare earth and metal manufacturer owned by Neo Performance Materials, which is the company that emerged from Molycorp after it filled bankruptcy in 2015.

[21] Other small operations of separation exist but have limited expression in the EU market.

[22] Except for europium which is recycled through phosphors. According to the European Commission the recycling input rate for this mineral is 38% (European Commission, 2020b)

with resilience that it does not currently possess. Supporting the current base of EU REE players is also essential to prevent further delocalization of activities to East Asia. These players have survived previous disruptions in Rare earths markets and hold essential capabilities and know-how on REE which are strategic to the EU's future.

2. REE policies – A critical view of EU REE policies

Public Policies aimed at rare earths, or REE policies as will be used hereafter, are closely related to the concept of Criticality. The REE challenge in the EU is not a novelty and several policies have been devised to tackle it. The EU has committed to improve circularity, increase recycling and supply from secondary sources of CRM.

REE policies have come a long way and, to a large extent, they have impacted Rare earths markets and stakeholders. Nonetheless, since the Raw Materials Initiative (COM/2008/699) recycling indicators are practically unaffected and recycling efforts have been seemingly insufficient to alter the overall state of EU supply. As will be argued in this section the public policies have been inadequate to provide the right conditions for rare earth recovery to flourish at an industrial level.

Part 2 provides a brief overview of REE policies before focusing on EU policies implemented in this policy area since 2008. This chapter begins by breaking down REE policies into different elements used in different regions. After providing a broad picture of what REE policies consist of, all the REE policies in the EU are summarized and their impacts considered. Special attention is given to efforts towards recycling or building closed loop systems for rare earths, while the most relevant policy aspects are highlighted.

2.1 Rare Earth Elements Policies

Supply shortages and price instability over the past decade have shaken Rare earths markets worldwide and criticality has become a pressing matter for countries looking to protect themselves from supply disruptions. In the EU, mitigating supply risks is a growing concern and a necessary condition to achieve a carbon neutral circular economy. It is important to keep present that in this context REE policies are conceptually identical to CRM policies for they solve the same issue. Although each material presents a different context, the policy paths used to tackle criticality of any material are essentially the same. REE policies are diverse and complex, thus it is useful to categorize them according to their focus. In fact, policy elements presented herein are often complementary and are seen in different combinations in REE policies depending on the economy.

In 2010, the US Department of Energy divided CRM strategies into 8 categories: (i) research and development, (ii) data collection, (iii) permitting for domestic production, (iv) financial assistance for domestic production and processing, (v) stockpiling, (vi) recycling, (vii) education and (viii) diplomacy (Bauer et al, 2010: 100). While Bartekova and Kemp studied REE policies of China, Europe, Japan, USA and Australia and have organized rare earth strategies in seven elements: domestic and foreign diversification of supply sources, stockpiling, resource diplomacy, recycling, R&D and resource protection (Bartekova and Kemp, 2016: 6-27). The categories created are practically identical, which suggest that REE policies and CRM policies do not differ substantially in their focuses.

Although they often share a common aim of tackling supply risks, differences in CRM strategies among countries can be attributed to 2 groups of factors: institutional and methodological.

Institutional factors reflect the national policy styles associated with the legal system and traditions, political structure, market structure, cultural attitudes, and acceptance of policy interventions in securing supply, the industrial organization and the type of participation in policy making process by industrial stakeholders, etc (Bartekova and Kemp, 2016: 2). National policies and the institutional factors affecting it are also closely related to a country's mineral endowments and its economic specialization profile (Kooroshy, Korteweg and Ridder, 2010: 9-13).

Methodological factors are related to the concept of CRM. Material criticality is a dynamic framework that can be adapted to technological and regulatory factors, as can be seen in the evolution of CRM methodology in the EU from 2014 to 2017 (Blengini et al, 2017). Meanwhile, the concept of criticality is highly subjective, depending mainly on which institution is undertaking the task (Graedel et al, 2016). In practice this implies that substantial divergence can arise, namely on the threshold that determines which materials are critical or on the desired conditions for a secure supply. Criticality should be carefully considered bearing in mind the period and the information available, the region or economy to which it refers, and the methodological approaches favoured (Graedel and Reck, 2012; Erdmann and Graedel, 2011; Binnemans et al, 2018).

The policy categories presented also reflect a policy diversity among countries in solving material criticality. The EU is a particular case because of its institutional architecture, in which some policy elements are not applicable. Take the case of resource protectionism– none of these policy elements apply to the EU reality given that natural resources belong to member states and not to the Union and consequently resource policies are largely uncoordinated.

REE strategy in the European Union is strongly oriented towards resource diplomacy and recycling, while diversification of supply and R&D are only moderately pursued. Some authors affirm that the EU is among the regions where recycling is most favoured, surpassed only by Japan. (Bartekova and Kemp, 2016)

2.2 The evolution of REE policies in the EU – A critical assessment

Considering the information on the state of Rare earths markets and the challenge it poses to the EU, we now turn to the EU strategy to tackle REE criticality and how it has evolved. It should be noted that EU policies tend not to focus on specific materials. Therefore, non-energy raw materials policies as well as CRM policies are addressed.

Concern with supply of raw materials and its security are present since the onset of the European Coal and Steel Community in the 1950s. But it was in the 1970s that recycling was suggested as a way to tackle supply risks, with an EC communication, where the EC[23]recognizes the EU's poor mineral endowments and growing import dependence to meet raw material needs (COM/1975/50). Since then, environmental policies in the EU have progressed but non-energy raw materials were not a focus of EU policies. It was not until 2008 that more attention was drawn to the subject.

In 2008 the Commission launched the "Raw Materials Initiative" (RMI) which established the EU's raw materials strategic policy framework to respond to old dilemmas related to the access to non-energy and non-agricultural raw materials. This document was quintessential to determine the EU's CRM strategy and established the EU priority areas moving froward. This integrated strategy rests on three central pillars for fighting criticality: a) ensuring a level playing field in access to resources in third countries; b) fostering sustainable supply of raw materials from European sources; c) boosting resource efficiency and promoting recycling (COM/2008/699).
The Commission defines 10 levels of response in the RMI anchored in the three pillars previously defined. Among these, is the definition of CRM which did not exist for the EU up until then, and, on a separate level, the pursuit of recycling and use of secondary raw materials. However, the focus of these 10 responses leaned towards resource diplomacy and foreign diversification of supply through wider policies like trade agreements with third countries, challenging trade distortions, as well as aid support and cooperation with developing countries.

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[23] Which was then named the Commission of the European Communities

Although recycling is mentioned as one of the pillars of the RMI along with resource efficiency, the policies adopted did not grant this pillar enough importance. That being said, a substantial reduction of primary rare earths demand took place in the first decade of 2000, before increasing moderately in 2015 and 2016. Imports of mixed Rare earth concentrates and separated REE plunged nearly 60% from 2000 to 2010 but the use of secondary rare earths barely changed in the same period. This indicates that primary consumption fell because some activities effectively disappeared from the EU, namely through delocalization to other geographies (Kooroshy et al, 2015: 17). In other words, with REE recycling rates at 1% in 2011 (COM/2011/25: 22), the reduction in primary rare earth demand was achieved not through recycling, as the RMI preconized, but through a systematic delocalization of EU REE sectors under way since 2000. The RMI and the resulting policies did not revert that process. In fact, imports of rare earth compounds and metals increased only marginally from 2010 to 2015 (Mahacek and Kalvig, 2017: 75-81)

Around the time of the RMI, the EU reiterated its compromise with a more sustainable industry (COM/2008/397) and energy (COM/2007/723) with the approval of a strategy for key enabling technologies (KET) and a roadmap for low carbon technologies from 2010 to 2020 (COM/2009/512 and COM/2009/519 respectively). Despite not having a direct focus on CRM, these policies furthered the need for REE in the Union to meet energy and industrial goals.
In the midst of the 2010/2011 “supply crunch”, the EC published the first list of CRM along with the methodology to assess criticality in the EU (COM/2011/25). The document states that a stable supply of rare earths “is important for climate policy objectives and for technological innovation.”, given its role in permanent magnets, catalytic converters for cars, printed circuit boards, optical fibres, and high temperature superconductors. Aside from mentioning the lack of commercially viable substitution and recycling options for rare earths, the EC refers another crucial factor - REE is not traded in official exchanges but rather in more opaque markets (COM/2011/25). This makes rare earths harder to track and production methods are largely unknown which has repercussion on data quality.

In 2012 the EC launched the European Innovation Partnership - Raw Materials (EIP-RM), which is a stakeholder platform to promote EU research and innovation by reinforcing the link between public and private sectors. (COM/2012/82). The EIP-RM builds a cooperation-based strategy to bridge knowledge gaps and to improve the take-up of innovations and technologies to address key challenges in the EU. The EIP-RM, mainly through its High-Level Steering Group (HLSG), plays a crucial role in EU policy on raw materials by providing high-level guidance and feedback to the EC and MS on the challenges related to raw materials. In essence the EIP-RM's goal is to stimulate innovation to fuel industrial activity in the EU, long-term security of supply of raw materials and a reduction in raw material import dependency by 2020. Innovation is perceived as a means to enhance the EU's industrial presence and raw materials supply. This policy initiative has also proven useful as a mechanism to secure R&I funding that turns policy goalsinto actions and projects. Just a year after EIP-RM, the EU introduced the Horizon 2020 - Framework Programme for Research and Innovation from 2014 to 2020 – thereby substantially increasing funding for raw materials research (Regulation/1291/2013). Horizon 2020 and EIP-RM complemented each other under Horizon 2020 5th societal challenge - Climate action, Environment, Resource Efficiency and Raw Materials. And several research projects arising from EIP-RM consortiums have been granted Horizon 2020 funding, as we will explore ahead.

After the HLSG was nominated, a strategic implementation plan (SIP) for the EIP-RM was adopted in 2013, where specific targets and objectives were defined until 2020. This SIP was essential to incorporate inputs from the various stakeholders, which culminated in a 2-part plan with 95 actions, 7 priority areas and 24 action areas. Among its main contributions the SIP's action area II.8 – EU Raw Materials Knowledge Base – to what is now the Raw Materials Information System. Another contribution are the EIP's raw material commitments, whereby several partners commit to activities that tackle the EIP-RM targets.

In mid-2013, the EC reported on the implementation of the RMI, summarizing important developments and commitments of the EU (COM/2013/442). Among these an important section about stockpiling concludes that after considering the results of a study ordered by the EC, MS casted aside the possibility of stockpiling as a policy option.
By 2013, the main advances of EU action were achieved on the front of the first pillar of RMI – Fair and sustainable supply of raw materials from global markets – namely on diplomacy and on EU trade strategy with resource rich countries, including the WTO rulings against China on REE and other raw materials, for example. Pillar 2 – fostering sustainable supply within the EU - was developed through enhancing the knowledge base on raw materials through research projects and expert networks like ERECON; and promoting best practices exchange among MS to attract investment in extractive industries.
The third and last pillar of the RMI – Boosting resource efficiency and promoting recycling - was the one where least progress was achieved. EU actions on the third pillar were focused mostly on resource efficiency and waste legislation, namely the advances on the eco-design and the progress on enforcing waste shipment regulation. In fact, according to this Communication no progress was registered on recycling of CRM from 2008 to 2013.

Just under a year later, the EC publishes a new list of CRM along with additional information on the implementation of the RMI (COM/2014/297). Interestingly, the EC states that most progress on RMI was achieved on the first and third pillars, although a clear emphasis is given to resource efficiency in the third pillar. The new list of CRM assesses criticality of more raw materials than the previous list and REE, divided into HREE and LREE, remain among the most critical. The inclusion of supply chain assessment was a major step in improving the quality and policy relevance of the CRM list. There is only a sentence pointing to waste policy review and revision of targets as the priority for 2014. The end-of-life recycling input rate for both HREE and LREE was 0% in 2014 (COM/2014/297).

By 2014, the Union was fully committed to its renewable energy transition and into a low-carbon economy[24] while the focus was overwhelmingly on innovation and resource efficiency. In that year, the concept of circular economy was formally inscribed in EU policy. In this Communication, the EC considers to the need to recycle CRM as one of the main waste challenges and proposes that MS include measures for collecting and recycling waste containing CRM in national waste management plans (COM/2014/398). Three years later, in the report on implementation of the circular economy action plan, there was no mention of CRM (COM/2017/33).

In 2017, the third list of CRM is published and it is meant to incentivise “(...) the European production of critical raw materials through enhancing recycling activities (…)” (COM/2017/490). REE were assessed individually for the first time and significant differences were reported between elements for economic importance. Erbium and lanthanum scored so low in that dimensions that the criticality threshold for economic importance was not met despite scoring among the materials with highest supply risk. All the other REE are among the most critical materials and the reported EOL recycling input rates were 8% for HREE and 3% for LREE, mainly due to 38%, 31% and 10% for Eu, Yt and Pr, respectively. The key findings from the final report of the 2017 CRM list, point to reliance on Chinese supply of rare earths to the EU (40% of supply) as the leading supply risk factor and that no transformation and manufacturing activity exists in the EU. Furthermore, it clarifies that a large proportion of EU consumption and imports of rare earths is in the form of finished products (which means both intermediate and final products) (Deloitte Sustainability, 2017b: 48).

In 2018, an amendment to the WFD was introduced targeting CRM. According to the revised article 9 of the WFD, MS shall create measures to prevent waste generation targeted at

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[24] For more on this topic see the following policies in the lead up to 2014 - COM/2007/1, COM/2007/723, COM/2009/519, COM/2011/21, COM/2011/112, COM/2011/571, COM/2011/885, COM/2013/253

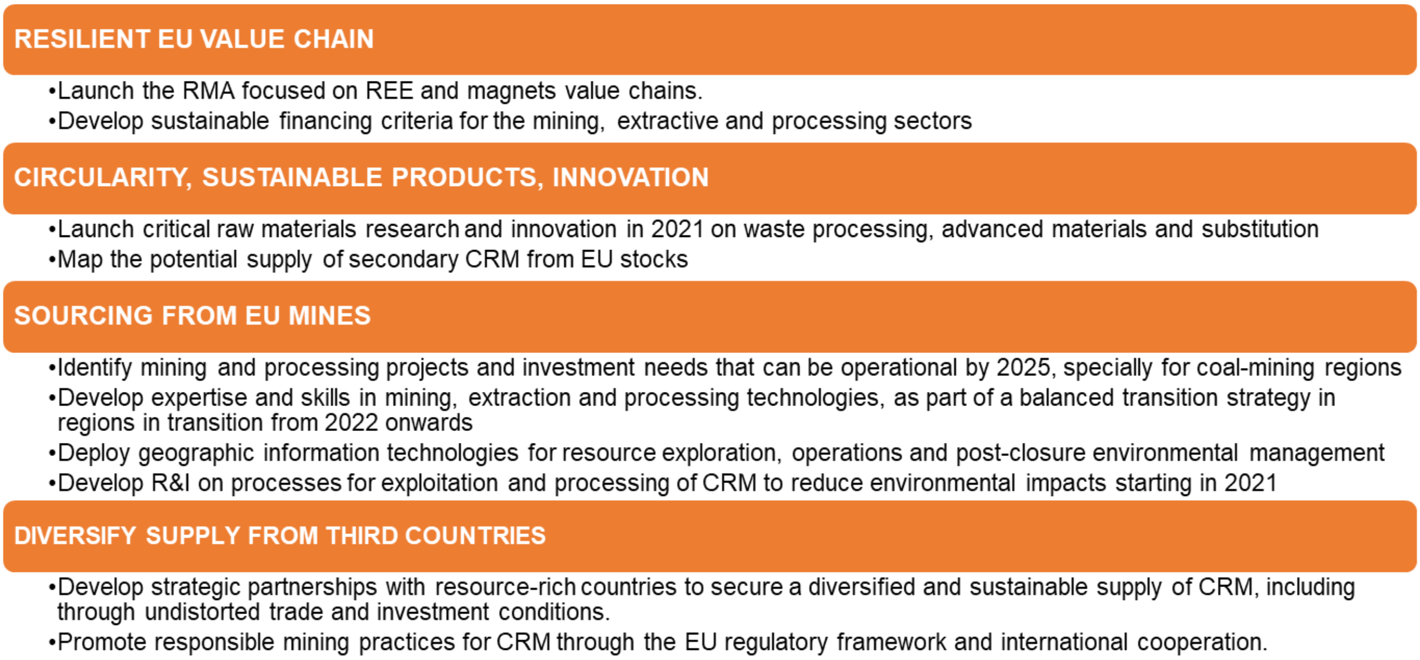
products containing CRM (Directive (EU) 2018/851). The amendment is vague and subject to interpretation by MS which are likely to take that into account only when reviewing Waste Management Plans, where waste prevention measures are usually inscribed. Waste policies in general tend to focus on recycling targets which are largely dependent on the bulk materials in products and thereby excluding any consideration on the recovery of REE or CRM (Guenter and Murguía, 2019: 44).

In March 2020, the Commission launched its “New Industrial Strategy”, laying forth the vision for the future of European industry as globally competitive, climate-neutral and digital (COM/2020/102). Among the fundamentals of Europe’s industrial transformation are a New Regulatory Framework for Sustainable Batteries and a Circular Electronics Initiative as commitments to building a more circular economy. Access to CRM is a fundamental piece in the industrial and strategic autonomy of Europe. However, the only direct consequences of this policy for REE policy was the announcement of an Action Plan on Critical Raw Materials (AP-CRM).

In early September 2020, the AP-CRM is published together with the EU List of CRM for 2020 (COM/2020/474). The most complete of all the CRM communications from the Commission includes a section on the most pressing issue to build resilience in EU CRM chains – The supply and sustainability challenge. It states that Europe needs more CRM resilience in “preparation for future shocks and to have more open strategic autonomy”. The AP-CRM follows the general narrative and objectives previously inscribed in EU’s CRM policy, with the significant difference that it lays down specific actions that the EC commits to. 10 actions are arranged within 4 topics – improve resilience in EU value chain, circular use of resources, sustainable products and innovation, promote sourcing from the EU, diversify supply (of primary CRM) from third countries. The actions are organized and presented in figure 9.

Of the 4 actions areas, 2 are focused on guaranteeing alternative primary supply sources. Most actions are concentrated in these 2 areas (60%), which signal the focus on mining and new supply/trade partners. The circularity area aggregates recycling and substitution efforts but the 2 actions proposed are focused on providing funding for innovation and gathering information about recycling potential in the EU. The policy focus when dealing with recycling and circularity of REE is on innovation. Innovation is conceived as the key to improving processes thereby making secondary rare earths competitive. It highlights the market-oriented perspective of EU policy makers, in the sense that the ambitions for recycling and substituting REE in products is left to the market players to achieve. Furthermore, this policy reveals the reluctancy in considering that the market actors may not invest in rare earths recycling or implement a circular use of materials in the framework or timeframe desired by the EU.

The EU will reinforce its approach, providing funding and guidance to market players as an attempt to reach circularity in the rare earths value chains. Besides the EU will bet on gathering more data on CRM flows in the economy, namely the in-use stocks and waste. Dependence on Chinese rare earth imports is at an all time high (98-99% for all REE) and RIR have not changed (38% for Eu, 10% for Dy, 1% and below for the remainder) (European Commission, 2020b: 8 and 24).



RESILIENT EU VALUE CHAIN

- Launch the RMA focused on REE and magnets value chains.
- Develop sustainable financing criteria for the mining, extractive and processing sectors

CIRCULARITY, SUSTAINABLE PRODUCTS, INNOVATION

- Launch critical raw materials research and innovation in 2021 on waste processing, advanced materials and substitution
- Map the potential supply of secondary CRM from EU stocks

SOURCING FROM EU MINES

- Identify mining and processing projects and investment needs that can be operational by 2025, specially for coal-mining regions
- Develop expertise and skills in mining, extraction and processing technologies, as part of a balanced transition strategy in regions in transition from 2022 onwards
- Deploy geographic information technologies for resource exploration, operations and post-closure environmental management
- Develop R&I on processes for exploitation and processing of CRM to reduce environmental impacts starting in 2021

DIVERSIFY SUPPLY FROM THIRD COUNTRIES

- Develop strategic partnerships with resource-rich countries to secure a diversified and sustainable supply of CRM, including through undistorted trade and investment conditions.
- Promote responsible mining practices for CRM through the EU regulatory framework and international cooperation.

Figure 10 - Diagram of the proposed actions in the EU CRM Action Plan (CRM-AP) (elaborated by the author based on COM/2020/474)

The creation of the European Raw Materials Alliance (ERMA) is among the most valuable actions for EU REE policy, since its initial objective is to "to build resilience and open strategic autonomy for the rare earths and magnets value chain, before extending to other raw material areas" (COM/2020/474 Action 1). This initiative was designed as a collaborative platform from the start, with participation from industry, investors, EC, EIB, stakeholders, MS and regions. ERMA is managed by the EIT Raw Materials consortium, which will lead the stakeholder consultations. ERMA's goal is to "identify, barriers, opportunities and investment cases to build capacity at all stages of the raw materials value chain", the most pressing of which is to increase resilience in rare earths and magnets value chains[25]. The main question remains as to the amount and form of investment the EU will make.

In summary, the EU has reinforced its commitment to tackling REE criticality and granting resilience to the value chains. It has done so by ensuring funds for industry stakeholders and innovation and R&D projects. More recently it has established the ERMA with acute focus to strengthen REE value chains. However, the actions proposed follow the same policy approach since the RMI. The resources channelled to solving the rare earths conundrum have increased but the logic of intervention have not and facilitating and promoting exploration and mining activities is generally favoured. The free-market imperatives have resisted despite the unwavering REE recycling rates over the last decade and the EU remains reluctant to actively intervene and shape European market dynamics.
As EU policy makers turn to an extractive answer, the free-market ideals will likely strike back, given that Chinese companies are involved in the exploration phases in large REE deposits in the EU, the mining companies will decide whether the ores extracted from European soil would remain in the domestic value chain or be processed elsewhere. If faced with the lack of separation capacity in Europe, mining companies will not hesitate in shipping the ores or concentrates to China for separation. And Chinese authorities will likely facilitate the process by establishing connections to downstream domestic firms. If the EU upholds free-market principles, then it struggle to devise policy instruments to process the rare earths domestically as it constitutes resource protectionism.

2.3 EU funded REE projects

The EU has been home to several REE related projects since the RMI became operational. Among these we highlight some notable projects for the EU rare earths value chains. An extensive account of all these projects would not be possible in this context. Several of these REE related projects have now been concluded and the impacts are hard to measure, some have culminated with patents and established companies and other have been extended to other funding windows.

The projects selected showcase the types of projects developed in the EU and diversity in REE-related research. The selection demonstrates the EU research funding programmes in action. Therefore, the specific funding call and the amounts associated with each REE related project will be specified.

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[25] From ERMA website - https://erma.eu/european-raw-materials-alliance-launch/ (accessed on 02/11/2020)

PROMINE – 2009 to 2013

The Promine project began in 2009 and was the first comprehensive attempt to map out CRM mining potential in Europe as well as to estimate the secondary CRM. The first two work packages focused on developing a pan-European Georesource database and exploring the use of 4D modelling tools to mineral deposits in Europe. This project is relevant because it was the first large scale integrated project on raw materials to receive funding in over 20 years[26]. The 4 work packages were developed by a consortium of 20 stakeholders including mining and nano materials industry players, public authorities and universities with a total budget of over 17 million €. The project received 11 million € in funding from the FP7[27], the EU research and innovation funding programme, under the "Cooperation - Nanoscience, Nanotechnologies, Materials and new Production Technologies" (FP7-NMP) specific programme[28]. The results were inspiring and extensive. A total of 7 patents were filled, several papers were published, training was provided on 3D and 4D modelling for geo-practitioners, production methods for[29] nano-silica from mining waste were developed. The most relevant results for REE policy include the first map of CRM in Europe as well as a modelling program for mine site geology, both of which refer to primary raw materials.[30]

REMANENCE (Rare Earth Magnet Recovery for Environmental and Resource Protection) – 2013 to 2016

This project was also funded under the FP7-NMP but for the topic "innovative recycling technologies for key metals in high-tec applications". The scope of the project is narrower given that the focus is exclusively on developing new and innovative processes for the recovery of NdFeB permanent magnets from various WEEE. The project was smaller in scale and was carried out by consortium of 10 private companies and the University of Birmingham. The total budget was roughly 5 million €, of which 3,7 corresponds to EU funding. The results presented in 2016 were positive for rare earths recycling from permanent magnets, given that new separation

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[26] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/228559/reporting (accessed on 02/11/2020)

[27] Seventh Framework Programme, active from 2007 to 2013.

[28] For more information on the FP7-NMP see https://cordis.europa.eu/programme/id/FP7-NMP and https://wayback.archive-it.org/12090/20191231084644/http://ec.europa.eu/research/fp7/index_en.cfm?pg=understanding

[29] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/310240 (accessed on 02/11/2020)

[30] For additional information see - http://promine.gtk.fi/index.php/about ; https://cordis.europa.eu/project/id/228559/reporting

techniques were consolidated based on sensing and mechanical processes and hydrogen decrepitation. The recovered materials were used to produce permanent magnets with comparable magnetic properties to virgin rare earth magnets, while achieving lower energy consumption than in new magnet production.

The Remanence project was chosen for 2 mains reasons. The first being that it is an example of a successful project whose results are being explored in another EU funded project – SUSMAGPRO. Remanence is a representative project of the type of research systematically carried out in EU funded REE-related projects. The extension of this project into a new funding framework and with more ambitious goals and new members, signals the success of EU REE policy in providing adequate funding for market players to explore rare earth recycling.

SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy) – 2019 to 2023

Building on the hydrogen decrepitation method of Remanence, SUSMAGPRO aims to "develop a pilot supply chain from recycled neodymium magnets in Europe. "[31]. With an enlarged budget of 14,7 million €, this project has united 19 partners including participants of Remanence like Birmingham University and Magneti Ljubljana and some big players in rare earth value chains like Less Common Metals, Kolektor, B&C speakers but also Leiden University and final product manufacturers like Sennheiser and Grundfos. 88% of the budget for this project was financed by the Horizon 2020 programme - "Societal Challenges - Climate action, Environment, Resource Efficiency and Raw Materials" under the activity line c) Ensuring the sustainable supply of non-energy and non-agricultural raw materials.

Essentially the plan for this project consists in setting up various recycling pilots and find reprocessing routes for the recovered materials. There are currently 4 recovery pilots and 4 reprocessing routes spread across 4 countries – Germany, Sweden, Slovenia and England. Additionally, magnets produced through the reprocessing routes will be sold online through a partner platform[32]. SUSMAGPRO is an ambitious pioneering project looking to establish a pilot closed loop supply chain, directly linking recovery of rare earths from permanent magnets to reprocessing activities.

This project has tremendous potential for the EU recycling chain given that it will allow to identify barriers and bottlenecks to recycling of permanent magnets from WEEE.

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[31] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/821114 (accessed on 02/11/2020)

[32] Website address - https://e-magnetsuk.com/ (provided in the official SUSMAGPRO website)

New methods will be tested at a commercial scale, namely the Hydrogen Processing of Magnetic Scrap (HPMS) in different contexts and reprocessing routes will be assessed. Besides, the project may also unravel the limitations and barriers to private recycling initiatives in comprehensively closing the loop on REE present in WEEE.

EREAN (European Rare Earth Magnet Recycling Network) - 2013 to 2017

EREAN was created in 2013 with the aim of training 15 young researchers in the science and technologies of REE in order to strengthen the pool of qualified chemist and engineers in the EU rare earths market. The focus of the training rests on rare earth magnet recycling and the goal is that the trainees will be able to "tackle the barriers to develop fully closed-loop environmentally-friendly flow sheets for recycling of rare earths from EOL consumer product". This project was fully funded with close to 4 million € by the FP7 – PEOPLE programme under the topic "Marie-Curie Action: Initial Training Networks" [33]

Various paths to recover rare earths were assessed, namely extract NdFeB material from scrap, roasting and leaching techniques applied to magnets, and solvent extraction of lanthanides. As a result, 2 policy briefs were published[34] along with 17 scientific papers by the participants and experts, which contributed to the training of the 15 researchers. It should be noted that aside from the universities participating, industrial companies like UMICORE and Solvay also took part in this project.

DEMETER (Training Network for the Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles) – 2015 to 2019

Integrally funded under the topic as EREAN[35] and for a similar value of 3,8 million €, the DEMETER project focuses on training 15 Early Stage Researchers through the development of both recycling methods for rare earths based permanent magnets used in EVs and design-for-reuse solutions for EV motors and generators[36].

Aside from the beneficiaries of the training program to which 15 PhDs were granted, this field of research was successfully enriched by the studies undertaken during the project. Sustainability concerns and recycling methodologies were furthered and as a

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[33] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/607411 (accessed on 02/11/2020)

[34] The policy briefs can be found in the following web address: http://etn-demeter.eu/wp-content/uploads/2017/07/Policy-Brief-DEMETER_EREAN_June-2017.pdf and https://core.ac.uk/reader/34634610

[35] In H2020 the topic was named - Marie Skłodowska-Curie Innovative Training Networks (ITN-ETN) - https://cordis.europa.eu/programme/id/H2020_MSCA-ITN-2015-ETN

[36] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/674973 (accessed on 02/11/2020)

result 21 peer-reviewed papers were published. A symposium and a summer school were held, policy briefs were published along with videos and a website to share the findings and promote recycling.

A large consortium of universities including the university of Birmingham, Catholic university of Leuven, Jozef Stefan Institute participated in this project as well as industrial partners like Less Common Metals and the FIAT research centre.

REECOVER (Recovery of Rare Earth Elements from magnetic waste in the WEEE recycling industry and tailings from the iron ore industry) – 2013 to 2016

REECOVER was a research project looking to evaluate the potential for rare earth recovery from both WEEE scrap and apatite tailings from iron mining through a range of different hydro and pyrometallurgical methods. With a budget close to 8 million € the project lasted 3 years starting in 2013 and received funding equivalent to 76% of the budget (6 million €) from programme FP7 – "Cooperation": Environment under the topic - Turning waste into a resource through innovative technologies, processes and services[37].

REECOVER resulted in innovative methods for recovering REE from both industrial waste and iron-containing electronic waste. Among the published articles reporting the findings of this project is one of the most comprehensive reviews on methods for recovering rare earths from permanent magnets - Yang et al, 2017.

PROSUM (Prospecting Secondary raw materials in the Urban mine and Mining waste) - 2015 to 2017

The PROSUM project kickstarted in 2015 with 3 million € funded through the H2020 – Societal challenges topic "Secondary raw materials inventory" under the line of activities - Enabling the transition towards a green economy and society through eco-innovation. The project has yielded a pioneering contribution to EU knowledge on REE. That is a comprehensive inventory on secondary CRM quantities present in EOL products from 3 waste streams – EEE, vehicles, batteries, and mining tailings[38].

The outcomes of this project have been relevant contributions to the EU knowledge base in the EU. In fact, a pioneering open-access data platform was created to provide project findings to the public. This platform was reorganize and renamed -

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[37] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/ 603564 (accessed on 02/11/2020)
[38] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/641999/results (accessed on 02/11/2020)

http://www.urbanmineplatform.eu/ . This platform is still accessible, and the consortium has devised a business plan to maintain the platform and further activities. The project partners have declared their intention to integrate the database on the RMIS managed by the JRC.

CEWASTE (Voluntary certification scheme for waste treatment) – 2018 to 2021

CEWASTE is 1,9 million € project fully funded by H2020 with 9 partners, including recyclers associations that aims to develop a voluntary certification scheme for collection, transport and treatment facilities dealing with designated waste streams. The goal of the project is to contribute to EU supply of secondary CRM through improving treatment processes.[39]

The plan consists of studying the practices of the sector, devise technical, sustainability and traceability requirements along with assurance and verification schemes. After testing the mechanism and consolidating the various aspects roadmaps will be delivered and dissemination of the results will begin, as to reach different actors for future certification. The project covers REE in fluorescent powders, NdFeB permanent magnets, NiMH batteries from WEEE and EOL vehicles, but in its reports states these are generally not economically feasible (Deubzer et al, 2019: 15).

EURARE (Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits) – 2013 to 2017

EURARE was a 13,7 million € project establishing a comprehensive network of public entities, universities, mining and metals companies to support mining of rare earths in Europe. Starting in 2013, the project gathered 9 million € in EU funding through FP7 – NMP under the topic "New environmentally friendly approaches in minerals processing ". The end goal of the project was to develop a sustainable exploitation scheme for Europe's REE deposits.[40]

Comprehensive mapping of existing reserves was done and over 156 REE occurrences were found. The findings and datasets were made available to the public and the website is still running. The project also explored metallurgical processes for REE resulting in 3 patents and 15 publications. Project partners worked directly with license-holders to the Kvanefjeld, Kringlerne and Norra Kärr deposits, with

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[39] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/820859 (accessed on 02/11/2020)

[40] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/309373 (accessed on 02/11/2020)

beneficiation, leaching and solvent extraction being done by European partners like Outotec, MEAB and in EURARE beneficiation pilot plant (Balomenos et al, 2017).

SCRREEN (Solutions for Critical Raw materials - a European Expert Network) - 2016 to 2019

The SCRREEN project was a 30-partner consortium fully funded with 3 million € under "Raw materials policy support actions" of H2020[41]. The project had the ambition to create a long-lasting inclusive network of raw material experts and stakeholders along with civil society. The SCRREEN project produced state-of-the-art reports covering technical and policy aspects in 11 work packages. A knowledge management portal was also created as to disseminate the findings and information to the public.

SCREENN has contributed to clarifying and consolidating available data on Rare earths markets. Besides, it has provided policy guidance by identifying pathways for increasing CRM production through primary and secondary raw materials. Important policy recommendation were provided among which are improving collection and dismantling of CRM waste, assert eco-design implementation, amending of WFD to include points on CRM, providing better data on SRM, track changes in product compositions and create reporting requirements for recyclers. Despite not covering the actions to promote recycling, the authors point that "Reduce our dependence on primary CRMs through fostering end-of-life recycling and through substitution strategies" (Guenter and Murguía, 2019: 33).

Numerous other projects, either directly or indirectly related to rare earths recycling have been funded by the EU[42].

2.4 Other relevant projects for REE policy in the EU

Three EU led initiatives should be mentioned for their importance in EU REE policy – ERECON, EIT Raw Materials, Raw Materials Information System

ERECON (European Rare Earths Competency Network)

ERECON was an expert group established in 2014 by the EC to provide recommendations for REE policy to improve supply security and resilience anchored

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[41] Information provided on official EC website for EU funded projects: https://cordis.europa.eu/project/id/730227 (accessed 02/11/2020)

[42] For further information see the following projects: Minerals4EU, RECLAIM, REE4EU, CRM Innonet, Remaghic, REE-CYCLE, RECUMETAL, SCALE, SecREEts to name a few.

in 3 topics, based on which the working groups were established - opportunities and road blocks for primary supply of rare earths in Europe; European rare earths resource efficiency and recycling; European end-user industries and rare earths supply trends and challenges.

This was a collaborative effort of over 100 professionals working in public policy, academia, think tanks and businesses which culminated in a final report, which still represents a major support document for EU REE policy. After this network, others were formed, some of which have been mentioned above. ERECON remains a reference of good practice in this field since it yielded important policy recommendations like supporting HREE exploration in Europe, funding pilot plants and technologies for HREE processing, strengthening EU knowledge and skill base, stimulating rare earth waste collection and furthering eco-design, and others (Kooroshy et al, 2015: 62-86).

EIT Raw Materials

Initiated and funded by the EIT (European Institute of Innovation and Technology) and among the most important EU projects is the EIT raw materials – a consortium in the raw materials sector. It was formed with the goal of raising competitiveness, attractiveness and growth of raw materials sector in Europe through innovation, education programmes and entrepreneurship.

The working format for the EIT Raw Materials is to bring partners together in innovation projects which are aligned with the innovation themes on the table. It provides business support with accelerator programs and calls for projects specifically targeted at SMEs and start-ups. The EIT Raw Materials has brought together industry players for numerous projects related to raw materials in general, but also to REE.

The GloREIA project is one example, whereby an internationalization project was launched among EIT Raw Materials partners in 2018 and culminated in the establishment of the Rare Earth Industry Association (REIA) in 2020 with 12 founding members. Projects like REEBAUX are still underway and attempt to assess the potential of recovering rare earths from pre-consumer bauxite mining residue.

The EIT Raw Materials recently funded a 3-year project initiated[43] by the BRGM and SUEZ in 2019 to explore solutions in disassembly, short loop recycling and an indirect recycling route with hydrometallurgical methods. Other partners are involved, namely

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[43] The financial details of the operation have not been announced.

Kolektor and universities of Delft and Leiden, all of which have participated in EU funded research projects related to the rare earths value chains.

Raw Materials Information System (RMIS)

The RMIS is a digital information platform and knowledge service centre for raw materials and is managed by the D3 unit of the Joint Research Centre (JRC) the knowledge focused Directorate General (DG) of the European Commission[44].

The RMIS is an important gateway to knowledge and data arising through EU funded projects like PROSUM, MICA, MIN-GUIDE. Its focus is broad, and covers the whole value chain for non-fuel, non-agriculture primary and secondary raw materials. It aggregates policy documents both from EU and national level, geosurvey information, news, reports and updates on JRC initiatives like the Raw Materials Scoreboard. It also provides country profiles covering many dimensions relevant for researchers, miners, recyclers, traders and stakeholders in general.

The EU REE strategy has been focused mainly on resource diplomacy and recycling, but the latter has been left for the market to achieve. The EU has relied mostly on soft law instruments and R&D has been the basis on which the EU hopes to achieve a circular management of rare earths. EU’s efforts to support mining exploration should not be overlooked. These are questionable from a circular economy perspective as the EU is promoting the extractive potential and attractiveness of the continent.

The EU has financed REE projects extensively under the FP7 and Horizon 2020 but supply security has not changed substantially. In fact, reliance on Chinese rare earths is still at 86% for most of the elements according to the latest data from the Commission (European Commission, 2020b: 5). Despite the indispensable results from these projects and the reduction in costs achieved, recycling activities still face crippling pressures to operational profitability. In technical terms, recycling of rare earths will progressively become viable and EU funded research is certainly speeding this process. However, uncertainty will remain, thus undermining supply security.

The policy solution to tackle criticality is overwhelmingly to explore primary resources while recycling, circular economy and resource efficiency are secondary. Instead recycling could be a strategic sector of common interest for the EU and contribute to supply security and resilience.

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[44] The RMIS can be openly accessed through the following website: https://rmis.jrc.ec.europa.eu/

The ERECON expert panel, in their final report raise the question: How we define supply security and what level is acceptable for the EU? As the authors put it – Is it enough to have imported ores from the US separated in the EU, shipped to component manufacturers before ending in European manufacturing facilities? Or is it enough not bothering with building an alternative to Chinese supply chain dominance provided that there are non-chinese supply alternatives at all stages of the supply chain? (Kooroshy et al, 2015: 73)

The answer proposed is to separate oxides, phosphors and alloys from EU post-consumer waste in Europe to be sold downstream, preferably to EU suppliers and inevitably to non-EU suppliers, eventually re-entering the Union for final product manufacturing or embedded in an imported product.

3. Policy discussion and recommendations to tackle REE criticality

Despite its REE policies, the EU is still import dependent and recycling is not yet established at a commercial scale. The EU rare earths conundrum is therefore a persistent issue and a liability to the EU industry. Ensuring a circular management of raw materials should be an integral part of a REE criticality strategy. Closing the loop on REE can yield benefits for supply security and independence, reducing exposure to external shocks (Schüler et al, 2011: 110).

The recommendation presented consists of establishing a geographically integrated collection-dismantling system for rare earths in EOL products and undertaking recycling activities in dedicated co-created pilot plants. Moreover, it is an opportunity for the EU to align its industrial policy and CE principles and promote an unprecedented long-term investment into Green industry and jobs. To capitalize on this opportunity, the EC and the Council of the European Union need to step outside their usual role to take initiative in correcting a market failure by launching a joint venture with private actors to close the loop of rare earths in certain waste streams, thereby placing circularity at the heart of waste management.

Section 3.1 provides an initial discussion on the importance of closing the loop on REE and the limitations of EU market-oriented policy instruments are pointed out. Alternative political commitments by the EU institutions for a European rare earth waste management system are then laid out. Before putting forward recommendations based on 3 pillars – waste streams, inputs and outputs - for setting up such a system in Section 3.2.

3.1 Policy Discussion – Going beyond free-market policies

The EU has for a long time recognized the importance of recycling and of secondary raw materials as an integral part of its raw materials policy (COM/1975/50, COM/2008/699, COM/2011/25). Several policies and projects have tackled REE criticality by filling information gaps, building industry and expert networks, funding research, best practice sharing along with resource diplomacy efforts. Despite not directly affecting recycling rates, some of these policies have provided support for rare earth recycling research and pilot projects to develop in the EU. But some aspects of EU REE policy need tweaking while others may require a totally different approach if recycling is to become a relevant and secure supply source.

Failing to find policy alternatives to build circularity in the European rare earth value chains will aggravate the REE conundrum. As the energy transition is gaining speed, so is the need for a reliable supply of rare earths. This conundrum is undermining the CE objectives from both a practical and an ethical perspective.

From a practical perspective, decarbonizing the EU economy requires replacing significant amounts of assets, many of which require rare earths. This means that transitioning to a CE will rely on third countries to supply either the rare earths to the EU industry or the final product (e.g. EV or wind turbines). The EU is faced with the dilemma of working towards a CE while relying on a foreign supply of REE and equipment containing rare earths which does not abide by EU environmental and social standards. To put it simply, the EU circular economy depends on foreign trade partners which are not playing under the same rules. From an ethical perspective, even if the necessary “green” materials and products are secured, the EU has a moral obligation to deal with waste containing rare earths which at present is a major challenge for the Union. According to the CE principles waste should cease to exist and instead a recovery of embedded materials should take place, thereby reducing extraction of primary non-renewable resources.

In the WEEE stream where a large share of REE is concentrated, there are significant gaps of uncollected scrap, in 2018 the recycling rate of WEEE was below 35% for the EU 27, decreasing from 2017[45]. Closing the loop on rare earths is necessary given that substantial amounts of REE are present in EOL product being landfilled or contaminating other metals recycled.

Aside from being technically viable, rare earth recovery could provide a substantial contribution to EU supply (Du and Graedel, 2011; Golev et al, 2014; Schüler et al, 2011: 100-110; Guyonnet et al 2015) [46]. There are growing amounts of rare earths present in products currently in-use, also knows as in-use stocks, in addtion to the REE present in EOL products

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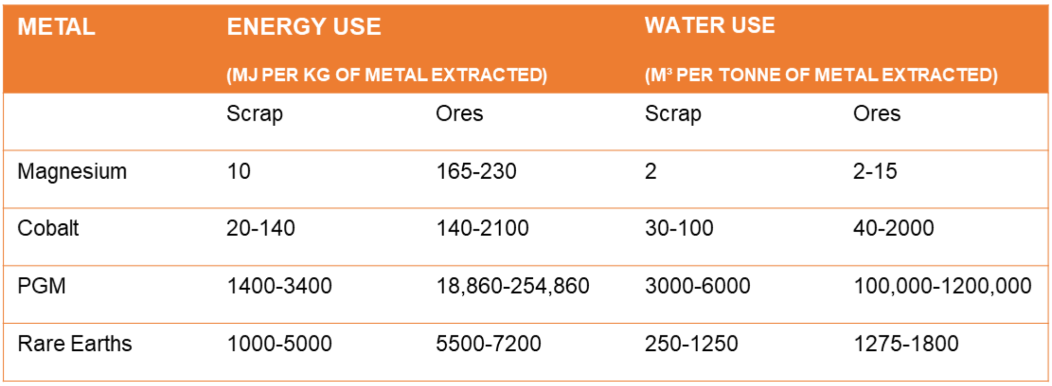
[45] Data retrieved from Eurostat through: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=t2020_rt130&plugin=1 ; for timeseries data see: https://ec.europa.eu/eurostat/statistics-explained/images/0/02/Electrical_and_electronic_equipment_%28EEE%29_put_on_the_market_and_waste_EEE_collected_and_treated%2C_EU-27%2C_2010%E2%80%932017_%28thousand_tonnes%29.png

[46] Technical feasibility of recycling - The potential of different criticality mitigation strategies such as recycling and substitution have been discussed intensively, especially with regard to their respective technological and engineering challenges - for further detail read: Cheisson and Schelter (2019), Massari and Ruberti (2013), Pavel et al (2017), Rademaker et al (2013), Smith and Eggert (2016), Sprecher et al (2014), Binnemans et al (2012), Yang et al (201~7).

continuously being discarded (Guyonnet et al, 2015, Rademaker, Kleijn and Yang, 2013; Buchert et al, 2012). Recycling contributes to a more environmentally sound rare earth value chain, considering the lower environmental impacts when compared with primary production (Yang et al, 2017: 144; Binnemans et al, 2013: 19; Machacek et al, 2015). Table 5 compares the estimated values for energy and water use in rare earth production from ores and from scrap (recycling). The ranges presented account for the differences in ore grades (European Commission, 2018: 11).

Table 5 - Energy and water consumption in production of metals from scrap and ores (adapted from European Commission, 2018).



METAL	ENERGY USE (MJ PER KG OF METAL EXTRACTED)		WATER USE (M^3 PER TONNE OF METAL EXTRACTED)	
	Scrap	Ores	Scrap	Ores
Magnesium	10	165-230	2	2-15
Cobalt	20-140	140-2100	30-100	40-2000
PGM	1400-3400	18,860-254,860	3000-6000	100,000-1200,000
Rare Earths	1000-5000	5500-7200	250-1250	1275-1800

Therefore, closing the loop on rare earths is a pressing strategic objective for the EU, for it contributes to securing a sustainable and local supply of CRM through secondary raw materials which is crucial for a CE (Machacek et al, 2015: 82-84). Besides, it channels investment to create sustainable industrial capacity and develops domestic value chains, in addition to enhancing REE technological innovation, knowledge and skills.

The EU has a declared goal to guarantee sustainability in both access and management of raw materials whether from primary or secondary sources (COM/2008/699, COM/2011/25, COM/2012/82). What is the impediment to achieving a circular management of rare earths with growing recycling rates and use of secondary rare earths?

3.1.1 Market failures and the need for an alternative policy approach

Can rare earth recycling in the EU be achieved by market players?

The answer is that we do not know. Although some market initiatives are positive testimonies in this regard, the broader picture suggests that it all depends on market conditions. EU REE recycling projects are private business initiatives (even if they are often partly publicly funded), which obey to market dynamics. If operations do not reach financial sustainability, they are likely to halt. This is precisely what took place in Solvay's La Rochelle and Saint-

Fons factories where phosphors from EOL lamps were being recycled (Delamarche, 2016). In other words, even if technically viable, recovery of rare earths is largely dependent on market conditions which can be volatile and unfavourable for rare earths recyclers (Guenter, T, and Murguía, 2019: 42-43; Schüler et al, 2011: 105-118). This means that under a strong demand coupled with sustained high REE prices (which has not been the case for the past decade), private business could establish recycling plants, given the business opportunity, in spite of the high capital expenditures. However, as we have seen, market conditions are exogenous to the EU and recent shocks can cripple EU industry.

Another important factor is that the EU looks to promote its waste hierarchy and to recover materials from waste streams. But companies are concerned mainly with operational efficiency, which often implies recovering only the most valuable materials. In other words, market recycling is centred on high value materials and not on minimizing waste disposal. The remainder of materials are not recovered and often sold downstream as scrap and eventually lost in slags (Schüler et al, 2011: 109). It seems logical for a company not to recycle something whose recovery costs more than the value of the recovered material. Basically, the loop might not be fully closed through a market competition mechanism alone.

Another weakness of a market-based recycling system is that it may require a dedicated collection and dismantling system for waste containing rare earths which will overlap with already established waste collectors. Namely for the WEEE stream, it is not yet clear how private rare earths recyclers will integrate the established waste management chain. It may be that the WEE collectors find more profitable destination for WEE scrap recycling through PGM[47] or precious metal recyclers which leave rare earths unrecovered, for example. Hence there is an incentive for rare earths recyclers to set up operations in a closed loop system with fixed partners supplying the scrap and buying the recovered rare earths, parallel to existing waste management schemes. Despite closed loop systems being positive in principle, measures need to be taken to coordinate parallel waste management systems. Recycling magnetic scrap for example is challenging and costly since it requires demagnetisation before air transport, which is challenging for dismantlers.

The REE global markets are predictably unstable and judging by the last 40 years, free market economies have been completely outmanoeuvred by a Chinese coordinated industrial policy. Therefore, commercial recycling activities in the EU cannot be conditional on favourable market conditions, or else we risk never achieving consistently profitable and resilient waste management operations. During the supply crunch, the market failed to come up with a solution (Tukker, 2014). It seems unwise to trust the market to solve a

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[47] Platinum group metals

fundamentally environmental and societal challenge - closing the loop on rare earths. If closing the loop of REE (and of all materials) is a strategic goal of the EU, then it should be the EU ensuring the necessary means to achieve this goal.

A strategic goal justifies going beyond funding market players in research and pilot projects. Or else it cannot be expected of EU firms alone to successfully undertake this task, especially under everchanging market conditions and a systematic competitive advantage from Chinese companies. The EU must choose between allowing the markets to operate freely and without direct government or EU interference, knowingly that this could imply the progressive contraction of EU rare earths value chains and intellectual capital, or its strategic objectives. The experience and efforts of the last 10 years show us that there may be no overlap between market outcomes and policy objectives in the field of REE.
The Japanese government was recently confronted with this reality when Lynas' processing plant in Malaysia, faced deteriorating market conditions. This plant separates rare earth concentrates from Mount Weld (Australia) into oxides which feed Japanese industries. Japanese authorities which had already financed the plant through JOGMEC[48], were faced with the dilemma of either letting an unprofitable business go under or ensure further funding for operations to resume, based on a strategic national interest. Japan opted for the second option, thus extending the loan for 10 years[49] and guaranteeing the supply of rare earths to its industries.

Overall, closing material loops might not be left to a pure cost evaluation. Its justification comes from societal choices anchored in a framework of sustainable materials management. Moreover, if rare earth recycling activities in the EU are to withstand external shocks and unfavourable market conditions, some protection mechanisms must be devised. The EU should equate taking a proactive approach in building a comprehensive and regionally integrated rare earth waste management system, rather than merely funding ad-hoc initiatives that risk never becoming financial autonomous. The key rests on public policies, in specific REE policies to close the loop.

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[48] Lynas reached an agreement with JOGMEC and Sojitz for a 250 million loan to ensure roughly 8500 tonnes of REE annually to the Japanese market. (announced in a joint press release by Sojitz and JOGMEC in 2011) - http://www.jogmec.go.jp/english/news/release/release0069.html (accessed on 20/11/2020)

[49] Lynas press release of 27 Junes 2019 – *Ten year extension of JARE loan facility* - https://www.lynascorp.com/wp-content/uploads/2019/07/190627-Ten-Year-Extension-of-JARE-Loan-Facility.pdf (accessed on 20/1172020)

3.1.2 A disruptive closed loop system: A first step toward circular materials management

The basis of these REE policies is to create a fundamentally European-based waste management system focused on rare earths recovery, from collection all to way to SRM, building on existing policies and principles. This system would function as a backup to ensure resilience and industrial capacity to recover rare earths while complementing existing players operating in the EU recycling chain. In essence, it is a catch-all system that will be a last resort for REE contained in post-consumer waste, when no alternative is available, notwithstanding that companies set up their own closed loop systems. Unconventional policy means are required to build such a system, culminating in a different approach to the one taken by the EU so far.

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It all starts with a commitment by the EU institutions to build capacity to recycle rare earths in the EU, in partnership with EU companies and universities through ERMA and EIT-RM networks. This sort of commitment is a declaration for a market intervention where market players are invited as co-creators and engaged stakeholders. Tension within the EU's conventional market approach would naturally arise. Nonetheless this system is vital for the EU's economic resilience and environmental goals, thus possible exemptions may be found in the form of "important projects of common European interest" (COM/2014/188/02). This is a strategic area of common European interest where the market outcome diverges from EU's vision for CRM. Hence this compromise on the "free market" ideals is necessary if environmental objectives are upheld in detriment of profitability and if the EU is to build domestic rare earths value chains. Ideally this compromise would result from an unwavering EU commitment to environmental goals, to resource efficient innovation, to building industrial capacity, to green jobs.

A disruptive policy is required to build resilience of EU secondary supply of REE in the face of market shocks and generalized volatility, while being in clear disadvantage with state supported Chinese rare earths companies. Merely protecting businesses from adverse conditions might keep them at float but will not guarantee that recyclers will overcome market failures. It is a case where the EC, Council, Parliament, EIB would coordinate efforts to "co-design and co-create a solution with industry itself and all other stakeholders", as the New Industrial Strategy for Europe posits (COM/2020/102).

Building an EU-wide rare earth waste management pilot

This system contemplates collection and pre-treatment infrastructure and specific rare earth recovery plants. The main goal of this venture is to provide rare earths supply security and diversification while managing materials sustainably under a closed loop philosophy and strictly respecting the waste hierarchy (Directive/2018/98 EC and COM/2017/034). Meanwhile this pilot aims to positively influence the EU recycling chain by improving sector practices in collection and dismantling and providing better market conditions for future private rare earths recyclers. The intended output of the policy explored is to have a complementary and integrated system with capacity to collect, sort, dismantle and recover rare earths contained in designated wate streams. The desired outcome is to raise recycling rates; to develop secondary rare earth markets; to improve collection and dismantling; to increase resilience of REE related activities in the EU; to reduce reliance on foreign supply of rare earths, especially in the early steps of the value chain; to create green jobs. All these factors should contribute to EU rare earths supply security and provide conditions for the REE recycling chain to gain expression both as a relevant supply source of rare earths and as a crucial piece in the CE.

The principles guiding this intervention would be:

1. Co-creation and management of this system with EU industrial players
2. Closing the loop as the central goal – meaning reducing waste according to the waste hierarchy
3. Limit market crowding out effects to situations where collection and recycling is least developed

1 - The institutional architecture of such a system would benefit from a close articulation with the Council of the EU as well as with private investors and partners. Nonetheless, considering the integrated nature of this REE policy and the strategic value it poses, the EU should refrain from merely funding and subsidizing the waste management system. Such a policy would represent a major barrier to entry of new players, and it would leave environmental objectives at the mercy of a volatile market-based system.
An innovative intervention should be equated, in which the EU directly participates in the social capital of a non-profit venture possibly with the financial support of the EIB. The EU would take on part of the risk and financial burden and would socialize the gains – by implementing the best available standards on resource use, minimize environmental impacts and by reducing exposure to primary supply disruption.

The EC should establish an internal multi-level group with the DG Grow, DG Environment, DG COMP, the D3 unit of the JRC and the ERMA to coordinate the collaboration process and involvement of other institutions. A broad call for participation could be issued for industrial partners to establish an EU-wide recycling project for rare earths, provided that these partners can contribute to the project with know-how, infrastructure and capital. An expert panel should also be created based on previous experiences like ERECON, EURARE, EREAN and SCRREEN to provide technical support and guidance for the project as well as periodical monitoring of operations.

2 - The main goal of this venture is to provide rare earths supply security and diversification while managing materials sustainably under a closed loop philosophy and strictly respecting the waste hierarchy (Directive/2018/98/EC and COM/2017/033). Despite not being primarily concerned with profitability this system looks not to replace existing players but rather to ensure the best practices available in the field and to maintain close articulation with well-established collectors and dismantler, ideally collaborating as to ensure functional recycling destinations for EOL products not covered by this system.
This way the EU can directly stimulating the REE ecosystem of Europe, providing a comprehensive and circular waste management system for a couple of designated waste streams, while leveraging European competencies and capital in a collaborative industrial policy. The system should be broad as to complement the existing recycling chain and correct inefficiencies along it. It implies establishing facilities across Europe to raise recovery rates and improving sorting and dismantling whenever it is possible. Such that the designated scrap would end up in this system ether directly introduced in the system or purchased to collectors, dismantlers, etc. In other words, in addition to collecting its on waste the system should be a client for other collectors and dismantlers, providing a viable and competitive recycling destination to adequately dismantled REE-rich scrap.

3 – Limiting the market interference may look contradicting since this policy contemplates an out-right market intervention. Nonetheless it should be a necessary and strategic market intervention in the context of a market gap in a niche sector. There are important loopholes in the recycling chain and insufficient capacity in the EU rare earths industrial ecosystem that the EU should address. Therefore, this policy should be understood as a temporary intervention to stimulate a strategic infant industry while reinforcing collection and dismantling activities. The EU should avoid interfering with the private sectors ability to operate and enter in this market.

In establishing the recycling chain infrastructure, the consortium should equate the availability of the EOL products targeted in the EU market as well at the recycling capacity of the recovery pilot plants. The construction of collection infrastructure should be focused on MS where collection is most deficient and should be avoided in MS where the collection works better. Likewise, dismantling and pre-treatment facilities should be projected in MS where practices are least sustainable, and where the scrap material is of least quality. To this end, a close cooperation with recycler associations is advised and the adoption of waste certification schemes like CEWASTE should be equated for both system plants and for its partners upstream and downstream in the recycling chain.

Additionally, the consortium for this project should eventually define the precise conditions and circumstance under which the EU can sell its equity in this system. The EU's role is not to participate in the market indefinitely but rather to stimulate and guide industrial activity in this sector while delivering better conditions for private actors to operate. As such, an exit mechanism should be studied from the onset.

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In the EU context, achieving closed loop rare earth waste management systems will require building on existing policies and applying the principles of the Extender Producer Responsibility and Polluter-Pays, as means to internalize negative externalities related with waste containing REE. As well as respecting hard norms such as the Waste Framework Directive (WFD) and Ecodesign Directives (e.g. Directive/2009/125/EC and Regulation/2019/2023) and the guidelines presented in policies previously summarized in Section 2.2

European experience with existing recycling systems as well as with rare earth recycling pilots can lend some important lessons to this REE policy. Building on these lessons, policy recommendations for this REE policy are presented.

3.2 Policy Recommendations - 3 Pillars sustaining a closed loop pilot system for rare earths recovery

The recommendations presented herein build on the best knowledge currently available and focuses on operational aspect of the proposed rare earth waste management scheme to work in parallel with private recyclers. Based on 3 pillars, this exploratory approach discusses several crucial factors to build a closed loop system - Prioritizing waste streams, guaranteeing input and establishing partnerships for re-processing (with REE sectors).

These 3 pillars will cover firstly the scope of this waste management system, then the functioning of the collection and dismantling steps and lastly the sale of the generated output.

3.2.1 Prioritizing waste streams

The main challenges both in setting up a complementary EU rare earth recovery system and in the existing recycling chains is insufficient collection and inadequate sorting and dismantling practices, all of which re fundamental to sound waste management practices. Among these challenges is determining which products should be targeted for recycling and the waste streams containing them. The materials are scattered across products in different quantities and assembly types, often making it hard to even know if a given EOL product has rare earths which is common for electric motors[50].

Therefore, focusing on the most abundant and well-studied waste streams is determinant to reach operational efficiency and to reduce system complexity and uncertainty. Among the most relevant waste stream for rare earths, two distinctions must be made between EOL products and industrial waste. Industrial waste includes pre-consumer scrap and residues (slags) and recycling is less problematic, given that inputs are easier to access (bulk quantities) and process (homogeneity of the feed)[51]. The focus will be on the more environmentally challenging post-consumer waste streams.

Within post-consumer waste, among the applications with most potential are permanent magnets and phosphors. These 2 products may contain up to 10 different REE depending on the specific product in the form alloy, oxide, or salt. These applications are economically and environmentally relevant since there is an abundant in-use stock as well as a continuous flow of these applications in many final products. In fact, Europe is among the world's largest consumer and producer of automotive and EEE containing rare earths (Kooroshy et al, 2015: 48) and WEEE in the EU is among the fastest growing waste stream in recent years (COM/2020/98). Besides EU institutions have been involved in several recycling projects and studies that point to the feasibility of recycling rare earths from these applications.

Multiple factors are considered in choosing the most relevant applications. These include concentration of rare earths and presence of the most critical REE, potential value of the

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[50] Statement from REE recycler – RockLink - in the Webinar "REIA Webinar on Rare Earth Elements in Sustainable Circular Economy" organized by REIA on 01/10/2020.

[51] It should be noted that recycling of industrial waste mostly takes place in China and South-East Asia, given the large quantities of this waste type from REE sectors. For REE recyclers in general, industrial waste is generally more attractive than EOL products like permanent magnets and phosphors.

waste stream, the forecast of future EOL flows, EU-based know-how and capabilities in specific recovery solutions, technical barriers to recycling, overlap with regulated waste streams and collection. Phosphors and permanent magnets have a significant environmental and economic potential, besides both can be found within an already regulated waste stream – Waste from Electrical and Electronic Equipment (WEEE).

Within WEEE, phosphors can be found in displays from cathode ray tubes to plasma and flatscreens. The focus will be on WEEE – plasma and flatscreens (LCD) – flatscreens are the most relevant given their abundance in current and estimated future waste streams. However, plasma screens are no longer being introduced in the market and the EOL products are not being recycled. Besides phosphors used in plasma screens and LCD are similar, hence they should be covered by this system.

The use of permanent magnets is more widespread than phosphors, as they tend to be present in any electric motor. 3 groups were considered – WEEE, EOL wind turbines and automotive components – although only WEEE is covered by this system. The reason is that the current WEEE already regulated and a collection and dismantling networks already exist across Europe. This waste management system should resort to these networks and complement them seeing that their coverage is still insufficient[52]. Given the heterogeneity of the WEEE stream a product-centric approach to recycling (Reuter et al, 2013; Guenter and Murguía, 2019) is favourable. To limit the scope and complexity of the system, permanent magnets in Hard Disk Drives (HDD), CD and DVD players, loudspeakers and air conditioner compressors should be prioritized before enlarging the scope to cover other EEE including mobile phones, and smaller items with limited rare earth amounts.

Wind turbines will be a significant waste stream in the future given the increase in wind powered electricity. Given their restricted used in industrial contexts of wind farms, specific regulation should be prepared to anticipate the growth in EOL products. Considering their size and economic value, it is likely that functional recycling can be established, prioritizing short loop recycling. Automotive components are already covered by EOL vehicles legislation – electric motors, batteries (Directive/2000/53/EC; Directive/2018/849/EC; Directive/2006/66/EC). Separate policies should be devised to deal with these waste stream, attending to the specificities of the wastes. These policies should also deal with the foreseeable changes in this waste stream – the rise of electric, plug-in hybrid and hybrid vehicles.

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[52] Data available on: https://ec.europa.eu/eurostat/statistics-explained/images/0/02/Electrical_and_electronic_equipment_%28EEE%29_put_on_the_market_and_waste_EEE_collected_and_treated%2C_EU-27%2C_2010%E2%80%932017_%28thousand_tonnes%29.png (accessed on 20th of September)

Since this pilot should intervene across the recycling chain, the focus on the products covered at each step of the chain will differ. The principle is to cover all the WEEE stream at collection facilities and to funnel down all the way to recycling only phosphors and permanent magnets from the designated WEEE, as demonstrated in figure 10, showing the range of EOL products covered along the system.

Ensuring good practices at this level could be the key to a long-term resilient rare earths value chains in Europe. Processing of rare earths into products and components is the most urgent bottleneck in the EU value chain and providing these activities with consistent inputs is key.

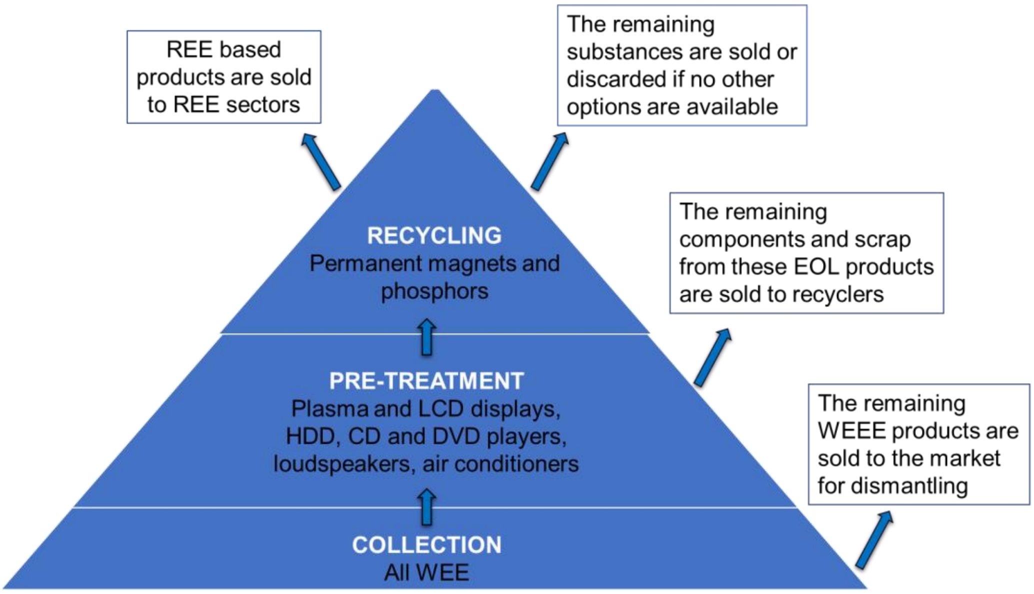

Figure 11 – Diagram of simplified operational flows into and out of the proposed EU rare earths waste management system.

3.2.2 Input - Ensuring an abundant and stable input of material to recyclers

Studies on recycling of rare earths (and CRM more generally) from WEEE affirm that the main challenge for these recycling activities is in the collection and dismantling phases (Kooroshy et al, 2015; UNEP, 2011; Reuter et al, 2013, Binnemans et al, 2013; Yang et al, 2017; Rademaker, Kleijn and Yan, 2013; Schüler et al, 2011; Buchert et al, 2012). The initial steps of the recycling system are determinant to the quality of the recycling input and output.

In the current waste management schemes for WEEE, REE along with other CRM and valuable metals are left unrecovered (Binnemans et al, 2013; Ford et al, 2016). In the case of fluorescent lamps, glass, metal and mercury are already sorted but rare earths are left in a fraction that is usually landfilled. For the case of permanent magnets, the situation is a bit more complex. Only large magnets present in generators and motor or vehicles or wind turbines are pre-dismantled (Yang et al 2017:128). For most permanent magnets in WEEE, the electronics are shredded before the magnets are removed, which can compromise future recycling of the magnets (Kooroshy et al, 2015: 51).

Permanent magnets and phosphors are not homogeneous, and neither is are the rare earth compounds in them. Not only are there different types of magnets and phosphors but even within the same denomination substantial differences can arise. Ensuring the right practices in collection and pre-treatment is therefore essential for this system to be efficient and sustainable.

A product-centric approach should be complemented with a comprehensive and systematic documentation of the products collected and sold downstream. This approach could provide extensive product information which is currently missing from the EU knowledge base. By working closely with the JRC and devising a platform for data storage, valuable information could be gathered on the following aspects: quantities of waste collected and processed, type of magnets and phosphors, rare earths contents, assembly types, optimal disassembly methods, potential contaminants and the recycled rare earth output.

A product-centric approach while implementing this sort of digital platform could allow for increases in efficiency in both detecting, sorting, and dismantling equipment. Besides, it could constitute an important tool for the recycling chain in future by providing guidelines on dismantling and along with information on which products have rare earth permanent magnets, their composition and recycling methods.

It should be noted that developing this thorough waste management inspection mechanism, could also enable the identification of functional product and components to be sold to repairers or back to the manufacturers. Thereby preventing waste and increasing circularity through re-use and repair of equipment and components. This aspect should be considered at a later stage when a better knowledge of the EOL products is attained.

The potential added value of establishing these facilities is tremendous given that the recycling chain for WEEE presents significant loopholes. These facilities represent a strategic asset to both the REE sectors and the recycling industries. There is a predictable spill-over effect to recycling of other elements since most of the EOL products and components reaching the facilities of the system do not have REE and hence will transferred to recyclers downstream. This generalized improvement in dismantling quality should motivate recyclers to demand similar input quality to other suppliers, leading to an improvement in dismantling, be it manual or mechanical. If that is the case, then improvements of sorting and dismantling are generally expected as a response to the rapid increase of high-quality recovered materials.

An essential part of this system would be to devise a cost transfer mechanism to implement the EPR principle, sharing the financial onus with manufacturers. The system would provide a new bottom line for rare earths recovery and it is likely to be more costly initially. The ideal solution would be to charge product manufacturers for the collection, sorting and dismantling according to the design properties of the product, provided that the relevant information on the products is acquired shortly after being placed on the market for the first time. Eco design principles would be rewarded with lower fees and unfriendly design would be penalized. Such that when dismantling and pre-treatment is more costly and timely, the fee charged to the manufacturer is higher for that specific product.
This would complement soft and hard law instruments in promoting ecodesign practices. The product-centred information on processing methods are critical to adapt EPR fees accordingly. If done successfully, it would contribute to lower cost of recovery operations, thereby increasing recycling of rare earths and improving market conditions.

Recovery costs would be divided between collection, sorting and dismantling cost on one hand and recycling costs on the other. Partially transferring the later to the polluters should be equated, considering that the sale of the recovery compound or elements re unlikely to cover the recovery cost. However, manufacturers should reserve the right to establish parallel recycling schemes for their own products, conditional on periodic reporting and auditing. A manufacturer of WEEE containing REE would be exempt of any EPR fees should he prove that his product placed on market was recovered through its own system. Naturally though it is reasonable to admit that some products would end up in the EU-run rare earth waste management system. In such cases, a record would be kept of the different products and the step at which they entered the EU-led system. A settlement in the EPR scheme would then be re-established periodically with all the polluters – manufacturers or importers of the designated WEEE containing REE.

In addition to building infrastructure to complement the recycling chain, this system should also foresee the need to stockpile components containing rare earths. If at any moment pre-processing capacity is not being used, then the system operators should purchase scrap from collectors and dismantlers. If the opposite happens, and recycling capacity is insufficient to process the scrap absorbed by the system, then the purchases of scrap to dismantlers should be limited and the dismantling facilities should proceed to isolate and stockpile permanent magnets and phosphors for future recovery. Stockpiling these components will not only ensure feed for future recycling but it will also prevent that material from entering sub-optimal recycling or even being lost to the environment. If there are no recycling solutions for rare earth, the system should refrain from selling its excess materials containing REE, as to avoid non-functional waste management.

Ensuring a high-quality recycling input free from impurities and contamination is the central concern of this pillar. It means establishing facilities to collect, detect, sort, and dismantle to reach the lowest possible component containing the REE before shipping them to the extraction-refining facilities. EPR principles would be respected and cover ecodesign factors in its fee system, which would be a novelty. Additionally, manufacturers should not be forced to contribute and participate in such a system if they ensure a viable parallel recycling solution.

3.2.3 Output - Competitiveness of secondary rare earths

The end-goal of this system would be to generate high-quality competitive REE products to supply REE sectors. Ensuring the required quality relies heavily on the quality of the previous steps. The sale of recovered rare earths and EPR fees would be the main sources of income of this system. Even if profitability is not the main objective of the system, it is the cornerstone to turning rare earth recycling into a commercially viable business. Additional income sources should be explored, namely the sale of the data on products properties and assemblies to stakeholders along the recycling chain or the sale of functional equipment and components back into the economy.

A batch-based approach should be adopted in the pilot recovery plants, such that recycling is segmented based on the specific materials recovered. In other words, it means that recycling capacity in that plant would be allocated to a set of permanent magnets or phosphors which have similar characteristics, provided that the output quality would be improved. These batches would be prepared for recovery and the factory would operate based on a schedule, meaning that there would always be stock of certain magnets and phosphors ready for recovery. This would allow the plant to organize its operations based on foresight and stability. Batches can be prepared weeks in advance and scheduled to go into recycling. Quantities of recycled output are estimated and can be sold before recycling takes place.

This batch-based approach can be optimized if the information on specific products and models is systematically gathered and consolidated. If there is complete information on all the magnets and phosphors entering the plants, then these can be sorted and stored according to a range of technical similarities and the definition of batch properties can be optimized. Additionally, once this information system is matured, this batch-based approach can serve to recover alloys and phosphor mixes and sell them directly to REE sectors, thereby privileging short loop recycling routes. This would be an optimal approach given that energy savings and significant environmental impacts would be avoided if the isolation of REE is not required. Avoiding this step would substantially reduce costs through lower use of energy, water and hazardous substances, provided that there are clients for the alloys and phosphors recovered.

The recycled rare earth compounds or elements can be sold directly to selected REE sectors through an auction system. Nonetheless, to stimulate the involvement of REE sector partners in this strategy, these could have a right of preference in buying these batches for a designated trial period. It is important to prevent rare earths being sold below market value in order limit market distortions. Likewise, if operations are focused on recovering compounds instead of elements, then agreements should be previously established with EU REE sectors to sell the recovered outputs.

Among the main objectives of this policy would be to improve resilience in the value chain. This implies withstanding market shocks and artificially low prices. Several aspects can be considered in this regard, but the key is to use the strategic role of this system to work asynchronous to the market. Stockpiling recycled rare earths when prices plummet and selling them on when prices hike could be one option.
Another option is to adopt a price compensation mechanism such as the one devised and implemented by ECODOM members in Italy. In this case this EU system would “overcharge” for the recycled rare earths and would simultaneously compensate collector and dismantler suppliers when prices of either secondary or primary REE are low. Inversely, when REE prices are high the pilot system would pay below market value for scrap from collectors and dismantlers and would charge below market value for the secondary REE. The precise impacts would naturally depend on the specificities and threshold defined for such a mechanism.

Implementing this sort of asynchronous price system could be an opportunity to spread this practice to the whole EU recycling chain. Providing lower prices to REE sectors in times of rare earths crisis could be a gamechanger in protecting EU value chains and granting it more resilience and support when faced with adverse market conditions.

A product-centric approach in this recycling system could be useful in another dimension. If specific product identification can be effectively carried out from the collection stage of this system, means that at any stage of the system, batches of specific products can be made and sold directly to the manufacturer for repair, remanufacturing and even recycling with its own partners. This potential is unknown, and the operational challenges have never been assessed or encountered but it can be particularly helpful if manufacturers want to set up recycling of their own products.

Many factors in this system require careful examination, implementation, and adjustment. The definition of details depends on the specificities of the project and the partners involved. But these are merely guidelines touching on factors central to establishing this system.

Conclusions

The EU has for a long time recognized the importance of recycling and of secondary raw materials as an integral part of its raw materials policy (COM/1975/50, COM/2008/699, COM/2011/25). Rare earths have become increasingly relevant in the EU context, given the Union's ambitions to become a CE and the energy transition it envisions. These objectives have gained relevance in EU policy in recent years and are consolidated in the EU's Green Deal and the circular economy action plan (COM/2019/640, COM/2020/98). These policies have intensified the rare earths conundrum, calling on more attention to the EU rare earths value chains.

Several policies and projects have tackled REE criticality by filling information gaps, building industry and expert networks, funding research, best practice sharing along with resource diplomacy efforts. Despite not directly affecting recycling rates, some of these policies have provided support for rare earth recycling research and pilot projects to develop in the EU. EC initiatives like Raw Materials Information System (RMIS) are focused on access to key information on raw materials. The RMIS benefits from EU funded projects like ProSum which provide synergies to improve data and intelligence on secondary raw materials in the urban mine. Other on-going projects like CEWASTE, are looking to develop a voluntary certification scheme for collection and pre-treatment of waste streams containing CRM, as a means to improve procedures for the whole recycling chain.

The most recent initiatives include the CRM action plan and within this plan, the ERMA which was launched this year (COM/2020/474). These efforts demonstrate the growing importance attributed to REE and a pressing concern in providing solutions to rare earths criticality. However, these REE policies are an extension of previous policies and do not tackle the limitations of this approach. Namely the inexistence of recycling and absolute reliance in Chinese supply for most REE are the most striking. The free-market approach generally favoured by EU institutions is inadequate to the tasks of closing the loop on rare earths and of building a resilient rare earths value chain. It is unreasonable to expect EU market players to develop a comprehensive recycling capacity for rare earths, given the competitive disadvantage of EU firms in this sector as well as the weaknesses in waste collection and pre-treatment.

Nonetheless EU REE policies have unquestionably contributed to innovation and efficiency increments in this field, which might culminate in the establishment of recycling plants. However, REE players in the EU value chain are particularly sensitive to fluctuations in global Rare earths markets, such that recycling efforts can be frustrated in just a few months of low REE prices.

Solving the REE conundrum requires a distinct policy approach, anchored in a political compromise to carry out an explicit industrial policy agenda to build an effective EU-based rare earth waste management system. This compromise should rely on industry stakeholders and experts in this field, but more importantly it should convey a compromise on free-market ideals, without which the EU risks never achieving a comprehensive recycling system capable of systematically sourcing the EU market with REE and rare earth compounds.

This system should be an initial step to kickstart the EU rare earths value chain, by providing a valuable piece of this ecosystem which is not yet commercially viable. Having an EU supported system will strengthen EU REE sectors and contribute to fulfil the EU circular economy and Green Deal objectives. Besides improving practices in the recycling chain, this system would provide a resilient and reliable source of sustainable EU-based supply of rare earths, contributing to a lower import reliance and better environmental performance.

A disruptive rare earth waste management system covering collection, dismantling, sorting and recycling is proposed. It should be co-created between EU institutions and private firms, through a call issued to the newly formed ERMA. The founding principle for this system should be to close the loop of rare earths using the most adequate methods and techniques, while profitability is secondary concern. This system would complement the existing recycling chain, establishing infrastructure in regions where the waste management of WEEE is least functional. Additionally, the practices on the operational side, should abide by the best standards available and make use of the existing certification schemes. These principles should be asserted in the commercial partners of this system, whether these are recycling associations, waste collectors, dismantlers or recyclers.

The system proposed is supported by policy recommendations on 3 fundamental aspects – prioritizing waste streams, ensuring inputs and output competitiveness. By initially focusing on a narrow group of EOL products concentrated on the already regulated WEEE stream, the system can identify bottlenecks of the system and optimize practices before expanding coverage to other waste streams. The phosphors and permanent magnets are the focus of the system given the estimated potential of these flows but also because rare earth recycling from these EOL-products has been extensively studied. However, recycling remains challenging despite the technical knowledge available. Ensuring a high-quality input for the recycling is critical, therefore the system should focus on developing a product-centric approach to recovery coupled with a digitally integrated database of product and assembly information. This approach would certainly be challenging, but it is equally a strategic opportunity improving knowledge on products and their rare earths contents as well as optimizing collection, sorting and dismantling for the existing players in the recycling chain and for future market entrants.

Guaranteeing a high-quality rare earth output is crucial for the future of this sector. Therefore, the information gathered along the waste management sequence will be consolidated in the recycling step, though a batch-based approach. This improves foresight on the operational side and a stricter control on the quality of the recycling output. Besides this mechanism can contribute to achieve short loop recycling routes. Given the frequent fluctuations in REE prices, compensation mechanisms should be devised within the recycling chain to stabilize prices in EU markets and avoid substantial income losses when prices drop.

These are among the most relevant aspects in creating such system. The policy recommendations provided point to some possible solutions and paths within a EU-led waste management system. However other aspects are not covered in this work, namely the institutional and financial architecture of such a system are among the most structural dimensions but can only be discussed with EU institutions and the partners assigned to such a project.

This project has considered the EU situation with rare earths, pointing to the conundrum at the heart of EU policy. It considered all the EU policies focused on CRM and REE. A chronological account of these policies and a brief critical assessment are provided. The policy limitations are highlighted, and an alternative path is devised. The recommendations presented are by no means the only alternative to tackling REE criticality. They provide a path that combines the EU’s environmental and CRM goals in circular economy solution to a strategic problem. Additional work should follow on this topic, namely a comprehensive policy evaluation of REE and CRM policies as to quantify the impacts and better inform policymaking in the future.

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