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H2020 WORK PROGRAMME

D8.14: IMPACT ON THE CRM VALUE CHAIN

LEAD BENEFICIARY: LGI SUSTAINABLE INNOVATION

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Table of Contents

TABLE OF FIGURES

TABLE OF TABLES

1 EXECUTIVE SUMMARY

This report represents an impact study for the EU Research and Innovation project, BIORECOVER. The task of the report is aimed at evaluating the impact of the adoption of defined processes on the recovered raw materials value chains. The main metals, which are targeted for recovery using the BIORECOVER processes and covered in the report are Platinum Group Metals, Rare Earths and Magnesium.

After a global overview of the targeted metals, the report has mapped out the existing value chains and the key European stakeholders working with these materials. It includes an analysis of the financial performance of major corporate commodity producers and consumers to provide insights into different actors pricing power and ability to extract economic rent at different links along each chain. Moreover, the study draws upon expert interviews to explore the major governance mechanisms and public policies structuring each material's value chain, and the critical success factors considered during negotiations between suppliers and clients. Additionally, future shifts in demand and supply of the materials are outlined.

This research provides insights into how value chains can be expected to take up the project's re-mining innovations and how BIORECOVER may upgrade different stages of the value chain. Finally, new value chains for target materials are hypothesized to account for the ways that re-mining using novel biotechnologies could transform relations between stakeholders and lead to changes in their business models.

Ultimately it is argued that due the geographic concentration of PGM reserves, BIORECOVER will likely not create an entirely new European PGM value chain but could enable process upgrading by marginally reducing the amount of PGM losses at all stages while promoting avoiding chemical and energy intensive methods. Meanwhile, BIORECOVER could have the potential to unlock untapped rare earth reserves from bauxite residues that could drive the birth of a novel European industries in line with the sustainability transition. Likewise, if technical progress is made on recovering pure Mg using biotechnologies, BIORECOVER could create significant value by allowing magnesite mines to diversify their production and create a domestic supply of European Mg.

ABBREVIATIONS

CA	Consortium Agreement
CRM	Critical Raw Material
BR	Bauxite Residue
EU	European Union
EC	European Commission
ESG	Environmental Social Governance
FTO	Freedom to Operate
GA	Grant Agreement
IC	Interfering Components
Mg	Magnesium and/or Magnesium products (MgO, MgX_2, etc.)
NP	Nano Particle
PGM	Platinum Group Metals
Project	The BIORECOVER Project
REE	Rare Earths Elements
SWOT	Strengths Weaknesses Opportunities Threats
TRL	Technical Readiness Level
Partners	
CETIM	FUNDACION CENTRO TECNOLOGICO DE INVESTIGACION MULTISECTORIAL
MYTILINEOS	MYTILINEOS ANONIMI ETAIRIA - OMILOS EPICHEIRISEON
MAGNA	MAGNESITAS NAVARRAS SA
UCPH	KOBENHAVNS UNIVERSITET
UC	UNIVERSIDADE DE COIMBRA
UWITS	UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG

LNU	LINNEUNIVERSITETET
CeBER	UNIVERSITY OF CAPE TOWN
TR	TECNICAS REUNIDAS SA
ALGAENERGY	ALGAENERGY SA
JM	JOHNSON MATTHEY PLC
FAE	FRANCISCO ALBERO SA
LGI	LGI CONSULTING SARL
ENSO	ENSO INNOVACION SL

2 INTRODUCTION

Raw materials represent the physical basis for the global economy and are fundamental to ensuring the prosperity of human society. The rapid pace of technological progress in modern history has only been made possible thanks to rapid growth in the quantities and varieties of raw materials employed to enable everyday life. Our contemporary world is now confronted with rapid social and economic shifts that will further accelerate the demand for a diversity of raw materials. The macro-trends of decarbonization, increasing digitization, and improving living standards in the developing world, can be expected to intersect in the coming decades and dramatically boost global demand for a plurality of raw materials. The OECD forecasts global metal demand to more than double by 2060 (OCDE, 2019), with demand for key metals for the energy transition expected to multiply even more rapidly. Given this reality, we face an urgent need for material production systems that can supply the global economy in an environmentally, socially, and economically sustainable manner. The BIORECOVER project was launched to meet this challenge, by innovating a variety of biotechnologies for the recovery of rare earth elements, platinum group metals, and magnesium from several waste streams in the mineral industry.

The main objective of the BIORECOVER Project (Project) is the research and development of a new sustainable and safe process, essentially based on biotechnology, for the selective extraction of a wide range of Critical Raw Materials (CRMs), from relevant unexploited secondary and primary sources:

- Rare Earths (RE) from Bauxite Residue from Greece,
- Magnesium from Mg wastes of low-grade minerals and calcination by-products from Spain,
- Platinum Group Metals (PGMs) from flotation tailings from South Africa, PGM residues from the United Kingdom.

The Project is expected to progress from Technical Readiness Level (TRL) 2-3 to 5. Partners are represented in the following figure.

FIGURE 1. PARTNERS INVOLVED IN THE BIORECOVER PROJECT

Developing and piloting integrated biotechnological processes capable of treating waste streams and selectively extracting target metals will only be the beginning of BIORECOVER's journey towards improving sustainable raw material supplies. Truly achieving this ambition will require the project's technologies to come out of the laboratory and produce metal commodities for the industry at scale. This will be no small feat, given the numerous economic, technical, geological, and geopolitical variables that influence the global supply of metal commodities.

As has been made acutely visible by the supply chain disruptions linked to the covid-19 pandemic and the war in Ukraine (Swanson, 2022), the global economy relies on a highly complex and geographically dispersed network of interlinked actors. Changes at one stage in this global network can have major spill over effects for other actors upstream and downstream. The complex interconnection of the global economy poses major challenges but also creates major economic opportunities for actors capable of capturing value at their link in the network.

This report, therefore, seeks to explore the complex economic relationships between global actors extracting, processing, transforming, and consuming REEs, PGMs and Mg. Moreover, it will estimate BIORECOVER's potential for value creation, by modelling its possible value chain, and possible emergence and disappearance of stakeholders.

3 METHODOLOGY

3.1 Scope

The scope of this study was decided together with partners CETIM, Mytilineos, Magna, and JM in 2021 & 2022. Results from the project were considered together with the economic potential for each recovered CRM.

Therefore, the Impact Study focuses on platinum and rhodium for PGMs, and on scandium and yttrium for rare earths.

3.1.1 Platinum Group Metals: a focus on Platinum & Rhodium

The BIORECOVER project aims at obtaining Platinum Group Metals (PGMs) from low grade ores sourced in South Africa, and three industrial by-products containing PGMs produced during the refining and catalyst manufacturing process from the United Kingdom.

This section will focus on platinum and rhodium for different reasons:

- **Platinum** has the largest market size among the PGMs, the highest concentration (ppm) in the residues used in the project, as well as significant potential for the growing demand for use in hydrogen electrolysers
- **Rhodium** value chain will be studied due to the recent explosion in the price of this material it now represents the most valuable PGM in several of the residues used in the project (in terms of price per weight)

Technical results at this point in the project remain speculative, since laboratory research is ongoing. Therefore, it is not possible to provide data about process yields for PGMs across the entire BIORECOVER process. However, some promising results regarding palladium and platinum recovery have been obtained by ALGAENERGY, with about 90% absorption of these elements from synthetic leachates. However, final results of leaching and recovery from the target PGM feedstocks and are still not available.

3.1.2 Rare earths: a focus on Scandium & Yttrium

Rare Earths Elements (REE) are sourced in this project from Bauxite Residues produced by Mytilineos' alumina refining plant, which operates in Greece.

- This deliverable will focus on **yttrium** despite its small market size and relatively low economic value due to its importance in the design of the project, notably with the inclusion of FAE as a partner, who manufactures brake pads and oxygen sensors.
- We will also analyze **scandium** because at current market prices it represents the most valuable REE in the bauxite residues (in terms of price per weight).
- When considering mixed REE concentrates we will also highlight the importance of REE used in permanent magnets, particularly **neodymium** (which has the largest REE market size). However, in order to limit the scope of research, this is not the main focus of the report.

3.2 Management

3.2.1 Coordination with partners

This task includes the participation of Mytilineos, Magna, UWITS and JM. The scope of this study was agreed upon together with all partners and the coordinator, and partners provided contacts to be interviewed.

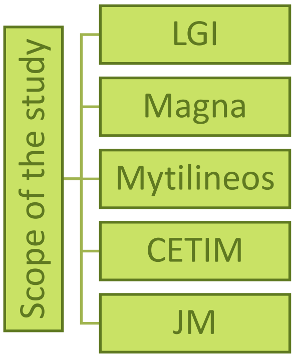


FIGURE 2. MANAGEMENT & SCOPE OF THE STUDY

3.2.2 Interviews

As described in the following, LGI selected experts from all along the value chain to have a holistic view of the future value chains of PGM, REE and Mg. Experts from different sectors, such as the mining industry, refiners, distributors, and traders were interviewed from October 2021 to April 2022.

Discussions were carried out with representatives from different expertise (a total of 10 representatives with expertise in CRMs) aiming at bringing out the most relevant macro-environmental factors. The below table lists the names of participating experts and their area(s) of expertise.

Companies within the consortium, such as Mytilineos, Magna, and JM participated in discussions. Other external stakeholders, such as Anglo American, REIA, Remretech, and IMA were also interviewed.

TABLE 1. INTERVIEWS

Company	Name of the Representative	Expertise	Date of the interview
JM	Anonymous	Autocatalysts in PGM value chain	29/03/2022
JM	Barbara Breeze	PGM value chain	21/03/2021
JM	Anonymous	Recycling	14/02/2022

Company	Name of the Representative	Expertise	Date of the interview
Anglo American	Anonymous	PGM sales	04/04/2022
REIA	Nabeel Mancheri	REE (Scandium)	10/11/2021
Remretech	Ajay Patil	REE (Yttrium)	06/04/2022
FAE	Francisco Ramos	Yttrium applications	10/12/2021
Magna	Pilar Perez	Magnesium	20/04/2022
IMA[1]	Martin Tauber	Magnesium	28/03/2022
Mytilineos	Panagiotis Davris	REE	29/04/2022

3.2.3 Workshops

Circular Value Proposition Design workshop

Given that Circular Economy is at the core of the BIORECOVER project, the LGI team proposed an innovative approach to model the new value chain of the BIORECOVER technology while incorporating circularity principles in the approach. Inspired by the methodology developed by the Ellen MacArthur Foundation on Circular Business Model Design (PA Consulting, University of Exeter and Ellen Mac Arthur Foundation, 2021) the LGI team adopted the guiding phases to facilitate a Circular Value Proposition Design (CVPD) workshop with the BIORECOVER partners.

Given the COVID-19 context, the CVPD workshop was organised as a virtual workshop in June 2021, which started with an overall presentation of the Circular Value Proposition Design principle and was followed by interactive sessions in parallel groups using a digital whiteboard 'Mural', enabling partners to collaboratively share ideas while writing digital post-it notes.

Five key steps were followed to arrive at mutually beneficial value propositions for BIORECOVER and its potential customers, as indicated in the following figure, considering lost value and value at risk, identifying circular opportunities, identifying key customers and partners needed to make the opportunity possible, and defining a mutually beneficial value proposition.

[1] International Magnesium Association

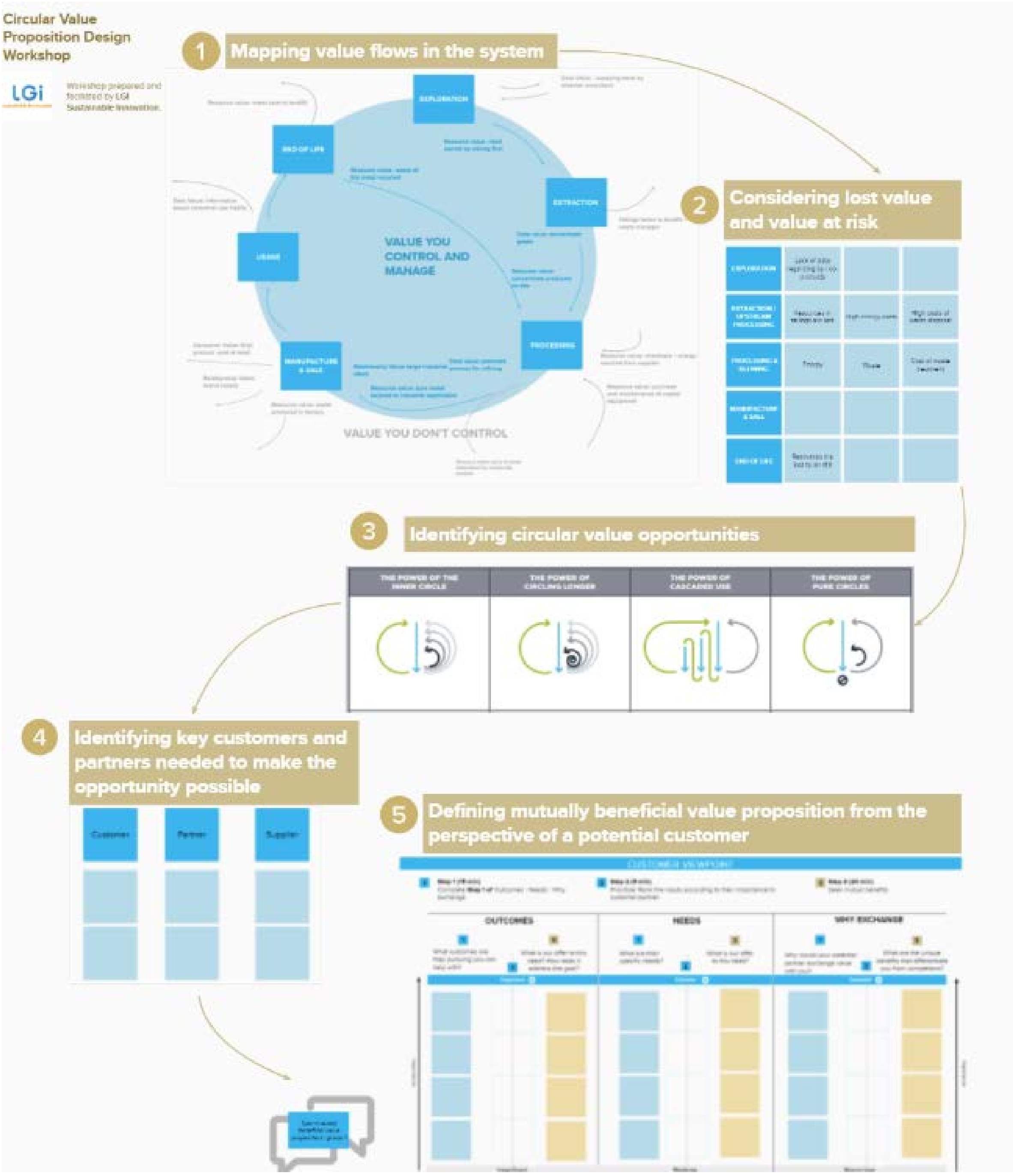


FIGURE 3. CIRCULAR VALUE PROPOSITION DESIGN WORKSHOP KEY STEPS

Tailored workshops to PGM and REE value chain

Two workshops were conducted in March and April 2022 to model the new value chain with the most recent updated results of the BIORECOVER project. Additionally, each workshop enabled LGI to assess the competitive advantages of the BIORECOVER technology along the REE and PGM value chains, and the remaining gaps and barriers to upscaling the technology, as highlighted in Figure 4.

One workshop gathered JM and UWITS regarding the PGM value chain, and another workshop led to a discussion with Mytilineos about concerning REE.

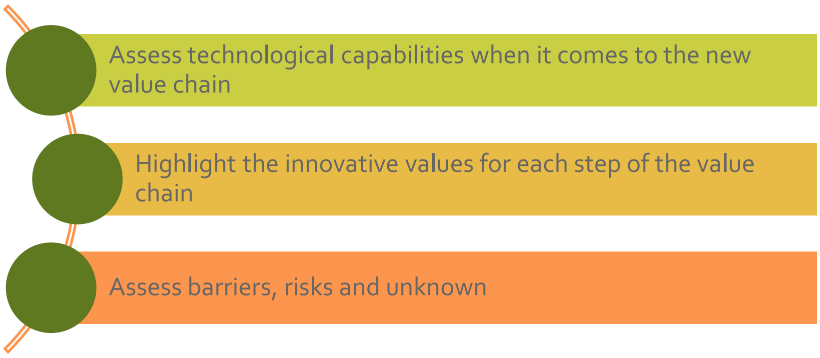


FIGURE 4. BIORECOVER VALUE CHAIN MAPPING WORKSHOPS

3.3 Research methods

3.3.1 Global view

The research methodology for this study is primarily inspired by the IDRC's "Handbook for Value Chain Research". Its working definition of a value chain is "the full range of activities that are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use." (Kaplinsky & Moris, 2000).

Accordingly, this report endeavours to paint a holistic picture of the interconnected global activities that enable PGMs, REE and Mg to be extracted, transformed, consumed, and disposed of. Below it is possible to find a chapter dedicated to each product (PGM, REE and Mg). The following figure illustrates the 5 different sections of each chapter:

FIGURE 5. METHODOLOGY OF THE RESEARCH

- Part 1. Introduction will first provide general information for each targeted metal. This section will give a good overview of global production and consumption for each metal, potential material scarcity, their main markets and substitution, their main players and the design of the current value chain of each metal. *Information will come from desktop research.*

- Part 2. Distribution along the value chain will highlight potential margins along the value chain, with a particular emphasis on potential value concentration. *Information will come from desktop research. A study will be made on the financial results of publicly traded companies.* Moreover, the concept of "economic rents" in the value chain will be applied and will gather resource rents, technology rents, and organisation rents for each metal value chain. Based on this analysis, key success factors will be drawn upon. *The methodology comes from Kaplinsky and Morris (see below part 3.3.2) and information will come for both desktop research and interviews.*
- Part 3. Factors structuring and/or governing the value chain will offer an overview of the most impactful parameters on each targeted metal market. An analysis of market concentration, logistics, and trade policies will be added. *This part will be based on interviews and desktop research.*
- Based on these results, Part 4. Emerging changes to the value chain will focus on potential dynamics impacting the value chain in the future. *Results will come from interviews and desktop research.* This section will foresee future trends in demand, due to technological improvements, and social perceptions. Future trends in supply will also be anticipated and will relate to innovations entering the market and new exploration techniques.
- Finally, Part 5. Upgrading the value chain will provide a value proposition of the BIORECOVER project. At each step of the process, possible upgrades of the technology will be projected. *Results will come from workshops with Mytilineos, UWITS and JM.* Potential impacts on logistics will be assessed. Ultimately, this section will highlight the potential emergence and disappearance of stakeholders.

3.3.2 Key concepts of value chain research

The concept of "Economic rents"

This deliverable seeks to go beyond merely describing the global supply chains of target materials, by also exploring how economic value is produced and distributed between actors. Therefore, after first mapping the activities carried out across each value chain, the report will explore financial data (Section 2. Distribution along the value chain) to decompose total value chain earnings into the profit extracted by individual firms along the chain. An emphasis will be placed on how actors at each link of the chain compete economically to maximize their share of the total value produced within their market (Section 3. Factors structuring/governing the value chain.)

This is described according to the concept of "rent", which refers to a firm's ability to extract surplus value from their product due to some form of competitive advantage. A producer has such advantages when they possess a scarce attribute with barriers to entry preventing competitors from creating and selling the same product at lower profit margins.

Numerous forms of economic rent exist and are defined in Table 2 below. A firm may control the endogenous factors that allow it to extract rent, or it may take advantage of exogenous factors outside of its control to gain a competitive advantage. To explain the unequal distribution of value along this project's target value chains, both endogenous and exogenous forms of rent will be identified.

TABLE 2. DIFFERENT TYPES OF RENTS ACCORDING TO THE HANDBOOK

Rents endogenous to a single firm	
Technology rents	Having command over scarce technologies *Ex: difficulty in separating and purifying PGMs*
Human resource rents	Having access to better skills than competitors *Ex: having a better expertise on CRM recovery*
Organisational rents	Possessing superior forms of internal organisation *Ex: Vertical integration*
Marketing rents	Possessing better marketing capabilities and/or valuable brand names
Rents endogenous to the value chain	
Relational rents	Having superior quality relationships with suppliers and customers *Ex: having a long-lasting supplier-customer relationship*
Exogenous rents (from nature or actors external to the chain)	
Resource rents	Access to scarce natural resources *Ex: limited access to PGM (concentration in South Africa)*
Policy rents	Operating in an environment of efficient government; constructing barriers to the entry of competitors *Ex: Air Quality legislation driving the demand of PGM in the automotive industry*
Infrastructural rents	Access to high quality infrastructural inputs such as telecommunications
Financial rents	Access to finance on better terms than competitors *Ex: having a better access to machine investments*

Value Chain Governance

The capacity of BIORECOVER's innovations to make a tangible impact will depend on how its targeted value chains are governed, since the governance of a value chain determines the way in which it is structured and upgraded over time. This concept will be concretely applied in Part 3. Factors structuring/ governing the value chain for both REE and PGM.

Concretely, governance involves setting parameters related to products, processes, and logistics in a value chain. If actors within the chain fail to comply with these parameters, they are subject to consequences, including potential exclusion from the chain. Thus, value chain governance reflects the asymmetries of power between different actors within the chain. More powerful actors can dictate the parameters structuring relations along the chain and enforce sanctions against non-compliant actors.

The dominant actor(s) governing a value chain can be understood to assume a portion of two roles: ensuring consequences along the value chain, and actively managing or coordinating the links along the chain to ensure it meets certain parameters. Kaplinsky and Morris propose three mechanisms through which this governance occurs.

- The first is the establishment of the ***rules for participating in the value chain***. This can be likened to the legislative branch of value chain governance, and typically takes the form of contractual agreements during corporate procurement negotiations. Historically these rules typically revolved around meeting a certain threshold of supply without violating basic cost parameters. With the emergence of "lean manufacturing"[2] the rules for participation increasingly also emphasize product quality and delivery timing as well as price. Moreover, actors along a value chain are typically subject to labor and environmental regulations that may go beyond national laws to ensure compliance with corporate ESG criteria.
- Governance of value chains also involves ***auditing*** links along the chain to ensure that they remain compliant with the rules. This can be likened to the judicial system, in that auditing interprets and enforces the requirements.
- Thirdly, a value chain is also ***proactively governed*** when a leading firm works directly with other participants along the chain to enable their compliance with certain parameters. This can be likened to the executive branch of government since it involves the enactment of active transformation to ensure compliance with a code.

Cycle of Innovation

Understanding the cycle of innovation will feed Part 4. Emerging changes in the value chain and Part 5. Upgrading the value chain.

Value chains are dynamic systems, and the competitive advantages leading to rent ebb and flow may change between actors over time. This dynamic process is driven by the "creative destruction" of innovation. The first firm to innovate a new competitive advantage (such as a novel technology,

[2] Toyota production system example

production system, or product) typically enjoys a period where they can dictate prices and generate surplus value through high profitability.

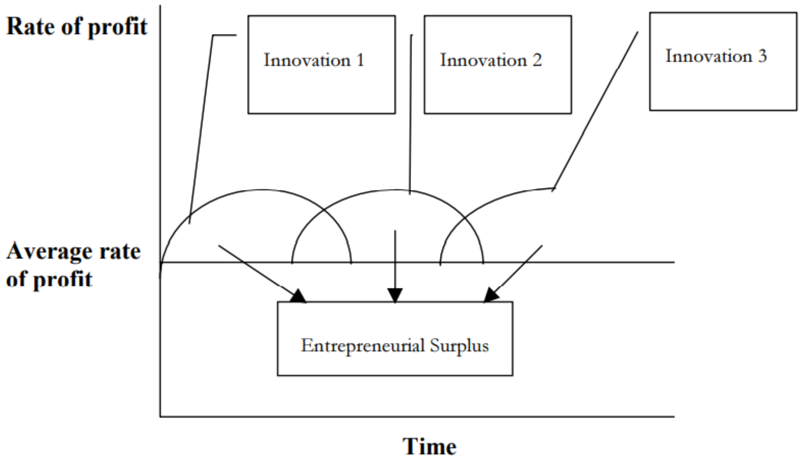


FIGURE 6. CYCLE OF INNOVATION

If successfully developed and upscaled, the innovative biotechnologies developed by BIORECOVER will fit within this cycle of innovation. To be taken up by the market, the project's novel mineral processing flows will need to demonstrate an ability to add value through improvements in efficiency and profitability. This report will highlight the potential of project results to create new competitive advantages across target value chains and disrupt existing production systems and ways of working.

However, competitive advantages are impermanent. Competing firms will seek to replicate successful innovations with lower profit margins to gain market share, thereby driving down prices and creating surplus value for consumers. Over time the profit margins of all firms in a sector will tend to converge on an "average rate of profit" before a leading firm again innovates a competitive advantage thereby restarting this constant search for entrepreneurial surplus.

In recent decades the global economy has seen barriers to international flows of capital lowered and a shift towards ever more complex and globalized supply chains. This has expanded the intensity and scope of the competition for economic rent. Kaplinsky and Morris argue that entrance into globalized supply chains can set an economy down two divergent pathways.

An economy risks going down the "low road", whereby intense global competition drives down margins and produces downward pressure on wages to keep costs low. However, it is also possible for an economy to climb the "high road", in which a virtuous cycle of improvements in economic development and living standards takes place.

According to this narrative, innovation is the key factor distinguishing these two paths. Therefore, when conceptualizing novel BIORECOVER value chains, this report will place a particular emphasis on using project innovations to drive economic development in Europe by helping to onshore high-value, future-oriented, industries and activities.

Innovation and upgrading value chains

The four concepts of value chain upgrading from Kaplinsky and Morris will nourish Part 5. Upgrading the value chain.

In a competitive globalised market, the speed at which a firm innovates versus its competition will determine its ability to charge rents. **When firms innovate to capture greater value, they are "upgrading**". Firms can upgrade by **realigning their internal factors of production** (capital equipment, technologies, human resources, product design and branding, etc.) as well as **their position relative to the external field** they operate in (partnerships, response to public policies, shift to new markets etc).

Analysing this process from a value chain perspective, rather than at the level of an individual firm, offers a more comprehensive perspective by emphasizing the *interrelations* between firms and how changes at one link in a chain can spill over onto other firms. Kaplinsky and Morris offer four typologies of value chain upgrading, which are presented in Table 3 below and applied to the BIORECOVER technology.

TABLE 3. POSSIBLE UPGRADINGS

Upgrade	Explanation
Process upgrading	Increasing the efficiency of internal processes such that these are significantly better than those of rivals, both within individual links in the chain (ex: increased inventory turns, lower scrap) and between the links in the chain (ex: more frequent, smaller and on-time deliveries) *Application to the BIORECOVER technology: PGM value chain - reducing the amount of PGM lost during extraction, processing, and manufacturing*
Product upgrading	Introducing new products or improving old products faster than rivals. This involves changing new product development processes both within individual links in the value chain and in the relationship between different chain links *Application in the BIORECOVER technology: Mg value chain – enabling magnesite miners to diversity their offer by commercialising magnesium metal*
Functional upgrading	Increasing value-added by changing the mix of activities conducted within the firm (*Ex: taking responsibility for, or outsourcing accounting, logistics and quality functions*) or moving the locus of activities to different links in the value chain (*Ex: from manufacturing to design*) *Application in the BIORECOVER technology: REE value chain – alumina refiners adding additional processing stages after the Bayer process*
Chain upgrading	Moving to a new value chain *Application in the BIORECOVER technology: REE value chain - diversification of aluminium producers & valorisation of Bauxite Residues*

Firms that are successful at upgrading to improve their value capture typically focus on their core attributes. These are the features of their business that provide clear value to their customers, have few competitors that also possess them, and exhibit barriers to entry. Kaplinsky and Morris argue that it is therefore wise to make core competencies the focus of innovation and outsource other features. However, they also claim that an over adherence to this philosophy can result in core attributes becoming "core rigidities", and that a certain flexibility is needed for firms to successfully innovate in response to ever-evolving market conditions.

When exploring the potential impact of BIORECOVER innovations for industrial actors, each of these four typologies of upgrading will be considered. It will be argued that BIORECOVER presents a different mechanism of upgrading for each of its three value chains. For the PGM value chain, BIORECOVER could enable **process upgrading** by marginally reducing the amount of PGM lost during extraction, processing, and manufacturing. However, for the **REE** value chain, BIORECOVER could enable **functional and chain upgrading** by helping aluminium producers to diversify their activities and contribute to building a novel REE value chain in Europe. Meanwhile, BIORECOVER could present an opportunity for **product upgrading** in the **Mg** value chain, by enabling magnesite miners to diversify their offer by commercialising magnesium metal.

4 ANALYSIS OF THE PGM VALUE CHAIN

4.1 Introduction to PGMs

Platinum Group Metals (PGMs), also referred to as Platinum Group Elements (PGE), gather 6 elements: platinum, palladium, rhodium, ruthenium, iridium, and osmium. All PGMs have similar chemical behaviour, but their physical properties are different from one another. All PGMs have a great catalytic activity, a good resistance to corrosion and oxidation, a high melting point, a high density, and a great electrical conductivity. Most PGMs are non-toxic aside from osmium, are able to form alloys, and are stable at high temperatures (SCRREEN, 2020).

PGMs are considered precious metals (like gold and silver) but are used for numerous applications and are crucial to certain sectors. Platinum and Palladium are the most sold PGMs, with Rhodium having a good place on the market (SCRREEN, 2020).

Scarcity

Worldwide, the estimated PGM resources are in excess of 100,000 tonnes, with a very high concentration in South Africa (68% of the total resources), 17% in Russia and 9% in Zimbabwe (see Figure 9). PGMs' reserves are estimated at 17,000 tonnes, with a high geographical concentration and distribution as resources in South Africa, Russia, and Zimbabwe, where 92% of the world's PGM reserves are located (SCRREEN, 2020).

Main markets & substitution

PGMs are extremely important to various sectors and products. Due to their excellent catalytic properties, they are used in emission control systems in vehicles and as industrial process catalysts for chemistry and Jewellery. The autocatalyst market alone weighs around USD 15 billion (Mordor Intelligence, 2021) with PGM incorporation accounting for 10 to 20% of its value. Other applications can be electronics, glass manufacturing, dental and medical special alloys. Research is ongoing into using more common elements (such as iron) as lower cost substitutes for PGM catalysts. However, currently, PGMs do not have substitutes in the market, but in many applications, can substitute one another. (SCRREEN, 2020)

Main Players

As highlighted by the following figure, there are 5 main companies involved in PGM mining. Anglo American Platinum, the world's largest platinum-mining company with an output of two million ounces, Impala Platinum, Sibanye-Stillwater and Northam Platinum are all located mainly in South-Africa while Norilsk Nickel operates in Russia.

There is no major European mining actor for PGMs. However, some European companies have important roles in downstream activities of the PGM chain. Evonik and BASF are major chemical companies that work with catalyst makers and refiners Johnson Matthey or precious metals manufacturing like Heraeus.

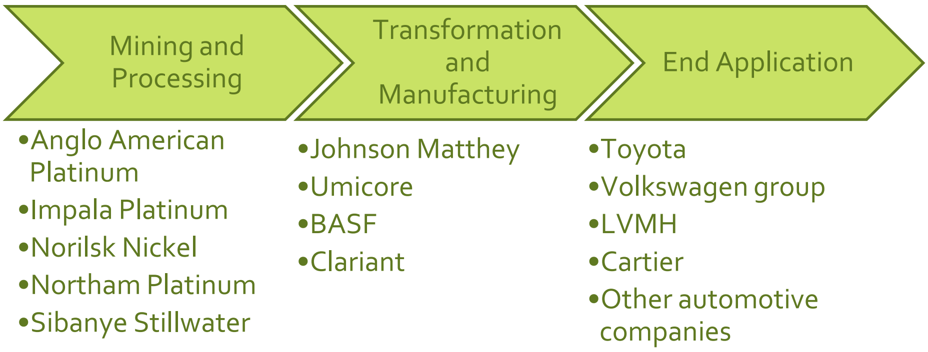


FIGURE 7. MAIN PLAYERS ALONG THE PGM VALUE CHAIN

BIORECOVER project goal: recovering PGMs

The BIORECOVER project aims at obtaining Platinum Group Metals (PGMs) from flotation tailings from South Africa, PGM residues from the United Kingdom. To this day, palladium and platinum were well recovered from ALGAENERGY (about 90% absorption) obtained from synthetic leachate. Results with real PGMs residues and flotation tailings are still expected.

This section will focus on platinum and rhodium for the following reasons:

- **Platinum** has the largest market size among the PGMs, the highest concentration (ppm) in the residues used in the project, as well as significant potential for the growing demand for use in hydrogen electrolysers (the prices is currently at 1000 USD/Oz)
- **Rhodium** value chain will be studied due to the recent explosion in the price of this material it now represents the most valuable PGM in several of the residues used in the project (the price of rhodium is currently at 17 000 USD/Oz)

PGM processing

As highlighted in the following figure, the extraction of PGMs from its parent ores is a multistep process and usually varies according to the host mineralogy (sulphides or silicates). The process summary we provide is related to the South African ores as they dominate world supply.

Three different steps enable to make PGMs out of extracted ores: concentration, smelting, and refining:

- The first step enables to get a concentrate. In primary PGM production (around 75% of annual supply), ores from the major deposits all go through a similar series of initial process stages involving crushing, milling, and froth flotation to produce a base metal-PGM concentrate (Antony, Haque, & Northey, 2021).
- **This concentrate, containing considerable quantities of silicates and iron from the original ore is then, smelted.** It is subjected to a pyrometallurgical separation at 1500 ◦C, resulting in a Cu-Ni-Fe-S matte, most producers use leaching processes in sulfuric acid in autoclaves under pressure, temperature, and with excess oxygen (blown air) to sequentially leach Ni, Cu, Fe, and then Se, As, and Te.
- In the final stage, the individual PGMs are refined totally or partially using a classical refining process with solvent extraction and molecular recognition developments (Sinisalo & Lundstrom, 2018). Separating the platinum-group elements in the converter matte from the base metals, either by magnetic concentration or by leaching, to produce a very rich platinum-group metal. The refining is done in successive steps of precipitation and redissolution followed by thermal reduction to metal. This final procedure allows the isolation of individual platinum-group metals with purities in excess of 99.9%.

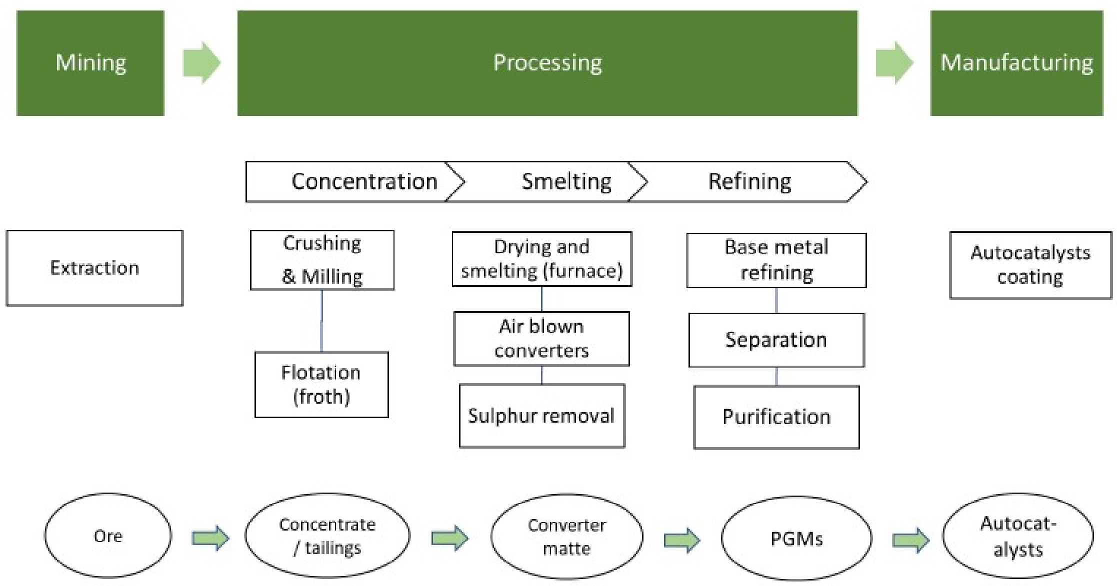


FIGURE 8. PROCESSING OF PGMS

4.1.1 Platinum

Chemical and Physical Properties

Platinum is a chemical element with the symbol "Pt" and atomic number 78. Platinum has a density of 21.45 g/cm^3, which makes platinum one of the densest metals, being about 10% denser than gold (SCRREEN, 2020). Like all PGMs, platinum has excellent catalytic properties, is relatively soft and ductile, and is exceptionally resistant to chemical corrosion and oxidation.

Given its high melting point of 1,770°C, platinum is stable in the most challenging operating conditions at high temperatures.

Platinum is mostly used as an alloy since its working characteristics, hardness and wear properties are optimised by alloying it with other PGMs. Making jewellery with platinum is possible due to its shiny silver-white colour and resistance to tarnish and wear (SCRREEN, 2020).

Production

As shown in the following figures, South Africa is the main primary producers of platinum, with 120 tons per year, followed by Russia (20 tons per year), and Zimbabwe (14 tons per year.) (USGS, 2021)

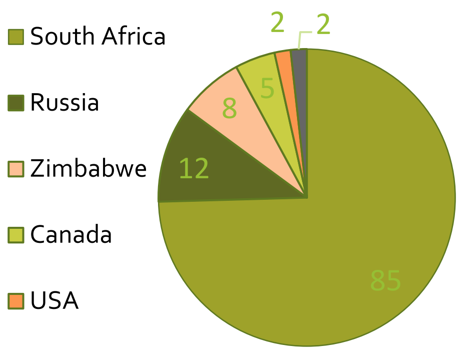


Figure 9. Global Platinum Production (% t/t)

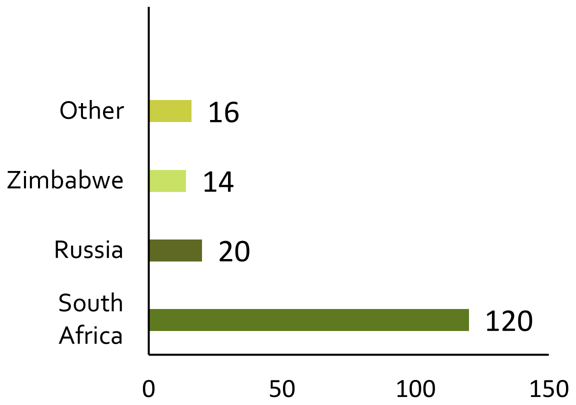


Figure 10. Production of Platinum (Metric Tons)

Applications

As shown by the following figure, the main applications of Platinum are autocatalysts (63%) and jewellery (10%). Other applications include chemicals (catalyst in chemical manufactures) and electronics.

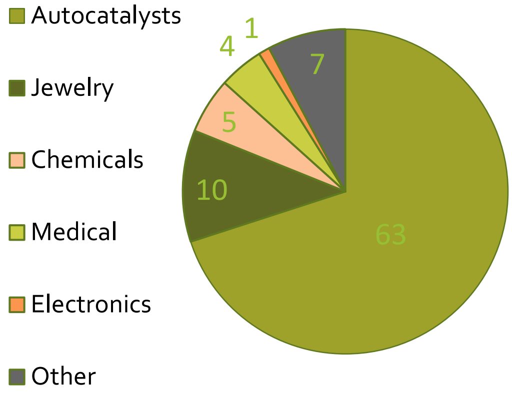


FIGURE 11. PLATINUM MAIN APPLICATIONS (%)

EU demand

Demand in the EU is driven by autocatalysts, which accounted for 63% of EU demand while they accounted for 39% of global demand. The demand averages 42 tonnes per year in the EU.

4.1.2 Rhodium

Chemical and Physical Properties

Rhodium is a chemical element with the symbol "Rh" and the atomic number 45.

Like all PGMs, Rhodium has excellent catalytic activity. similar to platinum and platinum. Its electrical conductivity is the highest among all PGMs.

Rhodium is mostly used as an alloy with other PGMs: it is less malleable and harder than platinum which makes it able to harden platinum when alloyed together.

With a density of 12.41 g/cm^3, Rhodium is lighter than Platinum, but has a higher melting point (1,960 °C). Like all PGMs, Rhodium has excellent reflective properties, is resistant to corrosion and does not tarnish in the air at room temperature. (SCRREEN, 2020)

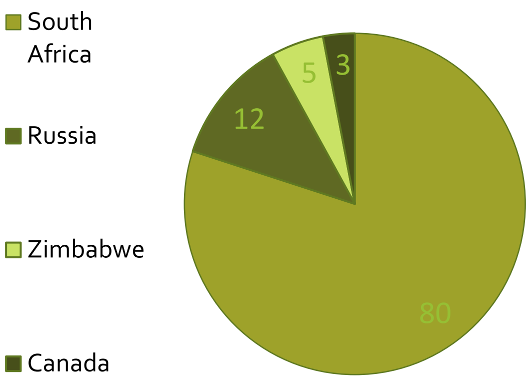
Production

As shown in the following figures, world demand is about 30t per year. South Africa is the main producer of Rhodium (20 T/y), Russia (3 T/y) and Zimbabwe (1,5 T/y)[3]. There is no primary production of Rhodium in the EU.

[3] There exists a relatively small Platinum and Palladium production industry in Finland, which represents respectively 0.5% and 0.8% of world production.

Interestingly, the EU supplies refined rhodium that is provided from secondary materials. Recycling of automotive catalysts is very important worldwide, as it accounted for 31% of rhodium global supply in 2018.

The average recycling rate ranged at 50-60%. (SCRREEN, 2020)



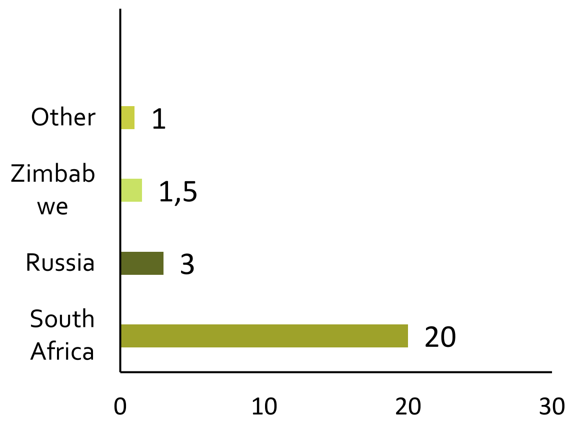


FIGURE 13. WORLDWIDE PRODUCTION OF RHODIUM (% T/T)

FIGURE 12. PRODUCTION OF RHODIUM (METRIC TONS)

Applications

As highlighted in the following figure, rhodium is used in autocatalysts (81%), chemicals (8%), and glass (5%), among others.

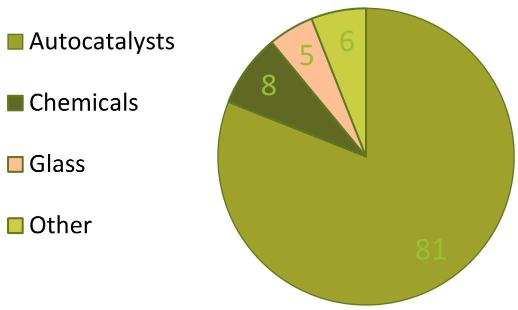


FIGURE 14. RHODIUM MAIN APPLICATIONS (% T/T)

EU demand

Global demand for rhodium was 30 tonnes/ year on average from 2012 to 2016 and around 4 to 6 tonnes in the EU. It was estimated that Rhodium demand in Europe for autocatalysts reach 4.5 tons in 2017 (Platirus, 2018).

After having detailed the global market for targeted PGMs Platinum and Rhodium as well as their applications and overall material flow the report goes on to analyse how value is created and captured along the different steps and actors of the value chain.

4.2 Distribution of value along the chain

4.2.1 Financial analysis

Value distribution is an essential step in mapping how the different actors of the PGM industry create and capture the added value along each stage of the chain. In other terms, the material flow of PGMs is accompanied by financial flows and specific behaviours by the actors involved. Moreover, the concentration of players in South Africa offers them resource rents, and the market is impacted by the technology difficulty in separating PGMs. Vertical integration is also widespread in the industry.

The analysis of the PGM value chain financial aspects will be based on a mapping of value distribution with the use of margins as relevant measurement followed by overview of costs and general trends affecting profitability in the sector.

Where value is created/captured along the PGM value chain

Along the PGM value chain, various main stakeholders can be identified. Indeed, in the following Table 4, we put forward 2 main actors in each representative macro sectors from extraction to consumer application. Those actors have been chosen due to their size and relative importance within the PGM industry[4].

As stated previously, Anglo American and Sibanye Stillwater are two of the largest PGM producers together representing 50% of global supply. Johnson Matthey and Umicore are world leaders in autocatalyst production and recycling for which PGMs play an important role (3 to 7 grams per catalyst produced). Finally, we included the Automotive sector, Toyota, and Volkswagen, as it incorporates PGM products (autocatalysts and sensors) as an end application example.

TABLE 4 : MARGINS ALONG THE PGM VALUE CHAIN

Company	Sector	Profit margin TTM (2022)[5]	Profit margin change (2017-TTM 2022)
Anglo American Pt (AAP)	Mining *(Integrated)*	40.07 %	222 %

[4] Representative actors are by no means the only important actors in the chosen sectors

[5] Calculated as follow: Growth Profit / Revenue

Company	Sector	Profit margin TTM (2022)5	Profit margin change (2017-TTM 2022)
Sibanye-Stillwater (SSW)	Mining *(Integrated)*	48.99 %	218 %
Johnson Matthey (JM)	Chemicals	6.80 %	-1 %
Umicore (UMI)	Chemicals	8.36 %	-19 %
Toyota (TYT)	Automotive	19.68 %	9%
Volkswagen (VW)	Automotive	19.44 %	0%

Table 4 indicates that **most of the added value seems captured at the earliest stage of the value chain**. Highly integrated companies in the fields of extraction and processing like Anglo American or Sibanye-Stillwater display profit margins that other sectors are unable to replicate. **The automotive sector, at the very end of the value chain, can exhibit healthy margins but PGMs represent a reasonably low amount of its costs**. Understandably, mining companies have profit margins that are very elastic to PGM prices, when prices rise those companies, margins will equally increase as can be seen with the 200% jump in profit margins between 2017 and 2022. The mining industry thus bears the costs of unfavourable cycles for PGM but also reaps most of its profits when the cycle improves.

Costs along the PGM value chain

Analyzing costs is a first step to better understand the revenue distribution. Most of the costs are sustained during the extraction phase of the value chain. As can be seen in the Figure 15 , mining represents by far the largest share of the Opex, the mining phase would be as much as 8 times more costly than smelting (571 vs 72 USD/Oz).

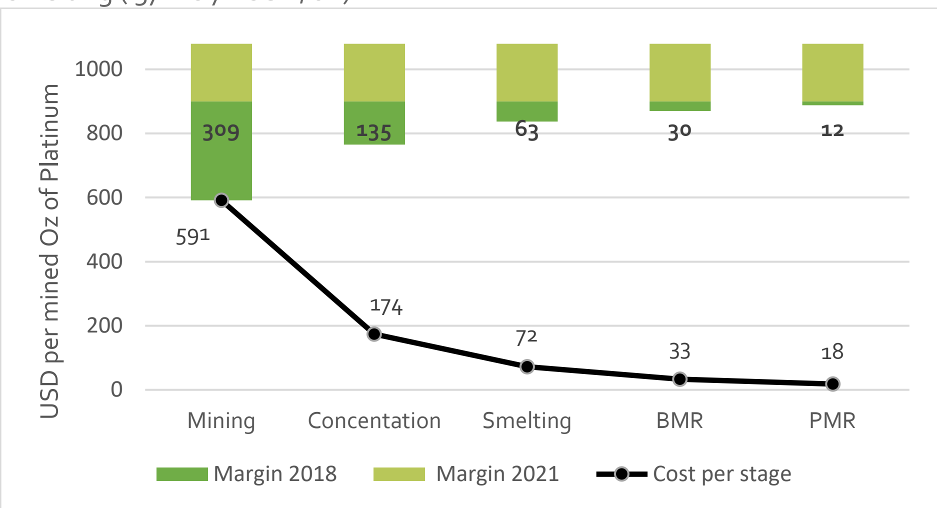


Figure 15. Mine operating costs and margins[6] at each stage of Platinum production (AngloAmerican, 2018)

[6] Theoretical margins based on the average Platinum price estimated at 900 USD/Oz in 2018 and 1080 USD/Oz in 2021

The gross profit margins established by mining and processing companies depend as on their capacity to reduce costs to hop for higher platinum prices, Figure **15** provides an example of how margins grew between 2018 and 2021 with the rapid increase in PGM prices driven by the economic recovery and renewed demand.

Financial Trends regarding margins and costs in the last years

When it comes to costs**, the average cost of production for platinum for 2015-2020 was slightly below 890 USD/Oz[7] versus an average price fluctuating around 900 USD/oz**. Those figures already indicated low potential margins for actors on the upper side of the value chain. However, it is the marginal cost of production that better defines the final price on the market: the producer the most likely to reduce its output is the one with the highest production cost, it is the one who is the most likely to impact the global supply. The marginal production cost for platinum dropped from around 1600 USD/Oz in 2015 to 1000 in 2019. The marginal production cost can be estimated as the next highest cost in the industry, in Figure 17 the last column on the right side displays a cost of 1000 USD per mined Oz independently of production size.

Profit reduction by lack of investment in new projects leads to a production plateau, and eventually a decrease in production unless the price of platinum is rising again significantly. In 2015, 45% of all PGM mines in South Africa were estimated to be unprofitable by the South African Chamber of Mines. (Baskaran, 2021)

Miners have had financial difficulties since the price slump in 2012 and have been trying to reduce costs since then, eventually causing social unrest. Recently with the upward trend in prices, profitability has come back to upstream actors (Figure **16**).

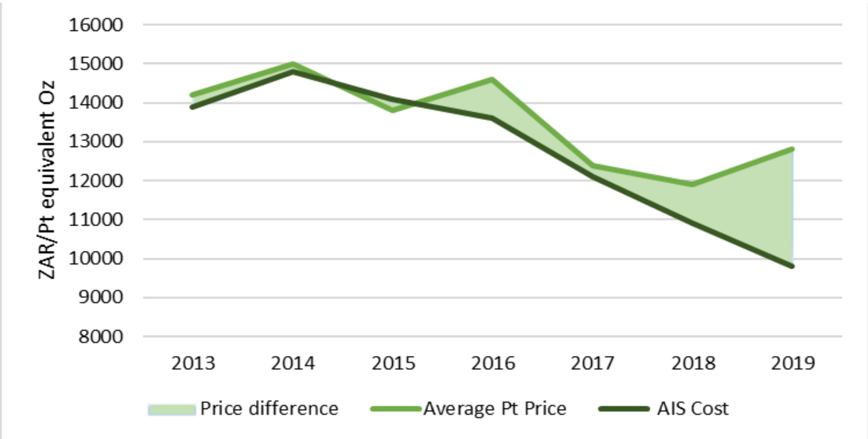


Figure 16. Historical cost[8] vs Average Platinum price[9] (Minxcon, 2022)

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[7] 1 Kg equals 32.15 troy ounces (Oz)

[8] All-in Sustainable Cost (AISC) includes cash cost incurred at each processing stage, from mining through to recoverable metal delivered to market inclusive of royalties and production taxes, sustaining and reserve development capital expenditure, corporate general and administrative costs, reclamation, and remediation costs and sustaining exploration and study costs. However, Platinum producers report costs in a variety of ways.

[9] Cost is displayed in ZAR (South African Rand), 1 euro equals 16 ZAR as of April 2022

The understanding of the current economic and financial situation of the PGM sector also leads to diving deeper into underlying mechanisms that exist in the value chain such as economic rents.

4.2.2 Resource Rents: Concentration of PGMs in South Africa

Concentration of PGM in South Africa, a resource rent

South Africa produces more 80% of global Platinum and Rhodium and over 30% of Palladium. Economically viable PGM reserves are in only a few locations, and therefore are one of the most geographically concentrated groups of metals.

Most of the PGM mines operate in the Bushveld complex, one of the most economically significant mineral deposit complexes in the world. In particular, the Merensky reef and the UG-2 reef represent about 75 per cent of the world's platinum and about 50 per cent of the world's palladium resources (Cawthorn, 2010).

Established mining companies in the area by being the only ones to access PGM resources are thus able to extract a so-called resource rent: a **surplus-value after all costs and normal returns** have been accounted for because **competition is limited**.

Secondary raw materials, a diversification solution

However, Europe's end-of-life recycling input rate, which is the percentage of overall demand that can be satisfied through secondary raw materials, is estimated at 21% (Johnson-Matthey, 2021). **Europe has an estimated potential to recycle ~60 ton of PGMs** per year by enhancing the current recycling rate from autocatalysts, which would cover most of its needs. **Secondary sources exploitation act as a counterbalance to resource rent.**

4.2.3 Technology Rents: Difficulty separating and purifying PGM explains industry concentration

A small market for a complex technology

Technological rents can appear when the used technology's complexity or cost acts as a moat for the competition to enter and disrupt the market. In the case of the PGM mining sector, the technological rent works twofold: firstly, the **costs to operate a mine are so high** that smaller actors cannot enter the market; secondly, **larger mining companies have few incentives** to join as the investment needed to reach the technological level and knowhow of competitors is too important for an already **tight market.** For Copper or other metal smelters despite a readily available capacity, techno/economic constraints make it unsuitable for PGM processing. For instance, Platinum smelting temperatures are significantly higher than other metals due to the presence of chrome making them incompatible as it requires special furnace design considerations.

As rents imply a surplus the best illustration possible can be found in Figure 17 below. The mines noted "M" belonging to Anglo American and "C" belonging to Impala Platinum present a 200 USD/Oz cost difference, as can be seen, most of the difference is due to labour costs. Indeed, the M mine in Mogalakwena is mechanized while the Impala mine C uses conventional manual labour. Thanks to large technological investments mines are shifting to new extraction methods and will see their rents increase.

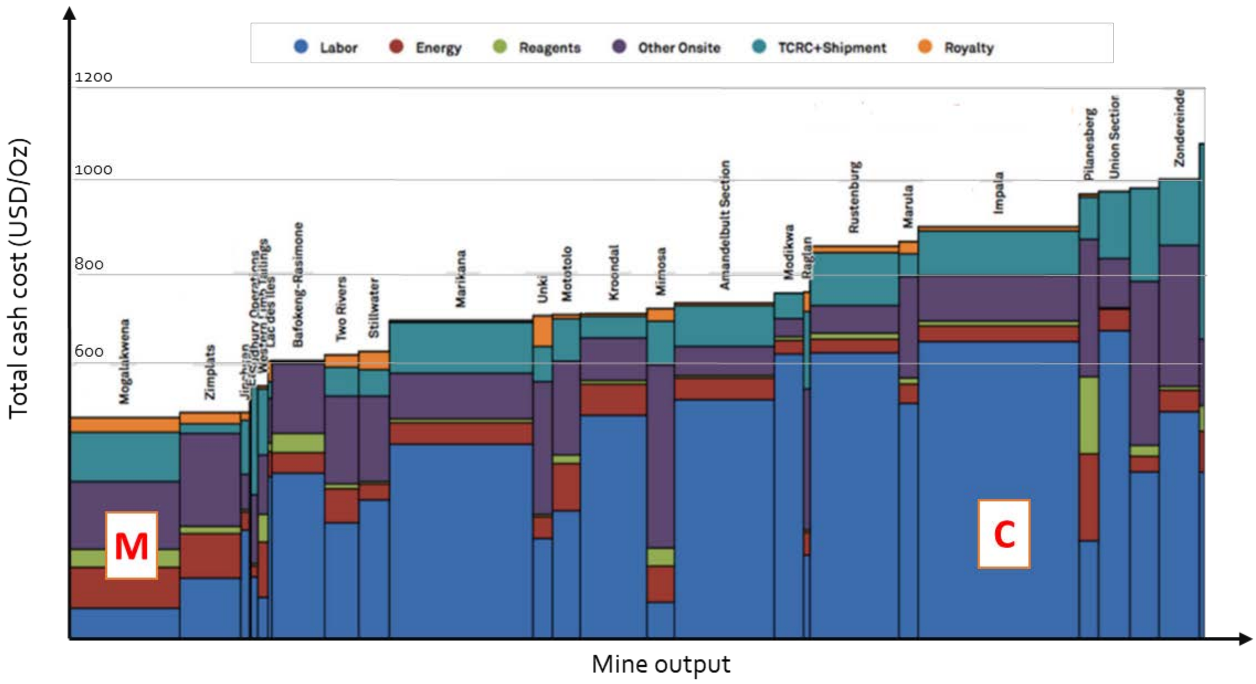

Figure **17**: Platinum mines total cash cost **(BASKARAN, 2021)**

PGM separation and purification: a technology benefiting from the growth of autocatalysts.

The industrial need for very high purity is driving the efforts of chemical companies that produce autocatalysts. Euro 1-6 regulations have strengthened the requirements in emission restrictions and pushed for more elaborated autocatalysts[10]. **The main companies involved in high purity refining of PGMs by their unique access to highly complex and cost-intensive technologies can extract a form of rent within the value chain.**

4.2.4 Organisational rents: Vertical integration enables higher margins and less competition

Over the years, PGM miners have been consolidating their activities downstream, as evidenced in Table 5 where all the largest corporations display a high level of vertical integration from mining to PGM conversion. In 2018, only 10% of PGM processing input came from non-integrated miners (AngloAmerican, 2018).

[10] Platinum and Rhodium 99,99% pure, even at 99.95% might be a struggle to find customers

Company	Mining	Smelting	Refining	Converting
Anglo American Pt	✓	✓	✓	✓
Sibanye Stillwater	✓	✓	✓	✓
Implats	✓	✓	✓	✓
Northam	✓	✓	×	×
Lonmin	✓	✓	✓	✓
Norilsk Nickel	✓	✓	✓	✓

TABLE 5: VERTICAL INTEGRATION OF MAIN PGM MINERS

There is a compelling economic case for deploying an integrated processing as alternatives are limited and expensive. Majors integrate downstream to maximise value therefore PGM's are to be processed in custom built plants. Moreover, above a certain scale of tolled out volume[11], it becomes profitable to have an inhouse capacity. With higher integration PGM producer become more customer centric and develop tailored capacities to match the needs of manufacturers and transformation (chemical) companies, one of the objectives is to create a form of monopolistic competition to maintain a form of rent (AngloAmerican, 2018).

The financial situation and economic mechanisms of the PGM value alone cannot explain firms' behaviors, when analyzing how these firm can create value it is necessary to understand their value propositions and how they manage risks

4.2.5 Value Chain Example

In this section, the value proposition will be explored, risks and advantages for each actor along the PGM value chain, by taking cars as an end product.

[11] Tolling: An agreement by a toller with an owner of raw materials to process the raw material for a specified fee ("toll") into a product with the raw material and the product remaining the property of the provider of the raw material. (Wiktionary)

Exploration of mineral resources

Example : *Podium Metals*

- **Value Proposition :** Defining the optimal technical pathway to production by providing low capital development cost, in a short development timeframe at low cost and at low risk.
- **Advantages** : Podium Metals has secure tenure mining lease, low-cost open pit, large deposit, established infrastructure access, making the company the main platform for development of a strategic Australian PGM supply
- **Risk :** PGM volatility impacting financial risks

Extraction, production of PGM concentrate and pure PGMs

- Example : *Sibanye- Stillwater in South Africa*
- **Value Proposition :** Ore extraction, transformation into a concentrate and then a PGM metal and delivery
- **Avantages :**
  - Operations located in a geologically unique region containing more than 80% of the world PGM resources.
  - Customers in both Jewellery and automotive industries (varied)
- **Risks :**
  - The volatility in PGM prices demands for constant adaptation of the business model.
  - Volatility due to endogenous factors (strikes, unrest) and exogenous (demand shocks). However, risks are mitigated through buffering (automatization) and stakeholders engagement

Manufacturing of autocatalysts

- *Example : Johnson Matthey*
- **Value Proposition :** Processing of PGMs into the fabrication of autocatalysts that filter toxic particles for the automotive industry.
- **Advantages:** well integrated & strong knowledge on PGM transformation
- **Risks** :
  - PGM volatility.
  - Investment in PGM refineries to increase the resilience and capacity.
  - Regulatory risks: developing the next generation of catalysts that will help customers meet new regulations.

Manufacturing of cars (EV/IC)

- *Example: Toyota*
- Manufacture of cars containing PGM autocatalysts
- **Value proposition :** quality and efficiency for customers (masses), cars that are safe choices. Toyota Production System (TPS) gives them an edge in competitivity.
- **Advantages:** Size, Know-how, reputation act as a good moat.
- **Risks :**
  - rising competition in new sectors of EVs,
  - need to position itself well (brand image is important as it is a consumer product).
  - Exposed to global supply chain risks

Recycling of autocatalysts

- *Example : Johnson Matthey*
- Platinum recovery from scrap metal (used autocatalysts)
- **Value Proposition** : Collect from scrap from intermediaries. Valorisation of waste. Enter agreements so the client keeps ownership of metal. Have their own network of Clients/suppliers: importance of domestic feed of PGM and supply.
- **Advantages:**
  - Advantage in being integrated,
  - closed loop with recycling in mind when manufactured.
- **Risks**: Recycling is dependent on the Automotive sector. Owners hold on longer to cars.

Firm level analysis, above, clarifies the value creation process and business behaviours. In the following part, the report will focus on the external factors that affect and govern the value chain.

4.3 Factors structuring/ governing the value chain

The ability BIORECOVERcan have in making a real impact for PGMs is determined by how the value chain is governed, as it defines how it is organized and its dynamics through time. The PGM value chain governance is, by definition, fostering actors of different strength that set and/or enforce the parameters under which others in the chain operate. The Figure 18 provides a quick understanding of the two main structuring forces of the value chain. The asymmetries of power between different actors with specific rules and sometimes diverging forces trying to structure the chain to adapt it to new realities reflect the implication of value chain governance.

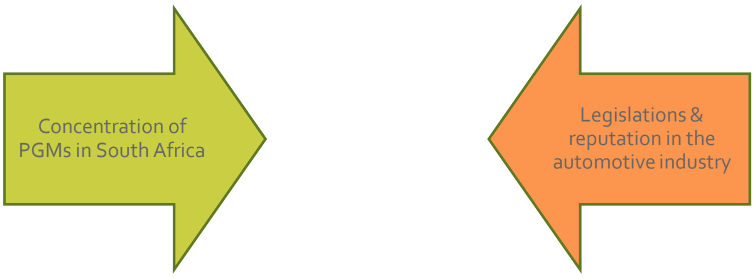

FIGURE 18. GOVERNANCE ALONG THE PGM VALUE CHAIN

The following analysis is seeking to identify the various governing factors and their effect on the value chain.

4.3.1 A value chain with concentrated supply in South Africa

Since South Africa alone is home to over 75% of global PGM reserves, understanding the local context is essential in identifying the factors governing the value chain. Mines in South Africa have experienced several events (strikes and massacres) that could lead to reputational and operational disruptions and has had increases in energy prices. The industry has started automatising mines & plants while aligning their volumes with demand, driven by chemical manufacturers and autocatalysts.

Strikes & Massacres in South Africa impacting reputation and impacting the value chain

Events in the south African PGM mining sector can have important repercussions on the global PGM market. Strikes are the main issues regarding the mining sector in South Africa and thus the PGM industry. The 2016 strike lasted 152 days and the mines lost 48.5% of platinum output, taking 440,000 oz out of production. The volatility and intensity of the labour issues in the sector remains marked by the massacre of mineworkers at the Marikana PGM mine in 2012, which caused major reputational damage to the sector (Cairncross & Kisting, 2015).

Increased costs of energy

Moreover, the steep increase in energy bills has also had a major impact on the South African mining industry. It has been one of the contributing factors to significant production cost increases in the 2010s. South African PGM mines have amongst the highest production costs globally (S&P Market Intelligence).

Automation reducing labour costs while mitigating risks and increasing efficiency

The South African mining sector has been developing strategies to increase its overall efficiency mainly by reducing labour costs and risks as well as increasing productivity (Baskaran, 2021) thanks to **automation.** This last point means heavy investments as well as a **shift toward palladium** production (in which South Africa is not a leader).

Volumes & Prices

The integration and concentration of PGM actors in South Africa will lead companies to better respond to changes in commodity prices. The sector is becoming more customer-centric as **more mines start aligning their output volume with demand** hence a characterization as a demand-driven value chain.

A demand driven by autocatalysts and chemical manufacturing markets

The PGM value chain is thus impacted by high geographic concentration. Its downstream components are also highly concentrated, with demand primarily driven by the autocatalyst and chemical manufacturing markets. This means that its demand is also governed by specific regulations.

4.3.2 A value chain structured from top to bottom by air quality legislations

The automotive industry driving PGM demand

The 2017–2021 period has seen significant changes in emissions legislation in several major markets. In Europe, the introduction of the Real Driving Emissions (RDE) standards under Euro 6d-TEMP and Euro 6d legislation and the subsequent tightening of conformity factors have increased the technical difficulty of meeting emissions standards. This has had a positive impact on the use of PGM autocatalysts, with an impact greater on rhodium, as the focus is mostly on NOx emissions. Elsewhere, implementation of the first phase of China 6 legislation (reductions of 50% for hydrocarbons, 40% for NOx and 33% for PM over Euro 6 levels) and the gradual roll-out of Tier 3 Federal US regulations will make for a global push towards new kinds of autocatalysts. In India, diesel volumes were hit by changes to automakers' vehicle production mix ahead of the introduction of BSVI legislation in April 2020 requiring the addition of complex NOx control technology (Johnson Matthey, 2021)

In 2025, the Euro 7 emissions standard is expected to be the final iteration of this type of legislation surrounding vehicle emissions. The U.S. Environmental Protection Agency (EPA) is proposing stronger standards to promote clean air and reduce pollution from heavy-duty vehicles and engines starting in 2027.

As just seen, both the socio-economic situation of South Africa, at the source of the PGM value chain, and the regulations at the destination of PGMs in Europe are two structuring forces. To complement this macro analysis, it is important to proceed on a micro level to better outline the intra-firm forces at work along the value chain.

4.3.3 Intra-firm Governance of Supply Chains

Market players dynamics

Most of the exploration and extraction activity is done by a handful of international mining companies with high levels of integration. Already among those companies, there is a level of cooperation in the form of **buybacks or exchanges of processed materials**. Smaller, junior companies in the exploration phase find themselves bought out by majors. With the quick market evolutions in autocatalysts, related production lines operate in a lean way. As such, deliveries are operated efficiently and when combined with the nature of PGM supplies and their price movements there is a strong case for **long term stable contracts.** These long-term contracts benefit both the supplier, who needs a secure flow of capital to run mines and processing and the customer who needs a reliable and quick supply of PGMs.

Interaction between players depends on the application

In other cases, PGMs are sold through **intermediaries** but this concerns more the **Jewel** or I**nvestment sectors of PGM** as the market structure and needs differ. For the autocatalyst industry, the biggest PGM consumer, only a few large companies dominate each step of the value chain leading to a more formalized flow among actors where loyalty is important.

Chemical companies such as Johnson Matthey, which transform PGMs, can **borrow them against a fee.** Then Johnson Matthey comes to some contractual agreement that they will return the metal after several weeks (Platinum usually requires a shorter waiting time Rhodium). During the transformation, it remains the customer's metal.

Within the **autocatalyst industry,** actors can use processing "templates", as ready-made models, and, for instance, tailor the **coating stage to specific needs**. Manufacturing is customer dependent with the consequence of adapting prices to demand.

Recycling

For the last stage of recycling, autocatalyst makers, such as Johnson Matthey, use intermediaries for recycling supply: smaller groups of upgraded collectors sorted beforehand to protect JM's reputation. Johnson Matthey takes in autocatalysts coming in different concentrations: 0.2-0.4 % PGM. Commercial contracts say the recycler will charge a fee for bulk refining, per ton. Contracts can cover smelting with a similar cost for whatever the grade. The last step in the negotiation between the recycler and the customer has to do with the quantities given back. Platinum returns usually in larger amounts (90%) than rhodium. In fact, they don't necessarily return all the metal from feeds or they can take a long time. The metals can also be bought back because integrated recyclers prefer having metals under control to feed their activities.

4.3.4 Logistics

As intra-firm relations are structured by the different needs of the market, logistics also play an important role of characterizing the material flows of PGMs. First and foremost, most ores are uneconomical for transportation because of low concentration. Smelters are mainly constructed in areas proximal to major mines like Norilsk in Russia and the Bushveld in South Africa (USGS, 2018). The smelters and refiners could use both primary concentrates and recycled materials to make PGM powder or bars.

When shipped to international traders or industrial groups, PGM producers can directly charter flights to the established destination. Indeed, PGM primary production is too low in volume to justify a specific cargo ship-oriented supply chain. Another reason for using quick flight delivery of precious PGMs is safety measures with safeguarding insurances representing potential high costs for mining companies. PGM logistics and the way they are shipped perfectly inserts themselves within the PGM trade structure

4.3.5 Trade Policies

The way international trade is structured for PGM explains and underlines the **specifics** of the PGM value chain governance would it be through its distinct trade flows **or where trade restrictions apply**.

Trade flows

A large part of PGM trade flows in 2020 took place among the top exporters, with the United Kingdom acting as a hub in the platinum supply chain. UK imports of PGMs increased markedly from the Russian Federation and the United States. The United Kingdom was the main PGM exporter in 2020 (US$ 11.6 billion) due to large stocks held by investment funds but its industry also refines PGMs (WTO, 2020). Other top exporters include the United States, Russia, and South Africa.

Leading importers of PGMs are, for instance, Japan who as an of hybrid vehicles and relies on PGMs imports for their production, which requires more platinum alloys than traditional internal combustion engines. China also greatly increased its imports of platinum materials from the United States by over 260%. The US and UK both export and import high quantities of PGMs not only for industrial needs but also for trading and stockpiling activities (WTO, 2020).

Stockpiling

Stockpiling of raw materials and PGMs is a very common practice. Stockpiles helped put a cap on prices when strikes in South Africa or trade restriction with Russia affected global PGM supply. World Platinum Investment Council said that estimated above-ground stocks of 2.56 million ounces for 2015. London is one of the main centers of platinum and palladium trading and is home to around half of vault stored PGMs (Harvey, 2013). Clearing and settlement services, which act as a buffer between buyer and seller, are an important part of PGM trading. Stockpiling can act as collateral in finance or raw material trading in general as it remains a sufficiently liquid asset.

Trade restrictions

Table 6: Trade restrictions for PGMs (OECD) summarizes the restrictions put in place by some PGM producers. Restrictions for PGM trading have the purpose to promote further processing and adding value.

TABLE 6: TRADE RESTRICTIONS FOR PGMS (OECD)

Country	Platinum	Palladium	Other PGM
South Africa	Non automatic[12] Licensing	Non automatic Licensing	Non automatic Licensing
Zimbabwe	5% export tax	5% export tax	5% export tax
Russia	Non automatic Licensing	Non automatic Licensing	Non automatic Licensing
Botswana	Non automatic Licensing	Non automatic Licensing	Non automatic Licensing

4.4 Emerging changes to the value chain

4.4.1 Changes in demand due to technological/ social shifts

An important part of the demand is driven by technological changes. Some of those news developments stem from social shifts, and changes in consumption behaviour, notably regarding sustainability. The transition to achieve European climate goals implies the emergence of new markets. PGMs will play an important role in the future in the following high growth potential industries of Europe.

Fuel cells

Fuel cells as an attractive clean energy technology have recently gained popularity for replacing IC engines. Hydrogen fuel cells are emerging as a high-potential technology that offers significant energy efficiency (Du, Prabhakaran, Xie, Park, & Wang, 2020). As such, the global hydrogen fuel cell market size was valued at $651.9 million in 2018 and is projected to reach at $42,038.9 million by 2026 (Market search, 2020).

Drones, Robotics and ICTs

PGMs are important components of digital technologies, especially microchips. Palladium is sought after for multi-layer ceramic capacitors, ICs and circuit boards while Platinum and other PGMs are in glass for displays and memories. This means PGMs have a key role to play in the booming markets of drones and robotics.

Automotive industry

[12] Non-automatic licensing is used to administer trade restrictions such as quantitative restrictions, which are justified within the WTO legal framework.

Additionally, Since PGM sales are to a large extent linked to autocatalysts, any technological and subsequent social shift regarding vehicles would have an important effect. As seen in the figure below, the market of passenger vehicles finds itself in the middle of a complete transition away from internal combustion (IC) vehicles in favour of electric alternatives. A lower number of new IC cars means a lesser need for PGMs that EVs can't completely account for. Since recycling from scrap cars autocatalysts represents a non-negligible source of PGM there will be a lagged effect in the form of a future reduced supply of recycled PGMs.

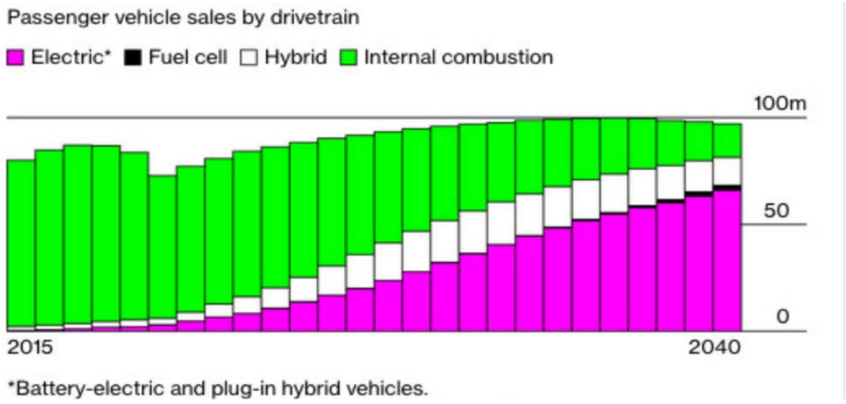

Figure 19. Passenger vehicles sales evolution (BloombergNEF economic transition, 2019)

In July 2020, the European Commission published its hydrogen strategy which aims at boosting the clean production of hydrogen enabling emission-free transport, heating, and industrial processes as well as inter-seasonal energy storage. The strategy has explicit electrolyser capacity targets of 6 GW by 2024 and 40 GW by 2030 (EU Commission, 2020), as well as production targets of 1 million and 10 million tonnes of renewable hydrogen per year. The uptake of clean hydrogen over grey hydrogen is expected to be market-driven, as realistic carbon pricing drives up the cost of grey hydrogen and blue and green hydrogen become more cost-effective.

PGM-based catalysts are expected to play an important role in the hydrogen economy, especially when considering exchange membrane (PEM) fuel cells. For instance, Palladium can absorb hydrogen with minimal energy. It is therefore an excellent metal to be able to purify hydrogen. It can also be used as a substitute for carbon-supported platinum as an anode catalyst in electrolysis and help reduce the use of platinum at the cathode too in proton exchange membrane fuel cells. PGMs also have interesting applications in water electrolysis and hydrogen refining. In general, different technologies compete in the market when it comes to the electrolysis of water. Anode catalysts in these electrolysers are usually based on PGMs iridium and ruthenium, with iridium being the preferred component. However, PGM loadings will probably diminish to maximize efficient use of metal over time as the inherent price and certain supply constraints will remain and slow the uptake (Hughes & Haque, 2021).

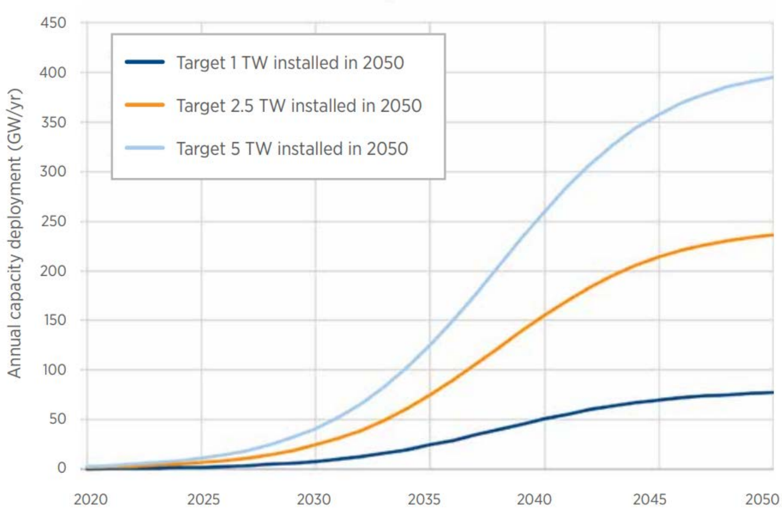

FIGURE 20: ESTIMATED NECESSARY ELECTROLYSER MANUFACTURING CAPACITY (GW/YEAR) (IRENA, 2020)

While not specifically in the front line of the green transition, the jewelry sector is unavoidable for PGMs. Indeed, platinum equivalent demand reached 2 million ounces or a quarter of total Platinum global demand. European and American manufacturers are among the world leaders in this sector. The spending rate of young consumers and rising disposable income in emerging countries such as India and China are boosting sales of platinum jewellery in Asia Pacific, and the region is one of the largest consumers of platinum jewellery. In Europe and North America, the demand is stable. The market can be expected to bounce back to over 3 million ounces in the coming years (PGI, 2020)

4.4.2 Forecasted changes in PGM supply and price

The Global supply in PGM is not expected to grow at a very fast pace. As shown in Figure 21, after the pandemic rebound there will only be a slow increase in the PGM supply. Most of this supply will be driven by higher secondary production.

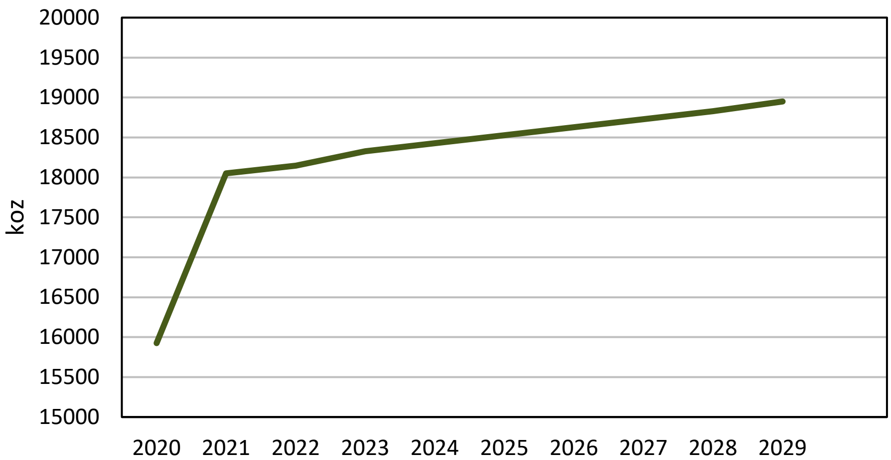

FIGURE 21. ESTIMATES OF PGM (PT, PD, RH) PRIMARY AND SECONDARY PRODUCTION (SIBANYE STILLWATER)

Both secondary production and primary production have an impact and themselves impact PGM prices.

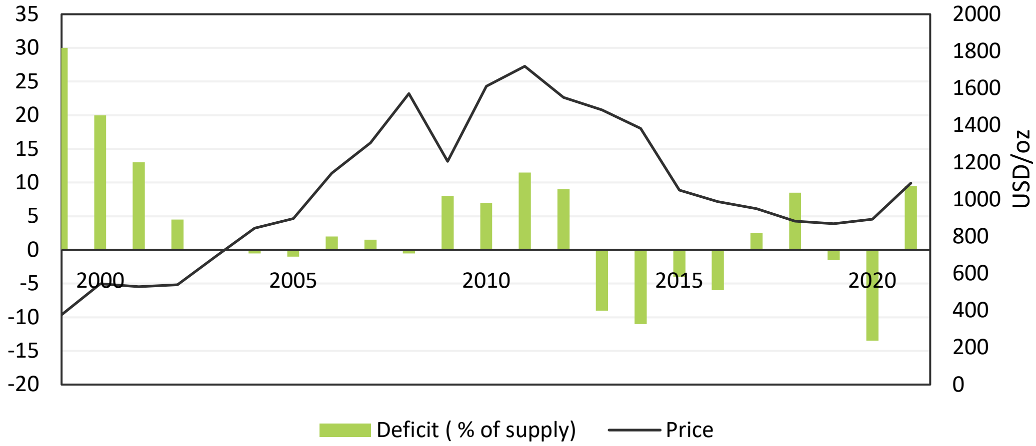

Figure 22. Platinum prices and market imbalances (World platinum investment council, 2021)

The increase in the price of platinum from 2000 to 2008 was in line with the shift from a large surplus to a slight deficit (30% over the years). The new deficit cycles since 2012 led the prices to decrease sharply instead of rising. This shows there are very strong deflationary forces for Platinum. Despite the anomalies in 2020-2021 with the COVID-19 induced market disruption, higher prices can be expected in the future. With a rise in the demand and only slight supply improvements, the deficit could reach downs at 40% of the yearly supply pushing prices up. The opposite is expected to happen for both Rhodium and Palladium whose supply will increase and catch up with demand over time and may lead to stagnating or decreasing prices (see figure below).

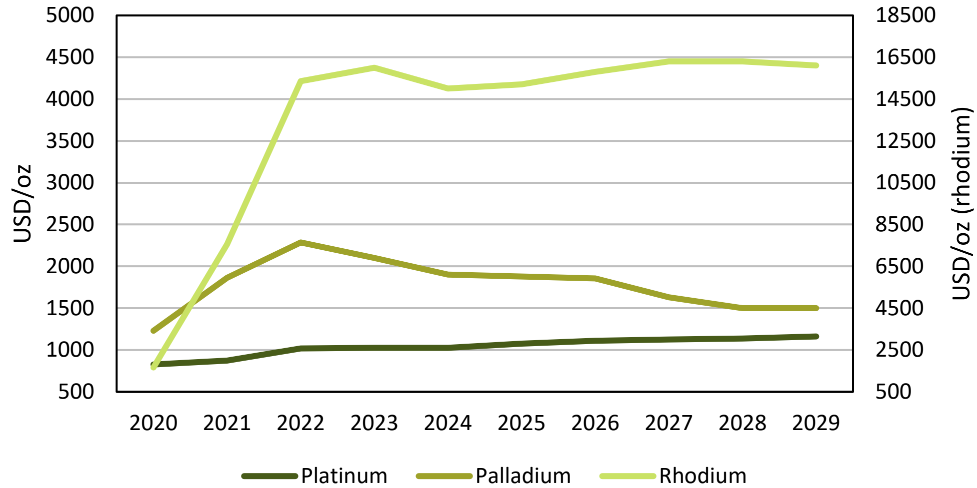

Figure 23. Estimates of PGM PRICES (Edison group, 2021)

Both demand and supply changes are crucial elements that will shape the future of PGMs. One of the goals of this report is to gauge both how BIORECOVER can insert itself within the future trends and enhance the procurement of PGMs by upgrading the PGM value chain itself.

4.5 Upgrading the value chain

As shown previously, the PGM value chain is highly integrated. It is dominated by a few major suppliers based in South Africa who have stable relationships with catalyst manufacturers and major automotive producers. PGMs are also subject to significant price volatility due to cyclic imbalances between supply and demand. This volatility is exacerbated by the geological scarcity of PGM's, as well as the fact that they are mined as a basket of metals but commodified separately. This price volatility is likely to persist as the downstream uses of PGMs undergo major shifts in coming decades, with their use in autocatalysts becoming obsolete, while demand for PGMs in the hydrogen economy is expected to grow exponentially. In this context of shifting demand and geographically and economically concentrated supply, how can BIORECOVER contribute to upgrading the PGM value chain?

4.5.1 Value proposition of the BIORECOVER Project in the PGM value chain: technologies for secondary processing rather than primary production

Value Proposition of the BIORECOVER Project

As detailed in 3.2.3, project partners working on technologies for concentrating, extracting, recovering, and transforming PGMs were invited to offer a preliminary response to this question during the Circular Value Proposition Workshop held in June 2021. Together partners reflected on the value that is lost or at risk in the current PGM value chain, and the potential for BIORECOVER to use the principles of circular economy to bring added value to the chain.

The result of the workshop was the following value proposition for BIORECOVER: **A mutually beneficial partnership between sustainable technology experts and the PGM industry to maximise resource value through the development of cutting-edge bio-based tools and services**

A value chain slightly modified by the recovery of PGM low-grade ores & industrial waste

Over the following months, LGI has worked in consultation with project partners and industry stakeholders to imagine and flesh out how BIORECOVER could achieve this value proposition and sustainably maximize resource value across the PGM value chain. Careful consideration of the drivers and barriers to upgrading each link of the PGM value chain indicates that **BIORECOVER will likely not create an entirely new European PGM value chain**. Rather, the BIORECOVER process could enable process upgrading by marginally reducing the amount of PGM lost by existing industrial firms during extraction, processing, and manufacturing.

This section of the report will detail how this conclusion was reached, and what a PGM value chain integrating BIORECOVER technology at scale could most feasibly look like. To do so, it will consider each stage in the value chain, and detail the possible impact of BIORECOVER, novel value propositions for that link in the chain, and key factors that remain unknown or at risk.

4.5.2 Strategically positioning the biotechnologies: targeting mine closure and industrial waste streams

Three possible commercial contexts for deploying BIORECOVER at an industrial scale were considered as possible, each with its unique constraints and opportunities.

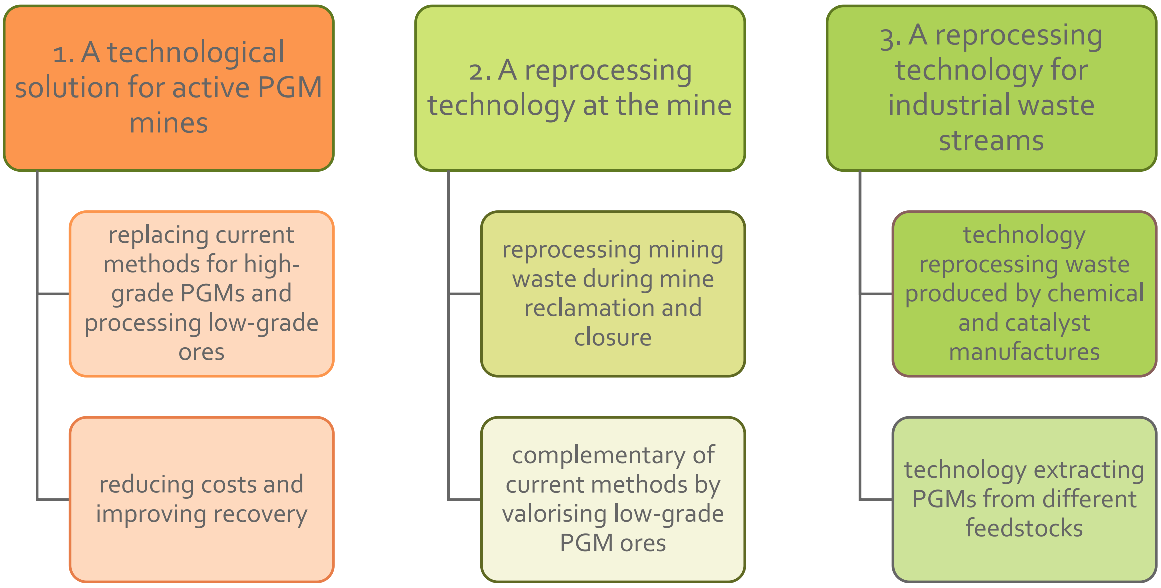

FIGURE 24. THE THREE SCENARIOS FOR DEPLOYING BIORECOVER

- The first scenario would be the deployment of BIORECOVER as a processing route for active PGM mines. This would entail BIORECOVER replacing conventional beneficiation and processing methods for high-grade PGM ores, as well the use of the technology to process low-grade ores that are not currently commercially viable for recovery. The biotechnologies would thus need to offer a competitive advantage in terms of reduced cost or improved recovery versus the standard processing routes deployed by the PGM mining industry.
- The second scenario would be the deployment of BIORECOVER for reprocessing mining waste during mine reclamation and closure. This would involve the technology being deployed as a complement to existing PGM beneficiation and processing flows. In this scenario, the BIORECOVER process would only be applied to low-grade waste rock at PGM mines. The biotechnologies would need to demonstrate that they can add value during mine closure, by extracting additional value from uneconomical mining waste or contributing to the environmental remediation of the mine site.
- The third scenario would be the deployment of BIORECOVER for reprocessing industrial waste streams produced by chemical and catalyst manufacturers. This scenario would involve biotechnologies being used at an industrial site to extract PGMs from a diversity of feedstocks produced as byproducts when consumer or industrial products containing PGMs are

manufactured. To be adopted under this scenario, the biotechnologies would have to extract enough PGMs from the feedstocks to justify the cost of deploying them.

Reprocessing ores & industrial waste, potential markets for the BIORECOVER technology

Ultimately, the decision was made to position the BIORECOVER process as a potential **solution targeting the second (reprocessing low grade ores) and third scenarios (reprocessing industrial waste streams)**. This strategy was chosen for a variety of reasons. Firstly, the major fixed capital investments primary PGM producers have made in their extraction and processing equipment would likely make them reluctant to transition towards novel processing routes that are yet unproven at scale. Major PGM mines have invested heavily in optimizing their process flows and have tailored them to fit their commercial-grade ores. Consequently, existing process flows perform very highly in terms of maximizing PGM recovery in a timely and cost-effective manner.

Rather than competing with primary processing routes then, **BIORECOVER can bring added value if it demonstrates a capacity to sustainably treat challenging feedstocks such as low-grade ores or industrial residues**. When viewed as a waste processing technology, BIORECOVER becomes significantly more economically interesting for potential clients in the mining and chemical industries. Under scenarios two and three the biotechnologies could simultaneously reduce the number of waste clients must deal with (and the associated gate fees) and produce an additional revenue stream that could help cover the cost of waste disposal.

Bringing the BIORECOVER technology to the market could be done by understanding how each stage of the value chain in order to be modified. The next sections will specify how the BIORECOVER could foster innovation in exploration and processing, extraction, processing, and manufacturing.

4.5.3 Upgrading PGM Exploration and Process Design

Reducing risks and costs, drivers to Innovation in Exploration & Process Design

As was highlighted in section 4.2.5, PGM exploration firms create value by conducting geological test work for the mining industry to identify PGM resources. Once resources are located, exploration firms typically conduct scoping, pre-feasibility, and feasibility studies to quantify the amount of PGMs that can be considered as reserves, and to determine the economic and technical viability of mining a specific deposit. Based on the geological conditions of a given deposit, the firm will then propose an optimized mineral processing flow aimed at maximizing recovery and minimizing cost. **An exploration firm's competitive advantage** will primarily be driven by its ability to **reduce both the cost of its test work (drilling, assaying, etc.) and the potential risks for future mines** (environmental, technical, socio-political, etc.).

Risk aversion about bio-mining technologies & unknowns, barrier to innovation

This risk aversion could represent a barrier to innovation in this sector and could prevent exploration firms from upgrading using the BIORECOVER process. Employees of geological consultants working with PGM ores are unlikely to be familiar with novel bio-mining technologies and may thus prefer to propose conventional processing routes during their scoping and pre-feasibility studies. The perception of biological processes as more variable than conventional pyro and hydrometallurgical technologies may also dissuade these firms from proposing an upscaled BIORECOVER process.

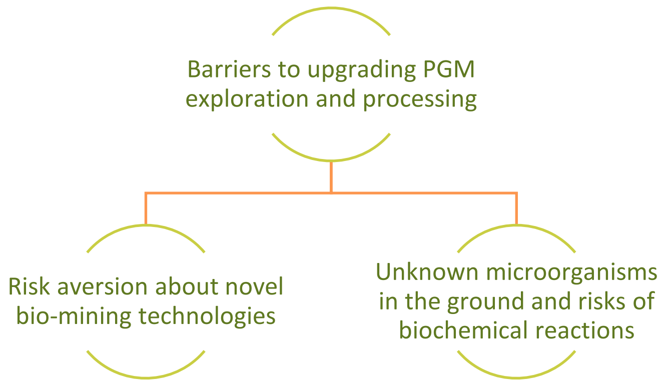

FIGURE 25. BARRIERS TO UPGRADING PGM EXPLORATION AND PROCESSING

Impact of the BIORECOVER technology on Exploration & Process Design

The proposed route for upscaling BIORECOVER therefore must respond to these dual objectives of **reducing the cost** of quantifying PGM reserves, **and risks** for mining clients. As previously mentioned, during the initial stages of upscaling, it is not recommended to commercialize the BIORECOVER process as a treatment for primary mineral deposits. Thus, BIORECOVER would not be proposed during exploration as part of scoping and pre-feasibility studies. Instead, it is suggested that the BIORECOVER technology should be sold to active mines nearing the end of mine life, as a processing route for *already extracted low-grade ores*.

Estimating the reserve quantity within above ground extractive wastes should be a lower cost than conventional exploration because it doesn't require drilling and can draw upon already existing test work done to characterize the ore before the mine became active. However, additional test work will likely be required to identify the existing microorganisms living within the feedstock that will be reprocessed, since their presence could alter the biochemical reactions produced by the microbes selected for bioleaching by BIORECOVER. Once an optimal consortium of microorganisms has been selected for a specific feedstock, reprocessing offers the potential to mitigate risks for a mining client. In theory, BIORECOVER could help reducing the quantity of extractive waste present at a mine site, while also generating revenue to pay for mine remediation. However, recoverable PGMs represent only a neglectable fraction of the mine waste. Therefore, BIORECOVER could only fully help reduce a mine's land use impact and the associated risks of negative environmental and social impacts if additional elements could be recovered.

Impacts on Exploration & Process Design stakeholders

Deploying BIORECOVER at the mine scale could have a **major impact on the actors involved in the exploration and process design stages** of the PGM value chain. Enabling the reprocessing of low-grade PGM ores, and bypassing standard routes for primary extraction, means that **conventional**

exploration firms may no longer be necessary for this novel PGM value chain. Yet, by expanding the realm of technical knowledge needed at these links in the value chain from geology to biochemistry, BIORECOVER may also require additional technical consultants to become involved in exploration and process development.

Recommendations to partners of the BIORECOVER project

It is therefore recommended that the **research institutes and universities designing the BIORECOVER process work** too well to document and protect the intellectual property they invent within the project so that these results can be transferred to a commercial partner (likely through a licensing agreement). This commercial partner with experience designing **industrial processes**, such as Algaenergy or Tecnicas Reunidas could then operationalize project results by selling them within a **tailored process design service.**

4.5.4 Upgrading PGM extraction

The global mining industry has been undergoing a major technological upheaval in recent decades, as the application of engineered microbes to selectively leach metals from their ores has rendered previously uneconomic low-grade mineral deposits commercially viable. The integration of living microorganisms into the process of extraction has helped to enable global commodity outputs to continue increasing over recent decades despite declining average ore grades (Arboleda, 2020). Yet the expansion of mining into lower grade ores has also dramatically increased the scale and complexity of extraction. Indeed, low-grade biomining has been made possible thanks to a host of other novel technologies, such as autonomous hauling equipment and high-tech GIS systems that render deposits legible (ibid). How can BIORECOVER situate itself within this shifting landscape of mineral extraction?

Drivers to Innovation in PGM Extraction

One of the drivers to innovation in PGM extraction is to reduce both costs of waste disposal and energy. The valorisation of low-grade ores that have already been extracted can create new revenue streams. Additionally, the ability to valorise mine waste will help reduce its disposal cost both because of lower volumes but also because of renewed economic potential.

However, the main driver in innovation for the extraction phase remains the costs. While labour represents a sizable part of the extraction costs, the main innovation drive in recent years has been automation. However, automation is driving energy requirements for energy upwards and hence pushes the need to find efficient and sustainable methods (Baskaran, 2021) .

Moreover, in order keep its license to operate, the extractive industry wants to reduce its overall environmental impacts. There are several environmental problems associated with the impacts of mining, the IPBES stated that "while still using less than 1 per cent of the Earth's land, mining had significant negative impacts on biodiversity, emissions of highly toxic pollutants, water quality and water distribution, and human health". (IPBES, 2019)

The Choice of the Microbial Consortia: an unknown

Given the low TRL of the BIORECOVER technology at the time of this report's publishing the optimal choice of microbial consortia and the optimal extraction parameters for the process are not completely refined. Therefore, proposals for extraction using the BIORECOVER process remain based on the results of stakeholder consultation.

Moreover, the choice of the right microbial consortia and the related parameters need to be weighted with the high expected standards regarding health and safety measures especially in an extra-European context for PGMs and with the aim to protect local communities.

Inspiration for upscaling BIORECOVER can also be drawn from existing bioleaching systems, which have been significantly developed in the Copper and Gold industries (Mwase, Petersen, & Eksteen, 2012).

The 4 most common commercial biomining processes are:

- **Slope Leaching:** Fine ore is kept in a large, slope-shaped dump. During slope leaching, a water solution made of inoculum is continuously sprayed over the ore. After that, the leach liquor (or remaining liquid) is gathered at the bottom and processed for supplemental metal recovery.
- **Heap Leaching:** In this technique, the ore is arranged in large heaps. During heap leaching, an aqueous mixture of microorganisms is sprinkled over the leach pile. Then, the solution is collected and processed to help recover even more metal.
- **In-situ Leaching:** The ore remains in its natural state while the leaching process takes place. Water that contains thiobacillus is pushed through drilled passageways within the ore. The leach fluid is then stored until it is time for metal recovery.
- **Tank Leaching:** Tank leaching is used to extract trace metal from ore. The material is ground sufficiently fine to form a slurry or pulp, which can flow under gravity or when pumped. Tanks are typically equipped with agitators, baffles, gas introduction equipment designed to maintain the solids in suspension in the slurry.

Impact of the BIORECOVER project

Though the BIORECOVER process will have environmental impacts, the reprocessing of PGM low grade ores will avoid the extraction of PGM at another site, and thus, all environmental impacts. The new tools provided by BIORECOVER mean that PGM producers can consider highly attractive solution to high-grade ore depletion and mine closure. BIORECOVER will lengthen the life of the mines and allow for smoother financial transition for mining firms. The project also offers highly cost effective mine remediation and reclamation solution in line with the global sustainability goals.

Impacts on stakeholders

The main stakeholder impacted by upgrades in PGM extraction are first and foremost the main mining companies. Since PGMs are highly concentrated the actors are few and well-integrated and will this imply shorter logistics routes. Local communities will in the long run benefit from an effective mine reclamation program.

Recommendation to partners of the BIORECOVER project

BIORECOVER could be used as a bioremediation tool for PGM mines. Bioremediation would mean the decontamination of polluted mining sites and tailings using the activities of living organisms. For this, we can build upon what has been done within the copper industry.

BIORECOVER could establish contacts with mining partners to scale up the technology and bring it to market.

In similar fashion to South-African PGM mine wastes, Chile is home to copper mining acid mine drainages (AMDs) characterized by high concentrations, which can be recovered. Passive biochemical reactors are eco-friendly technologies for the treatment of AMD. Copper miners use organic substrate mixtures to drive microbial sulphate reduction and metal sulphide precipitate formation. The valorisation of copper slags can be leached for the recovery of valuable metals, while the leach residues can be used as construction materials, thus improving the economics of the process and substantially reducing the footprint of the metallurgical and construction sectors, in line with the principles of a circular economy.

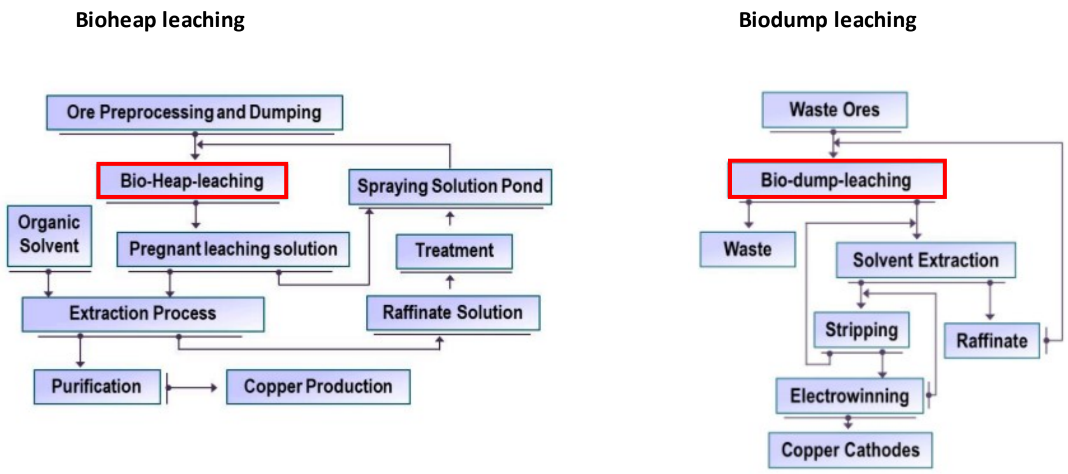

FIGURE 26: BIO LEACHING SYSTEMS FOR COPPER WASTE TREATMENT ((YIN, WANG, KABWE, & CHEN, 2018)

As seen in the figure above, the copper known processes to bioleach waste or dump could be applied to the PGM industry in South-Africa.

4.5.5 Upgrading PGM Processing (Pre-treatment &Refining)

Major PGM miners are integrated from mining to refining and therefore maintain considerable processing assets that produce both refined PGMs and by-products. PGM processing can currently be divided into 3 phases of concentration, smelting and refining. The value chain can be configured to suit the available capital as long there is suitable economic capacity which means that products can enter or leave (be sold) at each different step of the processing making it very complex to analyse.

Drivers to Innovation in PGM Processing

The main innovation drivers in PGM processing concern increasing productivity, using energy and capital more efficiently and enhance recovery rates. For this PGM producers have been focusing their research on grade engineering and geo metallurgy, the implementation of alternative flowsheets that include automation and modelling as well as better sorting and commination circuits and finally on the adoption of disruptive technologies such as novel reagents.

In an effort to further reduce costs there is also a real necessity to improve the elimination of hazardous impurities, as it represents key area where producers find room to improve.

Barriers to Innovation in PGM Processing

The barriers to innovation for processing are closely linked to limitations within the extraction phase as the two phases are increasingly integrated within the same international corporations.

The increase in environmental regulations acts both as a driver for innovation pushing companies to find new ways to lower their impact but it simultaneously constrains the investment flow to one aspect of their activity as to comply with strengthening rules.

Another potential innovation barrier regards the need for very high purity PGMs which is a barrier to overcome when developing new technics.

Impact of the BIORECOVER technology on PGM Processing

- Increase recovery rate, with lower energy and chemical costs
- Avoid or lowers energy intensive smelting
- Dramatically reduce the material that needs to be smelted
- Avoid hazardous chemicals such as Cl_2 / HCl

After the recovery of the CRMs, there are different possibilities of downstream processing to enable the application of the materials, depending on the required state and properties. When bacteria or other biomaterials are applied as a sorbent of Pt or Pd, a sludge can be created, which can be later processed too.

Impacts on stakeholders

Upgrading the processing stage, more particularly PGM recovery and refining will mostly impact both PGM miners and PGM transformers (Autocatalyst manufacturers). As recovery and refinery activities are often integrated either with upstream or downstream actors and are rarely standalone businesses significant upgrades have the potential to be attractive to a lot of major actors along the chain.

4.5.6 Upgrading Catalyst Manufacturing

Drivers to Innovation in catalyst Manufacturing

PGM chemical manufacturers or Autocatalyst manufacturers see their market driven by legislation changes concerning the exhaustion of toxic particles. The main concern of the sector is to adapt to changes and comply with the required performance of their products while keeping the costs low to remain attractive.

Barriers to Innovation in catalyst Manufacturing

The market power of autocatalyst manufacturers is limited. As such, they are constrained by their PGM supply, which they need steady but can only be provided by a handful of actors a reduced number of geographical areas. PGM chemical manufacturers are also hindered by the combination of PGM prices and the autocalyst centred structure, which reduces innovation incentives

Impact of the BIORECOVER technology on catalyst Manufacturing

Manufacturers being very reliant on PGMs, a more varied and steady supply of raw materials especially from in-house recycling could be very beneficial. There is potential hope to decrease PGM volatility at this stage of the chain and thus allow for better substitutions and investment opportunities.

4.5.7 Emergence and Disappearance of Stakeholders

Relationships emergence/disappearance

The following figure illustrates the impact of the BIORECOVER technology on the exploration phase, the mines, PGM processors and recyclers, car manufacturers, logistics, and civil society.

Mostly main stakeholders will remain the same as described in 4.1 : Mines and Processing will remain Anglo American Platinum, Impala Platinum, Norilsk Nickel, Northam Platinum and Sibanye Stillwater. Manufacturers on the market will be Johnson Matthey, Umicore, BASF and Clariant.

Car manufacturers will remain with big players like Toyota, Volkswagen, etc. and they will depend on the supply of platinum.

Exploitation of the technology

Johnson Matthey might want to commercialise the technology for PGM industrial waste streams, resulting in a competitive advantage, depending on cost of disposals and possible revenue streams.

Partnerships between owners of the BIORECOVER process and mines will need to be built to reprocess PGM low-grade ores at specific locations, which are likely to be located in South Africa.

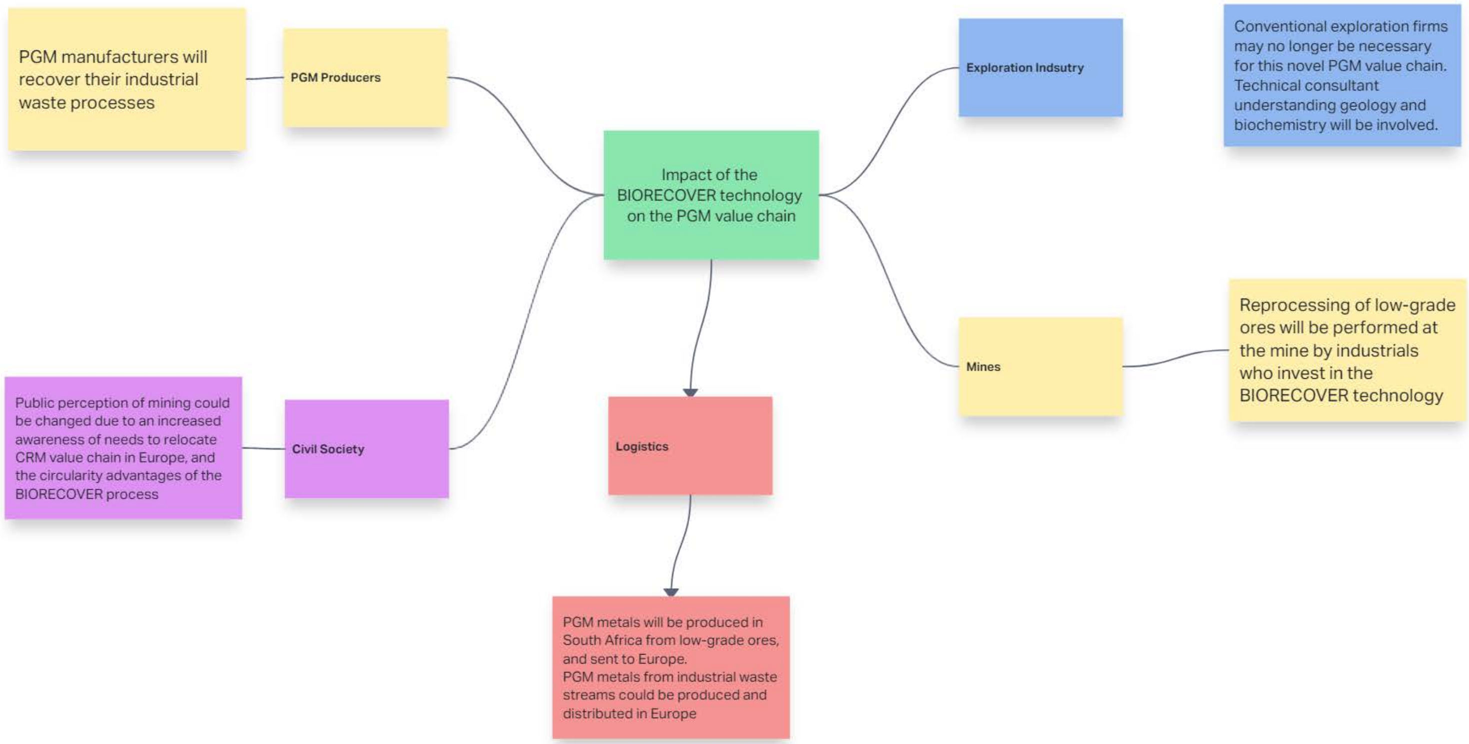

FIGURE 27; STAKEHOLDERS EMERGENCE AND DISAPPEARANCE

4.5.8 Overall impact of the BIORECOVER technology on the PGM value chain

To summarise the overall impact of the project: BIORECOVER, by proposing new technologies to recover PGMs from either low-grade ores, mining waste or industrial waste offers a set of possible solutions to some major shortcomings of the current PGM value chain. With the preferred scenarios of mine remediation and waste recycling, BIORECOVER would not radically change the European PGM value chain but rather enhance the financial health of upstream actors by creating value from untapped sources and increase the supply of critical materials on European soil by optimizing recycling.

As anticipated in deliverable D7.2 Environmental validation including a LCA 2, BIORECOVER will also impact the value chain by adding more environmentally friendly alternatives related to biotechnologies as a replacement for pyro and hydrometallurgy. Additionally, the project takes on social issues by aiming at enhancing the public perception on mining and raw materials (deliverable D7.10 Socio-economic repercussions & public perception study & its update D7.11) but also by offering solutions that could alleviate PGM industry related social trouble in South Africa.

As seen the section 4.5, BIORECOVER will implement alternative options if not real changes within each step of the value chain, from extraction to material recycling. Moreover, the BIORECOVER technology could also benefit the rare earths industry, by reprocessing the bauxite residues from the alumina and aluminium industry.

5 ANALYSIS OF THE REE VALUE CHAIN (FOCUS ON SCANDIUM AND YTTRIUM)

5.1 Introduction to Rare Earths

Rare earths or lanthanides are elements with very similar chemical properties. Despite their name, these elements are not rare, regarding earth crustal abundance, and are commercially available in the form of oxides, salts, or metals. Rare earths are a group of 17 metals, including the 15 lanthanides scandium and yttrium, which share many chemical and physical properties.

They are commonly subdivided according to their atomic weight into light rare earths (or LREE, which include the elements La to Sm including scandium) and heavy rare earths (or HREE, the elements Eu to Lu, including yttrium). Rare earths are distinguished for their optical and magnetic properties that have led to their use in particular as luminophores or in magnets for wind turbines for example.

Geological Availability

As shown in Figure 28, REEs are not physically scarce (vertical axis) and are in fact more common in the earth's crust than many other metals including gold, uranium, or tin. However, mineable concentrations are less common than for most other ores. Available reserves exceed current world production by a factor of 1000. The largest share of the known resources is contained in the mineral's bastnasite and monazite.

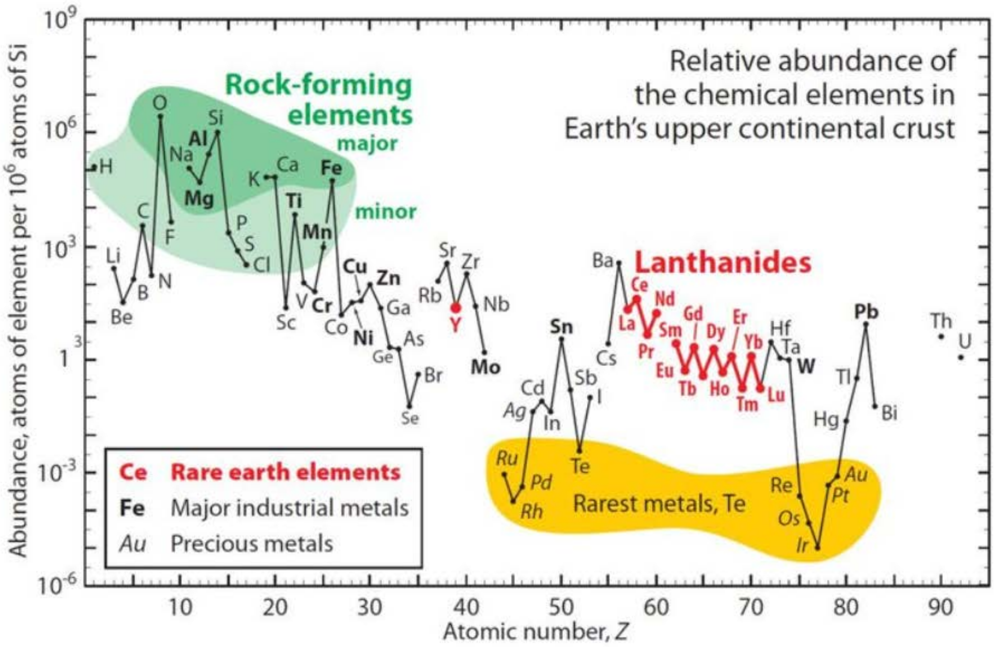

FIGURE 28. RELATIVE ABUNDANCE OF RARE EARTHS (HIGHLIGHTED IN RED) (USGS).

5.1.1 Scandium

Chemical and Physical Properties

Scandium is a chemical element with symbol Sc and atomic number 21. Scandium is a silvery-white light transition metal. Its main properties are its light weight, high melting point (1541 °C) and small ionic radius. It is a very active metal and can react easily with acids and combine with oxygen. Scandium is rarely concentrated in nature and remains widely dispersed in the lithosphere as it lacks affinity to combine with the common ore-forming anions.

Deriving from its inherent properties, Scandium exhibits very good electrical conductivity and heat stabilization qualities.

When used in alloys, in small amounts, Scandium bestows strength in addition to other properties such as corrosion resistance. Greater strength reduces the volume needed to meet strength specifications, which is important for weight costs energy in many industries. In Aerospace, the use of Al-Sc alloys can reduce aircraft weights by 15%-20%. In addition, the ability to employ weldable structures offers further cost reduction potential.

Main markets and substitution

As seen in the following figure, Solid oxide fuel cells (SOFC); an electrochemical conversion device that produces electricity, are now the biggest consumers of highly conductive Scandium with nearly 90% of its industrial use (EU Comission, 2020).

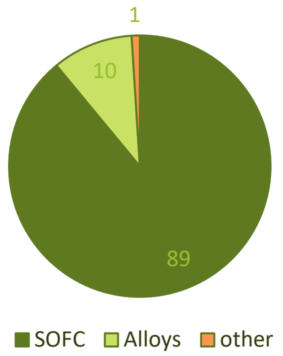

FIGURE 29. SCANDIUM END USES APPLICATION % IN VOLUME (KAISERSEARCH)

As the Scandium market is quite underdeveloped globally and especially in Europe, specific Scandium stakeholders don't have much weight.

Main Players

BloomEnergy is currently the world largest Scandium consumer with around 30% of total consumption (Halgarten & Cie, 2020) and has views to expend its activities in Europe. Other European stakeholders that can be named are: AMG al, KBM Affilips in the alloying industry, Sunfire in the SOFC industry and Airbus.

Production

In 2020, the world production of Scandium stood at around 35 tonnes (Figure 31) with a majority of the extraction and processing done in China (USGS -Mineral Commodity Summaries, 2022). Many new projects are underway especially in Australia.

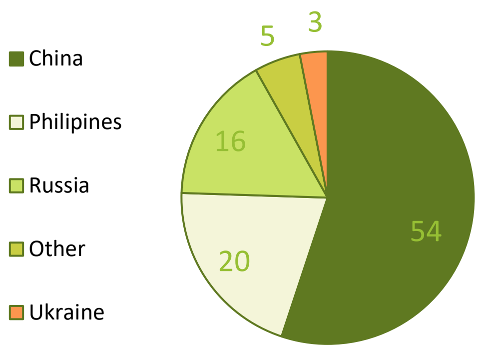

FIGURE 30. WORLD PRODUCTION OF SCANDIUM (% T/T)

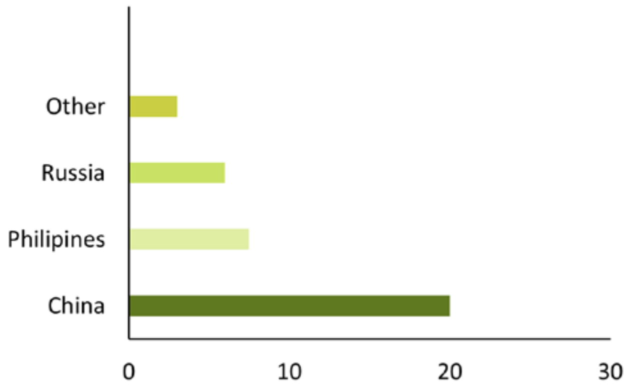

FIGURE 31: WORLDWIDE PRODUCTION OF SCANDIUM, METRIC TONS

Major technologies for processing and transformation of the material

Figure 32 describes the material flow from Scandium rich ores to Scandium industrial applications.

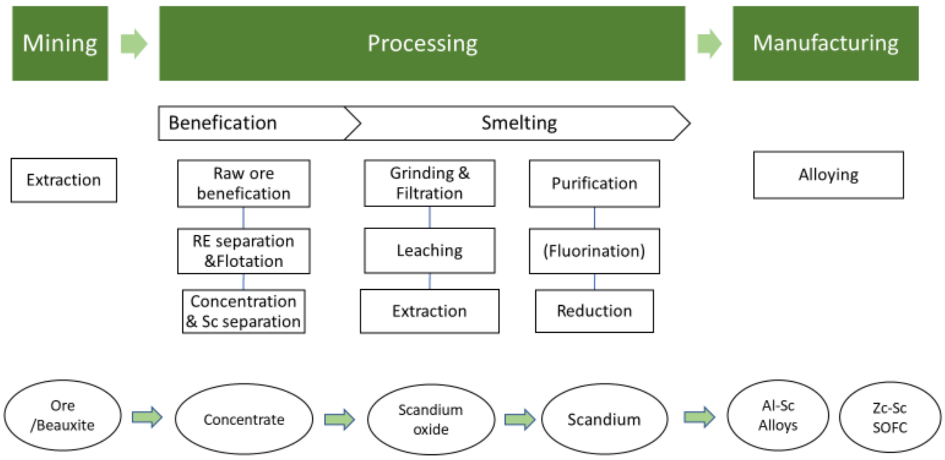

FIGURE 32. CURRENT VALUE CHAIN OF SCANDIUM

Following extraction, there are two major processes involved to obtain usable Scandium: the beneficiation stage and the smelting stage (Wang, Wang, Chen, & Wang, 2020).

The first stage is separation and concentration to provide a concentrate. There is a primary separation, secondary separation, and final separation. The main purpose is usually to separate the remaining iron and REs in the rare earths' tailings for further processing, separation, and bulk flotation. The tailings, which contain Scandium about 0.01-0.02%, are the raw materials of scandium oxide production. Remaining tailings from flotation are divided into mixed foam and mixed grit by bulk flotation subprocess to achieve the separation of easily floating minerals. The mixed foam is used to separate fluorite and the mixed grit, which contains Scandium at about 0.02-0.03%.

After a secondary separation, the mixed grit from the previous process goes to the secondary separation process. The main purpose of this process is the separation of remaining Scandium for the further enrichment. After the final separation, the content of Scandium can reach about 0.05%, which provides high-quality Scandium concentrates for metallurgy stage. In which, the previously obtained Scandium is concentrated, then grinded for improving the output rate and then at a content of about 20-30% is extracted from the acid leaching solution.

The last stage before obtaining pure metal consists of going through a purification process that can involve fluorination and reduction, which brings a 99.99% Sc_2O_3 solution to an equally pure ScF_3 and a final 99.99% pure Sc metal.

Once Scandium metal is obtained it moves to the manufacturing stages which is represented by alloying, mainly with Aluminium. The chemical composition of the aluminium-scandium master-alloy is 2% scandium and the balance is 99.7% aluminium. The master alloy is used to add scandium to Al-Mg-Zr containing alloys, which are used in the form of sheet and plate as well as for 3D printing applications performed by Airbus and Amaero companies.

Al-Sc alloys production is based on the use of master alloys. The basic idea of "master alloys" has its grounds in the fact that many alloying elements are very active or are just unsuitable to be entered in a pure form into aluminium alloys. The production of purified metals like scandium with the purpose of dissolving only a small amount of addition (0.01-0.2%) is not a cost-effective method but can be manufactured much more easily in its alloy form due to lower activity of the leading element Aluminium. Key approaches include direct fusion of aluminum with scandium, the aluminothermic synthesis using scandium salts or oxide as a scandium source and the electrowinning in molten salts using scandium salts or oxide as a scandium salt (Suzdaltsev, Nikolaev, & Zaikov, 2019).

It should be considered that one of the most common strategies to strengthen Al alloys is by using microalloying additions that result in a fine distribution of precipitates. Scandium is the most effective known microalloying element in strengthening Al alloys (Dorin & Langan, 2018).

BIORECOVER & other related EU projects

Final recovery rates of REE are unavailable at this point in the project development, making it challenging to speculate on the overall technical performance of BIORECOVER. However, some promising results have been achieved by partners from UC to selectively leach REE from BR using siderophore bacteria. Meanwhile, Algaenergy have achieved promising rates of biosorption for several REE using microalgae, and TR have demonstrated effective selective recovery of both Sc and Y using microcapsule columns.

The European Commission has backed several projects regarding Scandium retrieval from BR, such as RED MUD and SCALE-UP.

5.1.2 Yttrium

Chemical and Physical Properties

Yttrium is a chemical element with the symbol Y and atomic number 39. Yttrium is a silvery metal; it is fairly stable in air but can react strongly when heated or powdered.

Alloying of yttrium with aluminium is heat resistant. Yttrium oxide in glass makes it heat and shock-resistant and is used to reinforce it. Yttrium oxide is advantageous in the making superconductors, which are metal oxides that conduct electricity without any loss of energy.

Main markets and substitution

The leading end uses of yttrium are in ceramics, metallurgy, and phosphors. Though the use of Yttrium in phosphor lightning is quickly declining (EU Comission, 2020). Yttrium ceramics come often in the form of Yttria-Stabilised-Zirconia. It is then used in refractory products as well as oxygen sensors or various abrasives. In Metallurgy, Yttrium becomes a useful input in various Magnesium and Aluminium alloys. Yttrium is also found in microwave filters or in medical Yttrium aluminium-garnet laser crystals (YAG).

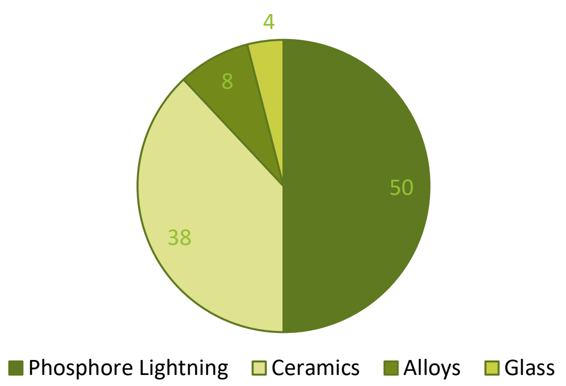

FIGURE 33. YTTRIUM END USE APPLICATIONS (% T/T)

Major European Stakeholders

Since Yttrium is currently not produced in Europe, the main European stakeholders can be found downstream in the value chain. Those include Solvay for processing, Saint Gobain in glasses and ceramics, EcoSense in lightning, Thales for YAGs and Bosch for Oxygen sensors and brake pads.

Production

As seen in Figure 35, the Yttrium market is highly concentrated in China producing more than 80% of the global 10 000 tons.

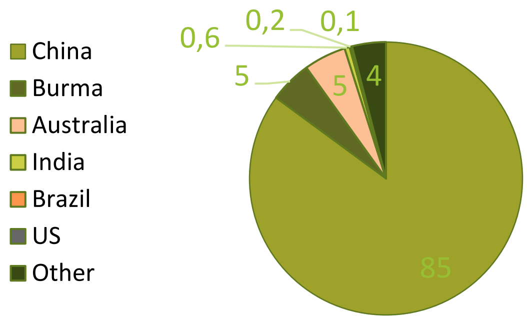

FIGURE 34: WORLD PRODUCTION OF YTTRIUM (% T/T)

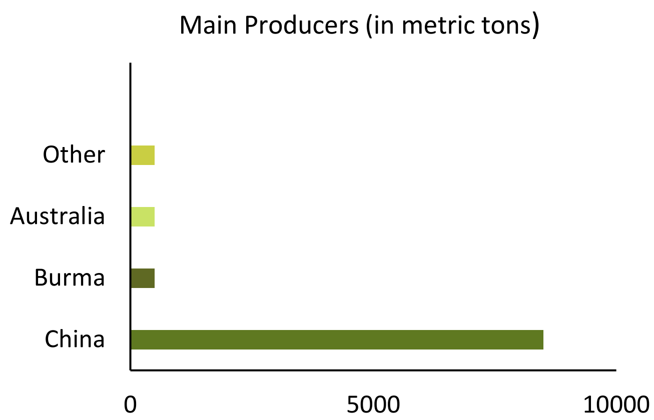

FIGURE 35:MAIN PRODUCERS OF YTTRIUM

Major technologies for processing and transformation of the material

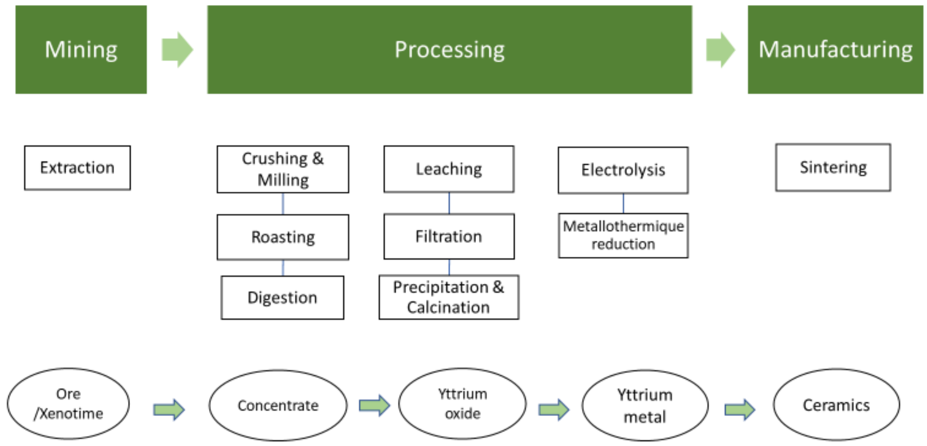

FIGURE 36. VALUE CHAIN MAPPING OF YTTRIUM

Figure 36 describes the material flow from Yttrium rich ores to Yttrium industrial applications. Most of the Yttrium value chain originates in China as it is the largest Yttrium producer worldwide with its "ion absorbing clays" and Xenotime ores.

Since rare earths in the ore mainly occur in the state of hydrated ions adsorbing on the surface of clay minerals, they can't be effectively concentrated by conventionally physical methods (li & Yang, 2014). Once mined, the used ore, xenotime, is first milled to a specific powder size and then roasted in a furnace. These operations ensure that good recovery is obtained in the next stage, which is sulfuric acid digestion of the roasted material (Innocenzi & De Michelis, 2014). By sulfuric acid digestion, YPO_4 in the xenotime is converted to a water-soluble sulphate.

Cold water is used as the leachant for better recovery. Oxalic acid is added to the yttrium sulphate solution to precipitate yttrium oxalate. The final stage is the calcination of yttrium oxalate to the oxide. A later stage of metal processing through electrolysis or Metallo-Thermic reduction is made before Yttrium can effectively be used in an eventual sintering process.

BIORECOVER & other related EU projects

The recovered Yttrium will be tested for application in products marketed by FAE, such as brake pads and oxygen sensors.

5.2 Distribution of value along the chain

The value distribution is an essential step in mapping how the different actors of the rare earths industry create and capture the added value along each stage of the chain. In other terms, the material flow of targeted rare earths is accompanied by financial flows and specific behaviours by the actors involved.

5.2.1 Financial analysis

To better understand the distribution of revenue along the rare earth value chain, a solution can be to analyse the margins of some of the main actors of each sector of the said value chain. Table 7 represents targeted stakeholders of the rare earth industry from mining to end applications. Since there are no publicly traded companies producing only Scandium or Yttrium, the representative companies chosen for this analysis are large scale producers of REE more generally, notably Nd and Pr for downstream use in permanent magnets.

To represent value creation during extraction in the REE value chain, China Northern Rare Earth was selected, because it operates the world's largest REE mine, in Bayan Obo Inner Mongolia. At the next stage in the value chain, REE processing, Shenghe Resources was chosen as a representative company. While Shenghe also is active in REE extraction, it has made REE separation and refining its key strategic focus. The company has taken minority shareholder position in REE mines around the globe (including the US, Greenland, Australia) in order to secure access to REE concentrate. Shenghe notably has a commercial agreement in place to be the sole purchaser of REE concentrate from MP Materials, the only North American REE mine currently in operation (Hui, A Chinese rare earths giant is building international alliances worldwide, 2021). The choice of BASF and Solvay is based on their leading position in the European chemical sector dealing with rare earth transformation. Their main clients, for rare earth, are often OEMs for which it was decided to include JL Mag and Bosch. Finally, as end applications Siemens Gamesa and Tesla are justified for their extensive use of parts containing rare earths and good examples of the green transition needs in specific raw materials.

Company	Sector	Profit margin TTM (2022)	Profit margin change (2017-TTM 2022)
China Northern Rare Earth	Mining	21%	17%
Shenghe Resources	Mining/ Processing	22%	47%
BASF	Chemicals	25%	-5%
Solvay	Chemicals	26%	-8%
JL Mag	OEM	24%	4%
Bosch	OEM	32%	-16%
Siemens Gamesa	Wind Power	-1%	-110%
Tesla	EV	25%	25%

TABLE 7: MARGINS ALONG THE RARE EARTH VALUE CHAIN

The evidence provided by the table above is that margin rates are evenly split along the value chain. However, the recent dynamics seem to indicate that miners are capturing more and more of the value while chemical companies, usually just behind in the chain, have slowly eroding margins, this could be because of even deeper integration of Chinese companies. Upstream companies would be able to offset rising energy prices, as it is the most energy intensive stage, by raising prices while the chemical sector would have less leeway. Downstream actors seem to display more heterogenous financials reflecting the noticeable differences of rare earth uses both in terms of volume and kind.

Price of sale

The understanding of margins along the value chain also demands for an overview of the price of the the specific elements that are analysed in the report.

Unlike most metals, scandium is not traded on any public market or metals exchange. Scandium product sells between private parties at undisclosed prices. Pricing for oxide products are influenced by product quality, volumes, availability, source, and of course demand (Duyvesteyn & Putnam, 2014)

Scandium oxide prices are also influenced by quality, with 99.9% or higher grades representing the top quality, required for electrical applications, but not for alloy applications. Consequently, from ore to refined metal the value of the raw material increases. According to SCALE, through the beneficiation stage Scandium is priced at around 0,9 USD /g, Scandium oxide Sc_2O_3 99.99% had an estimated value of5 USD /g and finally Scandium metal at 206 USD/g.

Regarding Yttrium, prices follow a more mature supply/demand scheme. Two prices set the market: Oxide and metal with the latter being on average 10 times more expensive at around 30 USD/Kg vs 3 USD/Kg. However, the rare earths industry seems to ride on the prices of magnet materials, which for observers seems unsustainable in the longer term, especially for yttrium not mostly used as in magnets (Hui, 2022).

Regarding Yttrium, prices follow a more mature supply/demand scheme. Two prices set the market: Oxide and metal with the latter being on average 10 times more expensive at around 30 USD/Kg vs 3 USD/Kg. However, the rare earths industry seems to ride on the prices of magnet materials, which for observers seems unsustainable in the longer term, especially for yttrium not mostly used as in magnets (Hui, 2022).

5.2.2 Policy Rents

Since the 1990s, Chinese rare earth exports grew rapidly but this fast development was possible only the expenses of high energy consumption and environmental devastation. It was more cost effective to ship tons of minimally processed ore concentrates to China rather than ensure environmentally sound practices on US soil. Indeed, the Mountain Pass mine in California, which use to be the largest, rare earth mine worldwide closed in 2002 due to environmental restrictions on radioactive waste. In fact, every ton of RE concentrate generates approximately 1 ton of radioactive waste and $75m^3$ of acid wastewater, a problem that the ever-growing Chinese competition ignored (Klinger, 2017). Chinese laxist environmental policy towards this mining waste while in the early years allowed for a combination of socio-environmental dumping began to shift in recent years along with a greater general concern for environmentally sound raw material sourcing, a strategy that studies show may counter Chinese losses in market shares (Pan, Feng, & Hu, 2021).

Moreover, Chinese policy have worked to increase a rest of the world dependency while at the same time extracting a form of rent. Firstly, China's state-owned banks granted subsidized loans to joint ventures and state-owned enterprises (SOEs) to maintain social stability. Throughout the 1990s, those loans helped expand the mining sector while state investment in rare earth applications research stimulated production and dumped global prices. Once in place, China has used a 3-way policy to capture surplus efficiently from its dominant position.

1) China wants to preserve its resources so it will buy foreign materials duty-free (no resource tax on these imports so this is very attractive for foreign company companies)

2) China will provide a cheap flow of finished material, to receive this of rare earths goods, one must accept higher costs than Chinese users, which is the VAT of 13% (with export refunds)

3) China will not provide easy market access to sell rare earths domestically, there is an import duty for an oxide whereas the raw material is duty-free.

In effect it helps China to focus on highly profitable activities while keeping competition at bay.

5.2.3 Technology rents: difficulty separating REE

Despite the fact that rare earth minerals are virtually ubiquitous, China produces more than 90% of all rare earth metals used globally and as a matter-of-fact China has gained a quasi-monopoly in rare earth elements processing technologies. Processing and extraction require high capital investments in different solvent extraction and solid separations in large scale facilities. China has been for decades willing to experiment new processes, often at the expense of the local environment (Jinxia, Hongmei, & Xiuchen, 2018), which combined with the availability of materials to process, has brought China to possess not only the most efficient technologies but in some cases to be the sole holder of specific processing techniques.

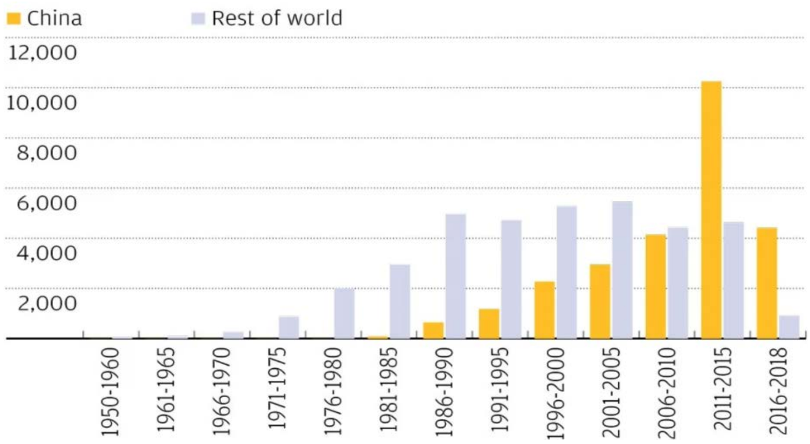

FIGURE 37: CHINESE RARE EARTHS PATENT FILLINGS (PATENT MANIAC, THREE CONSULTING)

China's technological advance can be seen in Figure 37, where Chinese patent fillings regarding rare earths in recent years has been over double that of the rest of the world. The industrywide technological progress displayed in mineral processing tends to induce a disproportionate and socially inefficient allocation of resources towards surplus appropriation or rent (Glode & Ordonez, 2022).

Additionally, as a consequence of Chinese technological dominance other rare earth producing countries have but no choice, to stay competitive, to ship the raw material to China for further processing. China possesses immense leverage on this segment of the market and can afford putting trade barriers that not only discourages competitors but also brings in new customers to its processing facilities.

5.2.4 Infrastructure

The world's largest REE deposit at Bayan Obo, Inner Mongolia, China has produced REE, since the late 1980s and currently, accounts for the majority of global REE supply. It accounts for more than 40% of the total known REE reserves in the world and nearly half of the global rare earth production (Fan, Yang, & Hu, 2016). The mined material is sent to Baotou, which is 180 km away, by rail. After being processed most of the material, refined metal or semi manufactured products are dispatched across China for shipping across the world with a number of specialized ports.

The scale of Chinese production comes with corresponding infrastructure development that is unmatched. The strength of Chinese ports is another asset in the trade of rare earth as they perfectly link up Chinese and foreign industries. The size and specialization of the Chinese rare earth industry allows for economies of scale and the leaves the freedom to modulate production to meet any need of the market.

5.2.5 Relational rents

In the context of global trade governance, the Made in China 2025 Policy, outlined in 2018, suggests that China's industrial policies have been viewed too narrowly without sufficient attention to longer-term global governance issues. The plan is aimed at helping the country overcome the middle-income trap by moving up to more value-added activities and being able to rely more on home grown technologies. This has been translated by an increased vertical integration and consolidation in the rare earth industry in China.

The case of China, the dominant actor for rare earths, is typical of relational rent extraction within the global value chain. With relational rents representing the value created by business groups based upon sharing, combining, and exchanging unique and specific resources or assets among affiliated firms.

FIGURE 38: RARE EARTH INDUSTRY INTEGRATION (MERRIMAN, 2021)

As can be seen in the Figure 38, Chinese companies (e.g. China Northern Rare Earth, Guangdong Rare Earth, and Xiamen Tungsten) are all vertically integrated from mined products to manufacturing. Meanwhile, companies from the rest of the world (including Lynas (Australian), MP Materials and Chemours (American)) have much more segmented supply chains. Chinese integrated and state backed firms are indeed combining, and exchanging unique and specific resources, here rare earths, among affiliated partners, other state-owned corporations. China's tax system is reinforcing the rent seeking behaviour by imposing actors worldwide to enter the Chinese value chain at one stage or another.

5.2.6 Value Chain Example

After a thorough examination of the economic specificities or the rare earths value chain, the report will provide 2 value chain examples regarding Yttrium and Scandium.

The value chain examples will display the “journey” of either Scandium or Yttrium from exploration to recycling going through all the transformation phases. The point of view adopted will be that of specifically chosen companies. The presented value chains display the value proposition, advantages and risks faced by each representative company along the chain. The goal is to have a realistic value chain and understand the underlying drivers for value creation at each stage.

As explained, this deliverable focuses on **yttrium**, for which its use in different car parts, like sensors and breaks has a certain importance in the design of the project because of the inclusion of FAE as a partner. The second example concerns **scandium** because at current market prices it represents the most valuable REE in the bauxite residues (in terms of price per weight) and could have big potential for European industries.

Exploration of mineral resources

Example : *Northern Minerals*

- **Value Proposition :** Carries metallurgical test work on samples
- **Advantages** : Provides several programs of geological mapping, soil and rock chip sampling, and portable Xray Fluorescent surveys.
- **Risk :** Risk regarding changing classification of lands to be explored/ and environmental regulations.

Extraction & production of Yttrium

Example :Shenghe Resources

- **Value Proposition :** Sells the final products from processing rare earth ores and producing high purity rare earth oxides, metals and alloys along with a range of rare earth elements
- **Avantages :**Large-scale rare-earth separation and transformation chain resulting in "end use" RE products from own-produced metals and alloys of the highest purities. It has an established international and highly diverse customer base.
- **Risks :** Hedges its risks by having operations spanning every part of the supply chain. Is involved in major RE projects abroad, to develop new partnerships, keep market shares, prevent supply risks and potential trade wars. The scale and scope acts as a moat against a growing competitions

Manufacturing

Example : Bosch

- **Value Proposition :** Aim to provide with reliable, economical and low impact car parts. Producer of brakes, bougies and sensors containing yttrium.
- **Advantages:** Bosch relies on an integrated supply chain run by a long established and experienced structure.
- **Risks** : Competition threat hedged by its important R&D sector and many patent filings. Strategy to cover a broad range of products and develop multiple situations of monopolistic competition.

Manufacturing of cars (EV)

- *Example: Tesla*
- Manufacture of cars containing REEs (Yttrium)
- **Value proposition :**Market leader and pioneer in mass produced EVs. Provide High quality cars to make the electric transition smooth or customers.
- **Advantages:** Size, Know-how, reputation act as a good moat.
- **Risks** : Rising competition in new sectors of Evs. Brand reputation is important is key. Global supply chain risks to be noted

Recycling

Example : SNAM

- **Value Proposition:** Processing used batteries SNAM concentrates metals, including some considered as strategic. Customers are battery-makers (EV mobility).
- **Advantages:** Long experience and links to large supplying partners. Access to «best available technologies» so is one of the few to master specific metal recycling technologies.
- **Risks**: Probable higher competition in near future but high potential with circular economy developments

39

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YTTRIUM

Exploration of mineral resources

Example : *Scandium International*

- **Value Proposition :** Goal to ppromote Sc use in the industry. Offer a steady and sustainable supply of Sc
- **Advantages** : Offers feasibility studies and mining facility building focused on Scandium.
- **Risk :**The risks are financial but also technical. Solve the chicken and egg paradox of the scandium market through information dissemination

Extraction & production of Scandium

Example : Sumimoto International Mining

Value Proposition : Sells the final products from processing rare earth ores and producing high purity rare earth oxides, metals and alloys along with a range of rare earth elements

Avantages : Extraction and processing of yttrium to supply the industry from trustful sources. Use of domestic HPAL technology gives them an edge. Use of own brand name to attract buyers specially in alloying industry

Risks : Growing competition but main risk comes from the lack of demand in scandium. Risks in exchange rate and mineral price volatility. Scarce technology can act as moat.

Manufacturing

Example : AMG Al

- **Value Proposition :** AMG Aluminum sells master alloys containing scandium
- **Advantages:** Commercializes a proprietary manufacturing method for the aerospace industry mainly (partnerships) and long term contracts.
- **Risks** : Dependent on price and supplies of metals and metal-containing raw materials to produce its products. Risk mitigation by diversifying. Stable competition due to entry barriers

Aerospace & Defence applications

- *Example: Airbus*
- **Value proposition :** Airbus is delivering highly technological and intensively processed products as aircrafts.
- **Advantages:** In a sector Duopoly : Price setters with little competition and strong support from public sector.
- **Risks** : Business model changes to make the industry look more sustainable as traditional fleet increases seem limited.

Recycling

Example : SNAM

- **Value Proposition:** Processing used batteries. SNAM concentrates metals, including some considered as strategic. Customers are battery- makers (EV mobility).
- **Advantages:** Long experience and links to large supplying partners. Access to «best available technologies» so is one of the few to master specific metal recycling technologies.
- **Risks**: Probable higher competition in near future but high potential with circular economy developments

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SCANDIUM

5.3 Factors structuring/governing the value chain

5.3.1 Policy impacts on global value flows

Policy regarding demand

Sector-specific policies will play a strong role in determining the demand for target metals in the coming decades by structuring how the transition towards a carbon-neutral and digital economy unfolds. The European Green Deal and the new EU Industrial Strategy acknowledge that access to resources is a strategic security question in the green and digital transformations of the EU. More recently, the Commission proposed an EU Recovery Plan, which includes the development of diversified, resilient supply chains of sustainable raw material.

EU's actions aim to reduce dependency on primary critical raw materials through circular use, to strengthen domestic production and diversify sourcing from third countries as well as to remove distortions to international trade. More broadly, the EU's new industrial policy, announced in 2020, will have an impact on all the sectors with demand for target metals. Similarly, the EU's trade and investment policy, "Trade for All", will have an overarching impact on demand in all sectors using the project's target metals by providing a framework for global value chains (European Commission, 2015).

The European Raw Ma"erials Alliance (ERMA) was announced in September 2020, as part of an Action Plan on Critical Raw Materials. **ERMA has a specific focus on REE**, and seeks to **ensure a reliable, secure and sustainable access to raw materials by creating value chain resiliency**, using circular resources and developing sustainable goods, increasing raw material sourcing, diversifying sourcing from foreign countries and eliminate trade distortions.

The "Fit for 55" package, the European Commission will propose reforms to a wide range of policies to deliver on the new 2030 climate target of "at least 55%". The package will revise all flagship climate and energy policies. Measures include additional support for clean transport, renewables, a Carbon Border Adjustment Mechanism (CBAM) tariff on emissions for high carbon imports and proposes to extend the Emissions Trading Scheme, which could impact the mining sector.

More specifically, to achieve climate neutrality, the European Green Deal sets out the need to reduce transport emissions by 90% by 2050 (compared to 1990-levels). Among others, the aviation sector will have to contribute to the reduction. CO_2 emissions from aviation have been included in the EU emissions trading system since 2012. Regarding e-mobility, the European Union has said it needs 30 million or more zero-emission cars. The EU stimulus package includes 20 billion euros to boost the sales of clean vehicles, and 1 million electric and hydrogen vehicle charging stations are to be installed by 2025 (European Court of Auditors, 2021).

Regarding specific policies that could impact Yttrium future demand, shifts in the lighting industry represents a key element. For instance, compact fluorescent lightbulbs are retiring from the market. These lamps represent a sizable part of Yttrium use in lighting and are being replaced by LED lamps. At the Minamata Convention on Mercury in March 2022, 137 governments adopted amendments to phase out a major category of fluorescent lighting. The reduction in demand coming from this sector is expected to amount to at least 65% between 2015 and 2030 (Guyonnet et al., 2015). The Basel convention to protect human health and the environment against the adverse effects of hazardous wastes also includes CF Lamps and gives potential to the rise of Yttrium recovery routes.

Policy regarding supply

Chinese policies on rare earths exportation have changed over the years. In 1953 already, China launched its 1st "Five-Year Plan" with the aim of optimizing its control over exploration, production, and exports of natural resources.

Western Policies and Chinese Policies coincidently pushed China in a quasi-Monopoly situation from the 1980's onward. Indeed, Western policies aimed at outsourcing polluting and expensive mining projects and China was willing to develop its domestic supply chains regardless of the environmental impacts.

Fast forward to 1999 and the introduction of quotas, China initially introduced a cap on exportations to foreign buyers but had to scrap it in 2014 after a WTO ruling.

Nowadays, China's main tools are a mix of production quotas and special tax system. **The production quota ensures that only a limited number of actors, all state owned, participate in the extraction of rare earths**, facilitating the emergence of large integrated companies along the value chain. Regarding the new tax system, it consists of a **13% value-added tax levied on all rare earth products**. Those tools create competitive advantage of 13% in favour of Chinese companies in the upper and middle parts of the supply chains and are supposed to serve as an effective defence against attempts to break China's monopoly (Hui, 2022).

China has used its dominant position in the rare earth supply chain as geopolitical tool. The dispute between China and Japan over the ownership of islands off the northeast coast of Taiwan caused Beijing to impose export restrictions on all 17 rare earths.

China also seeks to extend its influence on rare earths via **foreign acquisitions**. It already owns a facility in Vietnam and had been importing large amounts of ores from Myanmar, which it now only does informally, those two countries alone are thought to produce around 30 000 t of rare earths annually (Dryer, 2020). Chinese buyers have also been seeking to acquire **mining sites in Greenland** and possess shares in many mines **across the globe** including the notorious Mountain Pass mine in California.

Regardless of the discussions on Chinese dominance, China went from 98% of global mined production in 2010 to 58% by 2020. Chinese Policy implications are of course not foreign to this change.

Firstly, concerns of a too important dependency and Chinese aggressive policies fuelled domestic projects around the globe. New counter measures have emerged to reduce the agency of Chinese policies, for instance it has been said that stockpiles provide a short-term hedge against a sudden Chinese shortages or embargos (Stone, 2022). Rare earths recycling and remining as well as new processes being implemented contribute to balance Chinese dominance.

Secondly, a part of the answer comes from China itself: in 2016, China's Ministry of Industry & Information Technology (MIIT) issued the "Rare Earth Industry Development Plan (2016-2020)" to transition its strategy. In 2018, for the first time since 1985, China has become a net importer of rare earths, and this is a result of several factors:
- Increasing domestic consumption,
- Reduction domestic mining output,
- The clean-up of contaminated sites,
- The import from new mines opening overseas,
- An emphasis on value-added processing,
- And an increase R&D and technological applications to enhance the profile of higher tech exports

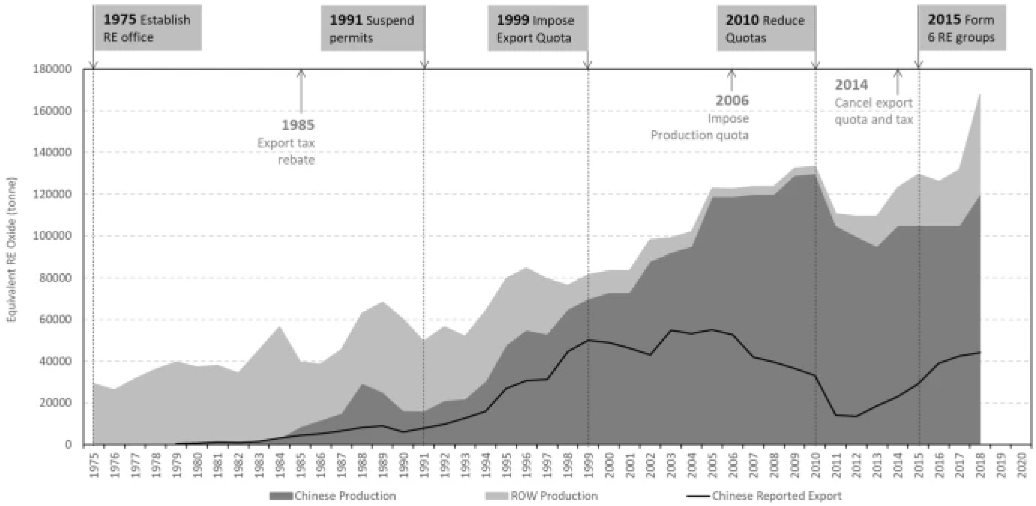


Figure 39. China's public policies toward rare earths, 1975–2018 (**Shen, Moomy, & Eggert, 2020**)

5.3.2 Supply Chain Governance & Logistics

The value chain of rare earth is indeed dominated by China, as consequence Chinese firms are among the leading actors. The statement is especially true when in recent times Chinese rare earth companies have been integrating vertically and consolidating to form "Super Conglomerates" managing rare earths from ore to manufactured goods (Zhou & Brooke, 2022).

In its southern region (provinces Jiangxi and Guangdong), absorption ores are used as raw materials and heavy REEs and metals of the average weight are produced. In the northern regions, lighter REEs as well as Yttrium and Scandium are produced based on bastnasite ore (Naumov, 2008).

As stated earlier, the Bayan Obo mine in Chinese's Inner Mongolia province, accounts for 40% of global REE production. Such a concentration requires specific logistical planning. The mined ores are brought by rail to Baotou 180 km west. Baotou is the world capital of rare earth processing and manufacturing. In Baotou ores can be refined but also alloyed or casted into permanent magnets.

Baotou being as far as 700 km from the sea most of the goods are transported through rail to the port of Tianjin south of Beijing, Tianjin Port handled 500 million tonnes of cargo and 18 million containers in 2021, making it the world's ninth largest port by throughput tonnage and the ninth in container throughput (World Shipping, 2022).

Given the importance of the Chinese and relative geographical concentration of Rare Earth industries, logistical issues easily affect the whole market. In 2021-2022, the Myanmar political instability and local lockdowns in southern China blocked the import of REEs to China for further processing. The capacity of rare-earth companies in Ganzhou, Jiangxi Province has been cut by at least 25 percent compared to 2020, after major border passageways for rare-earth minerals from Myanmar to China shut down (Xuanmin, 2022).

In 2022, single route from the Port of Tianjin to Inner Mongolia, delivery costs have risen by around 20 yuan per tonne to 130-140 yuan ($20-22) per tonne. With COVID-19 outbreaks and testing, trucks and trains are blocked in the port city with their cargo (FastMarkets, 2022).

While logistical issues affect price and delivery times of rare earths and Yttrium, the mined volumes are relatively modest compared to other main metals with around 150,000 tonnes for total rare earths from China (1% of mined copper volumes). In the larger considerations of supply chains governance, more intricate problems can arise.

A Lack of Integrated Value Chain Governance Limits Scandium Market Potential

The main obstacle for further development of the Scandium market is the element's dispersion in the earth's crust and the subsequent high costs related to its extraction. This element is central to the so called "chicken-and-egg" problem affecting Scandium, in which a lack of supply holds back demand that in turn holds back supply. In more pragmatic words, the problem is to know what comes first the chicken or the egg: "the CapEx funding or the filled order book?" Investors won't bring capital without guaranteed revenue for the output, and end-users won't commit to using Scandium that won't arrive until a mine is commissioned a couple years later.

According to Kaiser research (Kaiser, KRO scandium resource center, 2021), the solution to the chicken-egg problem would require increasing scandium supply incrementally in response to gradual demand evolution, without a significant Capex investment for that purpose.

5.4 Emerging changes to the value chain

5.4.1 Changes in demand due to technological/ social shifts

An important part of the demand is driven by technological changes. Some of those news developments stem from social shifts, and changes in consumption behaviour, notably regarding sustainability. The transition to achieve European climate goals implies the emergence of new markets. Rare earths elements, including Yttrium and Scandium, will play an important role in the future in the following high growth potential industries of Europe. These industries have been identified as Drones, Robotics, Fuel cells and ICTs.

Drones / Robotics:

Over the next 20 years, larger civil drones can start to make an important impact on the market (more than 20%), because mobility applications will rise exponentially (reaching circa 20% of the total professional market). These types of UAV, for applications such as urban air mobility (aerial taxis), would require to be certified in the future. This also concerns defence applications as the impact of drones on surveillance will be significant. Autonomous and robotic systems are expected to make a significant change to military operations within the 2021–2040-time frame (Bobba, 2020). Scandium would add its light weighting assets for frames while Yttrium can be found in optical and guiding parts.

Fuel cells

With the growing demand for unconventional energy sources fuels cells (FC) is one of the key factors fostering market growth. The overall fuel cell market could be worth around 23 billion € in 2024 (Global Market Insight Inc ,2016) with the specific solid oxide FC (SOFC) market valued at $2.6 billion in 2015 and is expected to reach $4.9 billion by 2022 and take off after 2025. In the US only, the SOFC market is expected to grow at a compound annual growth rate (CAGR) of 42.2% from 2021 to 2028. (Grandview research, 2021) European countries (France, Germany) are investing heavily in the R&D of SOFC for power generation and transportation application. SOFC's employ a hard ceramic material as the solid electrolyte a material for which Yttrium oxide (Y_2O_3) is very popular. However, Scandium oxide can substitute for yttria as a stabilizing agent for the solid electrolyte (typically zirconia) as it is a considerably better ionic electrical conductor than yttrium (Duyvesteyn & Putnam, 2014).

Information and Communications Technology

While there is no need to introduce the ever-growing importance of ICTs, Yttrium's use has been both extensive and niche, for instance Yttrium oxide sulphide activated with europium is used as red phosphor in cathode ray tubes. Growing incorporation of such rare earth element is likely to drive the rare earth phosphors market growth thanks to its luminescence potential. Yttrium doped laser crystals are used in many applications, for instance in yttrium aluminium garnet (YAG - neodymium-doped yttrium aluminium garnet) lasers to improve absorption and emission performance. Frequently used in material processing and in medical applications. Within YAG-lasers Yttrium is not replaceable for the same Wavelength. Regarding Scandium, it is used in the preparation of laser material, gadolinium scandium gallium garnet (GSGG) is used primarily in switches in computer.

Moreover, yttrium and scandium have high growth potential for hydrogen electrolysers, while yttrium is used in energy-efficient fluorescent lighting (Gielen & Lyons, 2022).

While future high growth sectors of the economy provide for a large potential demand in REEs. More traditional sectors are also expected, through demand shifts, to drive an increased use in Scandium and Yttrium. A detailed overview of potential markets for Scandium is presented in Figure 40 below. The market potential of Scandium is largely due to its light weighting properties when used in bulk metal alloys, which are increasingly attractive for the mobility sector as they reduce energy intensity and CO_2 emissions.

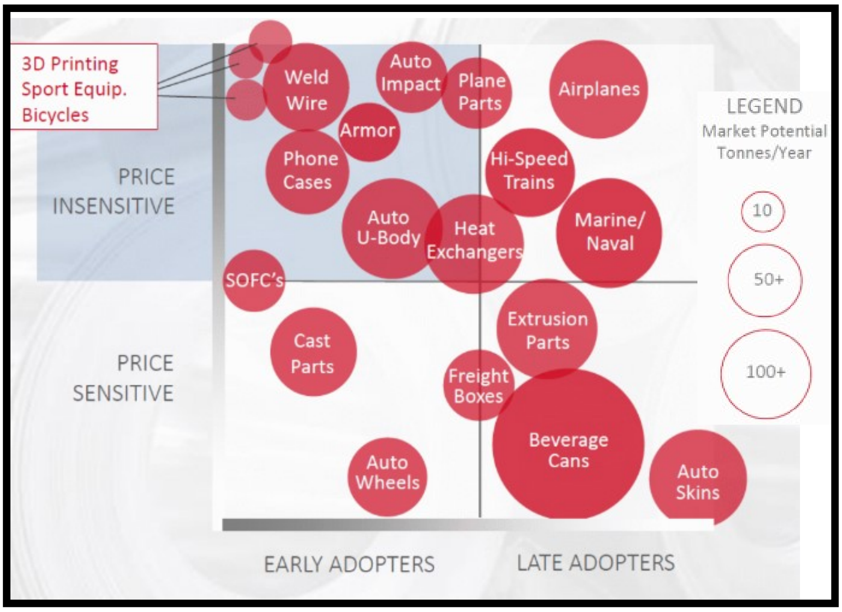


Figure **40**: Scandium future markets **(CM Group & Scandium International, 2021)**

While future high growth sectors of the economy provide for a large potential demand in REEs. More traditional sectors are also expected, through demand shifts, to drive an increased use in Scandium and Yttrium. A detailed overview of potential markets for Scandium is presented in Figure 40 below. The market potential of Scandium is largely due to its light weighting properties when used in bulk metal alloys, which are increasingly attractive for the mobility sector as they reduce energy intensity and CO_2 emissions.

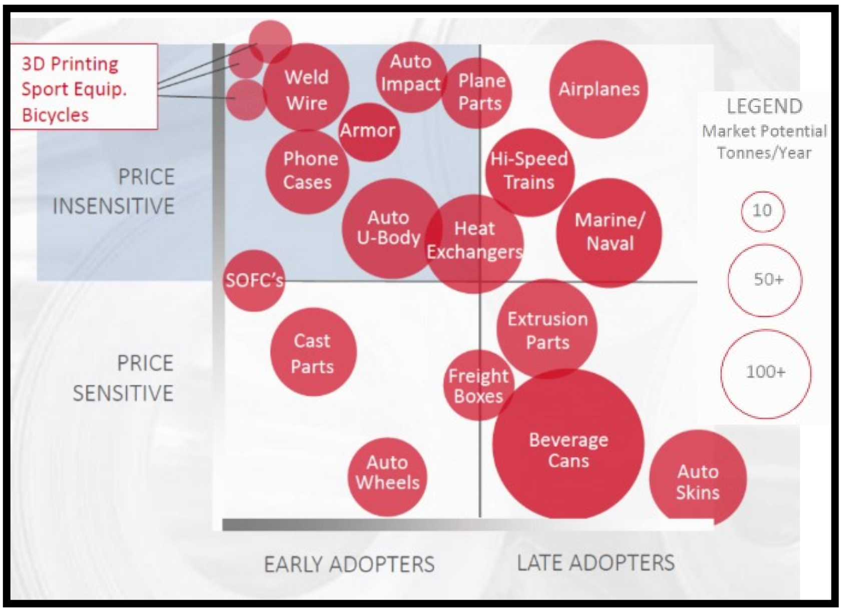


Figure 40 reveals the relative size of various end-uses, when during the supply evolution cycle, they are most likely to kick in, and the degree of price sensitivity. Sport equipment markets are ripe in terms of scandium demand but are, after all, quite limited in size (around 10-20 tonnes per year). On the contrary, light weighting solutions to the global transport sector are later adopter partly because of the engineering and certification cycles aircraft go through. Indeed, auto skins, airplanes, and high-speed trains represent altogether the biggest share of the potential Scandium increase but are expected to come later. Price sensitivity tells us how easily those markets may overcome relatively high prices for Scandium or Scandium alloys as highly engineered products can absorb high prices in an easier way than more basic goods such as beverage cans, representing a very interesting market in the long run.

5.4.2 Changes in supply due to innovation and exploration

The supply of scandium has a potential to grow exponentially over the next couple years. Several projects are under development that include Scandium recovery, in Australia, Philippines or Canada. (Kaiser, 2021) (Figure 41).

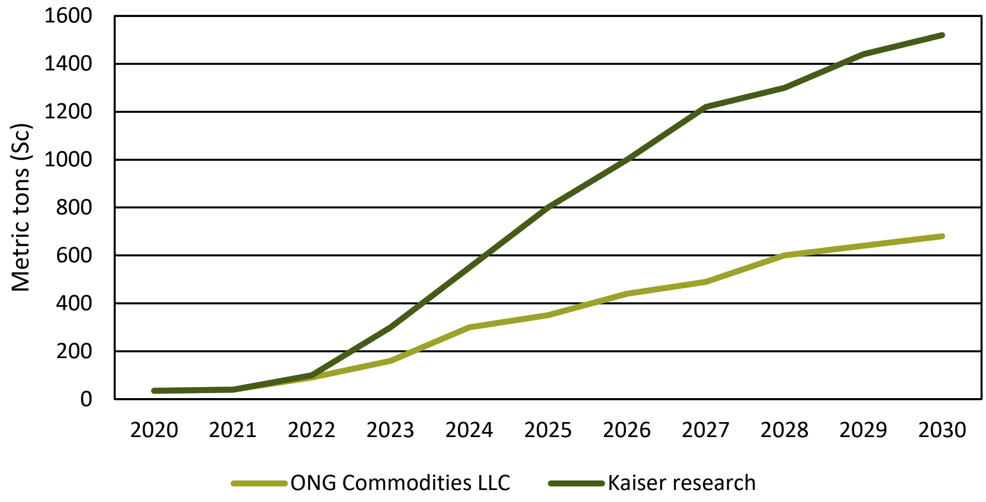


Figure 41 Estimates of future Scandium production

The outlook for Yttrium production is slightly less certain but will benefit from the increase in rare earth mining and a slowly rising demand (Figure 42)

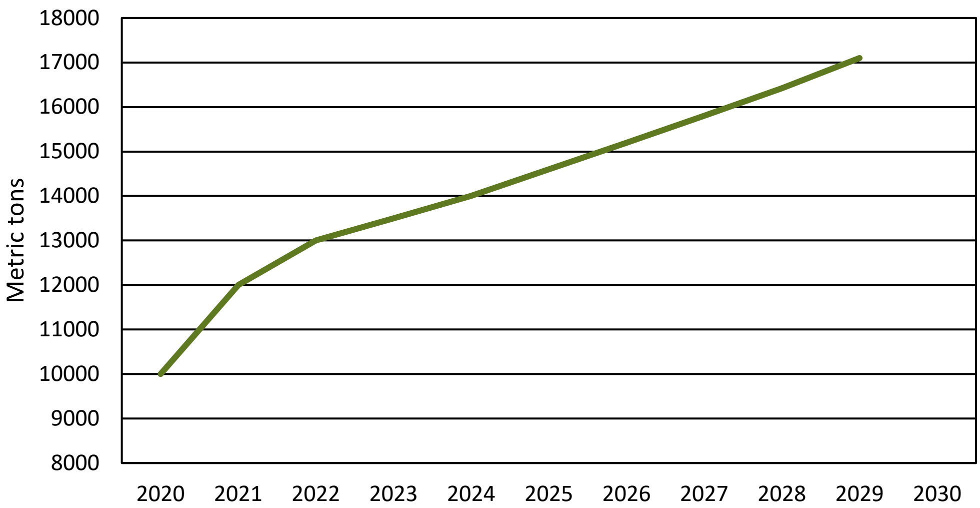


Figure 42. Estimate of Yttrium production (Mordor Intelligence, 2021)

Overall summary of emerging changes

As it has been shown, the existing REE value chain is dominated by Chinese primary extraction and processing. Global REE extraction is undergoing a shift towards geographic diversity, with new REE mines are at various stages of development around the globe, and China now a net importer of REE concentrates. However, separation and refining of REE remains a major bottleneck within the global value chain and is almost exclusively carried out in China for the time being.

With respect to downstream applications of REE, this chapter has detailed numerous socio-technical drivers of forecasted demand growth. REE are essential in many advanced technologies that are expected to enable the decarbonisation of the global economy, and China is explicitly leveraging its REE production capacities to support the emergence of downstream high-tech industries. **Without adequate strategic planning, REE supply gaps may emerge that hinder Europe's planned environmental transition.**

This chapter has also explored how Sc and Y have niche technological applications and small market sizes relative to the global market for REE as a whole. In the medium term, **Yttrium may enter oversupply as demand for fluorescent lighting phosphors decreases, while primary and secondary supplies continue to increase due to its coproduction with other REE**. Meanwhile, the emergence of a European Scandium market will depend upon the ability of upstream and downstream actors across the value chain reaching agreements to stabilize supply and demand for novel technological applications, particularly in master alloys.

5.5 Upgrading the REE value chain

Given the relative lack (at present) of a European REE value chain, how can the BIORECOVER process allow alumina producers to penetrate new value chains and create value for the European economy through technological upgrading? This section will explore this question in further detail, to offer insights about what an industrial scale BIORECOVER process could hypothetically look like. The key drivers and barriers to innovating at each stage in the REE value chain will be explored, and the potential impact that BIORECOVER could have on the emergence or disappearance of stakeholders will also be described.

5.5.1 Value proposition of the BIORECOVER Process for the REE Value Chain: Industrial Symbiosis to Create a Novel European REE Value Chain

As with the other target metals in the BIORECOVER project, partners working on extracting REE from Bauxite residues were invited to partake in the Circular Value Proposition Design workshop in June 2021. This served as an opportunity to collectively think about how the BIORECOVER process could deploy circular business models to create value for industrial clients. Numerous circular economy ideas emerged from the workshop, which will be detailed in further sections on specific stages along the value chain. The workshop also produced a unified circular value proposition for REE: **A sustainable technology for the aluminum industry that reduces the impact of BR disposal and generate a high value, marketable product (REE) with valuable byproducts (construction aggregates).**

Through dialogue with Mytilineos and experts working in the REE value chain, LGI has worked to flesh out this general value proposition and strategically position the BIORECOVER technologies related to REE extraction and recovery. In contrast with the PGM value chain, **the geological availability of REE within Bauxite Residues deposits that are present in the EU means that (if technically successful) BIORECOVER has the potential to create an entirely new REE value chain in Europe**. As can be seen in Figure 43 below, the estimated Scandium resources available in European BR are several orders of magnitude greater than current EU demand.

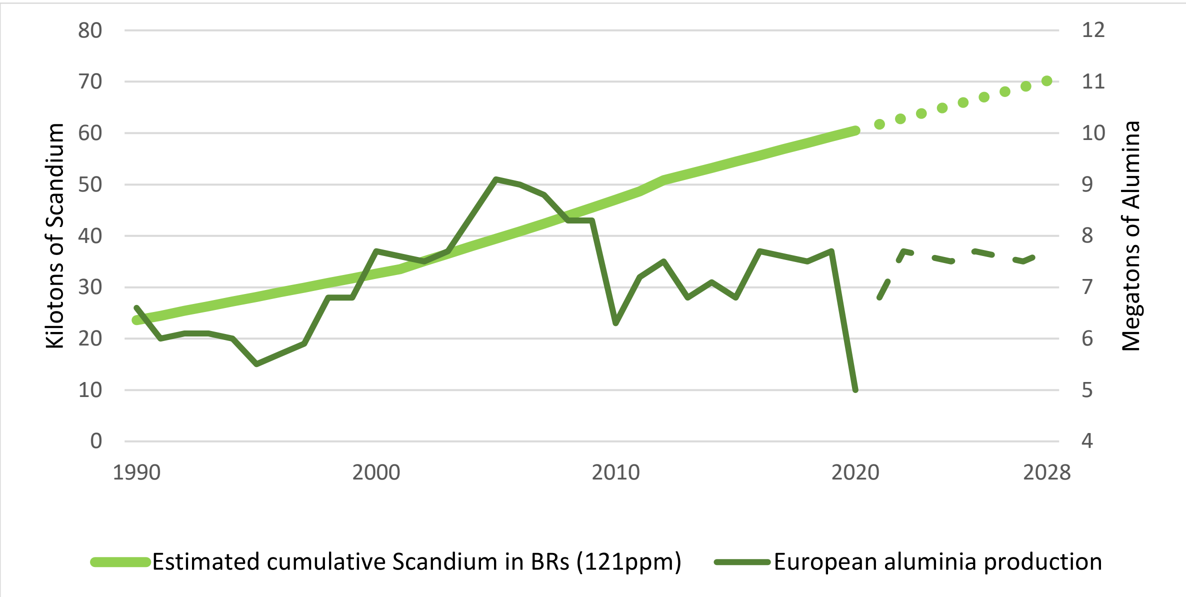


Figure 43: Estimated Sc in European BR **(Goodenough, Schilling, .Jonssonc, & .Kalvig, 2016)**

This geological availability of REE, and Scandium in particular, represents a major untapped opportunity for European alumina producers to diversify their operations and product lines. Yet as will be discussed, to unlock this potential, alumina producers will also have to transform their business operations and commercialize novel high value products. Therefore, **for the REE value chain, BIORECOVER should be considered an enabler of product and functional upgrading for alumina refiners.** Moreover, by transforming the REE resources in European BR into economically available reserves, **BIORECOVER can also provide new raw materials for downstream actors in Europe and enable chain upgrading.** Indeed, in contrast with other target value chains, the BIORECOVER process dedicated to REE extraction has the potential to be a model of industrial symbiosis that impacts at least three value chains: aluminium, construction, and REE.

5.5.2 Strategically positioning the biotechnologies: towards zero waste alumina production

As with the other target value chains, three scenarios were considered to strategically frame the upscaling of BIORECOVER.

- The first scenario would be the deployment of BIORECOVER as **a processing route for active alumina refiners**. This would entail BIORECOVER becoming an additional mineral processing stage after the Bayer process. The biotechnologies would thus need to produce enough revenue to justify their costs (CAPEX and OPEX), and also be able to treat large feedstocks of BR at the same rate as the refinery operates.
- The second scenario would be the deployment of BIORECOVER for **reprocessing Bauxite Residues for remediation of legacy sites**, including from dry stack mounds or tailings dams. In this scenario, the biotechnologies would need to demonstrate that they can add value by extracting additional value from uneconomical Bauxite Residues while contributing to the environmental remediation of the mine site.
- The third scenario would be the deployment of BIORECOVER for the **processing of REE concentrates**. This scenario would involve biotechnologies being used at an industrial site to separate and refine REEs from a diversity of feedstocks including from primary sources such as future European REE mines, or secondary sources such as electronic waste. To be adopted under this scenario, the biotechnologies would have to offer clear advantages (e.g., economic or environmental) over conventional solvent extraction techniques.

Recommendation to focus on active alumina refineries

While none of the three scenarios should be discarded for future exploitation, ultimately the decision was taken between LGI and Mytilineos to **focus the analysis in this study on scenario one, the deployment of BIORECOVER at active alumina refineries.**

This decision was taken because scenario one is the most environmentally, economically, politically, and technically feasible option for upscaling BIORECOVER.

- Environmentally, processing Bauxite Residues onsite at the moment of production ensures that it does not need to be stored in large quantities, thereby enabling alumina refiners to continue operating sustainably for decades to come.

- Economically this scenario offers several advantages, processing Bauxite Residues immediately after the Bayer process helps alumina manufacturers avoid the costs of BR storage or disposal. Moreover, by recovering Scandium, BIORECOVER can help aluminum producers commercialize new high value Sc-Al master alloys that have the potential to drive major revenue growth in e-mobility applications.

- Politically, there are regulatory challenges related to the governance of extractive waste that may make companies reluctant to reprocess legacy Bauxite Residues deposits for fear of facing liabilities in Scenario 2. Likewise, the transport of feedstocks containing heavy metals or radioactive elements faces heavy regulations that may make Scenario 3 challenging.

- Technically, treating freshly processed Bauxite Residues offers advantages in terms of feedstock quality control, since the feedstocks from Scenario 2 and 3 (legacy Bauxite Residues disposal sites or REE concentrates) may lack uniformity that poses challenges to the tailored processing solution developed by BIORECOVER.

The remainder of this section will now explore the key drivers and barriers of innovation along the novel REE value chain created by valorizing Bauxite Residues, with a specific emphasis on how BIORECOVER could drive changes in business practices of key stakeholders (such as alumina producers).

5.5.3 Upgrading REE Exploration and Process Design

Drivers and Barriers to Innovating in REE Exploration

In the last decade since REE were listed on the European Commission's first list of Critical Raw Materials in 2011, significant efforts have been undertaken in Europe to locate and quantify European REE reserves and to design novel supply chains for REE processing in Europe. Yet to date, no REE exploration project in Europe has yet borne fruit, and there remain no active REE mines in Europe. The saga of the planned Kvanefjeld REE mine, which was blocked by the government of Greenland in 2021 **(Meyer, 2021)**, can help offer insights into the drivers and challenges surrounding REE exploration and mine planning.

As Julie Michel Klinger details in her book Rare Earth Frontiers, exploration for REE saw rapid growth around the globe in the years following China's decision to restrict REE exports in 2011 **(Klinger, 2017)**. Klinger argues that this interest in exploration was primarily driven by geopolitical interests, as REE became viewed as essential to national security interests and exposed to vulnerability due to the Chinese monopoly of supply. The Kvanefjeld mining project in Greenland went through exploration during this time in the 2010s and received public geotechnical support from the European Commission through the EURARE project **(EURare, 2022)**. It is important to note that growing concerns over the environmental externalities of REE mining in China meant that Chinese geopolitical interests also favored diversifying primary extraction of REE to mines outside of China, while maintaining predominance in REE processing and applications. This helps explain why in 2016 Chinese REE processor Shenghe Resources became the largest investor in the company leading exploration at Kvanefjeld, Greenland Minerals Ltd **(Greenland Minerals, 2022)**.

Thus, REE exploration and mine planning are driven by growing market demand for REE, as well as geopolitical concerns about supply constraints. The failure of Kvanefjeld to move past exploration and planning into active extraction, also demonstrates the barriers to innovating at the beginning of the REE value chain. The major barriers to Kvanefjeld, and to REE exploration projects around the globe, are **a lack of legal permitting, and a lack of social license to operate**. Primary exploration generally faces complicated regulatory environments frequently resulting in lengthy permitting timeframes. This has produced extended lead times for new and emerging projects, and an underinvestment in exploration **(USDOE, 2020)**. In the case of Kvanefjeld, the co-deposition of Uranium and Thorium in the sites mineral reserves was perceived as a major environmental risk by local populations, which eventually led to a political movement to revoke its permitting **(Meyer, 2021)**.

Value Proposition and key stakeholders for REE Exploration and Planning

For BIORECOVER to succeed where other European REE exploration endeavors have failed, it will be essential to respond to Europe's geopolitical interests in onshoring REE production, while also ensuring the process offers clear environmental benefits in order to obtain approval from local and regulatory stakeholders. One clear advantage provided by the BIORECOVER process is that it could enable shifting REE production within Europe without the need for additional exploration to establish new mines, since BR has already been extracted from active Bauxite mines. Moreover, BIORECOVER avoids certain regulatory barriers faced by traditional REE extraction, since alumina refiners already have the legal permitting in place to handle BR. However, further attention must be given to the legal status of BR that has been treated by BIORECOVER and its future classification and handling protocols under European Waste Codes. In additional to regulatory approval, social license to operate must also be obtained. For this, local communities living near facilities where the BIORECOVER process would be implemented should be engaged with and informed about the process' potential to dramatically reduce the land use footprint of alumina refineries by shrinking the space needed for BR disposal.

The major activities in this stage of the upgraded REE value chain can be conducted initially by project partners. Mytilineos can establish REE production estimates, since existing material characterization conducted in WP1 of the project should be suitable to offer estimates of REE reserve quantities within BR. However, given that alumina refiners typically import and mix Bauxite feeds from around the globe, the company will still likely need to conduct batch testing to ensure the technical performance of an industrial BIORECOVER process. The technical design and construction of an upscaled process flow could be led by an engineering consulting firm such as Tecnicas Reunidas. Their experience within the BIORECOVER project, and their expertise in industrial design should offer advantages over firms specialized only in conventional, non-biobased, metallurgy.

5.5.4 Upgrading REE Extraction

Drivers and Barriers to Innovating in REE Extraction

As highlighted in the previous subsection, the choice of location and approval of REE mines is imminently political. Once a mine enters into operation however, its technical innovations in REE extraction are typically driven by economic calculations and efforts to minimize environmental externalities. Mineral processing technologies are selected based on their ability to maximize recovery of valuable elements, while minimizing production costs (e.g., labour, energy, environmental remediation, capital equipment, etc).

REE mines in particular face significant headwinds when investing in new technologies and facilities because the market is volatile and uncertain, and there is a lack of transparency in the rare earths supply chain. As mentioned in section 5.2, REE producers face barriers to entry into the market because of the rents extracted by Chinese producers. Moreover, the price of several REE is not sufficient to justify necessary investments in creating both a domestic and international supply chain that is not dependent on Chinese production. Since REE are mined as a basket of commodities, there exists the problem of balance (or imbalance) between the market demand and the abundance of naturally occurring REEs in mineral deposits. This is a barrier to long term production planning and poses major risks of some REE facing supply gaps, while others are in oversupply.

Value Proposition for Alumina Refiners and key stakeholders for REE Extraction

In contrast to conventional REE extraction activities, BIORECOVER offers the added value of being a secondary processing stage to valorise *already extracted* material, that is currently value negative. When viewed through the lens of alumina refinery, **the key added value of BIORECOVER is its ability to eliminate the need for onsite Bauxite Residues storage or disposal**. Indeed, rather than being merely a metal production process, when treating Bauxite Residues, BIORECOVER should firstly be considered a bulk material cleaning process. From this perspective, the production of REE serves merely as a high value revenue stream to help cover the costs of BR treatment. Viewing REE as a by-product commodity in this production process diminishes the impact that price volatility in REE markets could have on producers. Yet since REE make up only roughly 0,1% of BR content by weight, economic viability of BIORECOVER likely depends on its ability to valorise the majority of BR material in the construction industry.

Since the late 19^{th} century when the Bayer process was first patented as a method for alumina refining, efforts have been made to valorise the BR that results as a by-product of this industrial process. Yet to date, most of the over 3 billion tons of Bauxite Residues around the world remains unused, stockpiled in mounds or tailings dams. According to the International Aluminium Institute, "the most important barrier to remediation, re-use and long-term sustainability of bauxite residue is its high alkalinity" **(International Aluminium Institute, 2015)**. Indeed, the use of NaOH during the Bayer process gives BR a high pH, rendering it challenging to valorise as a bulk material.

If technically successful, BIORECOVER could offer a solution to this barrier, since bioleaching using acidophilic bacteria in order to extract REE offers the added benefit of neutralizing the caustic BR. WP7 of the BIORECOVER project is in the midst of researching several potential applications to valorise this neutralized BR that remains after an initial leaching stage, including in geopolymers, as a source of iron metal, or for application in the cement industry. In designing the upscaled BIORECOVER process, inspiration can be drawn from existing research, such as the proposed flow sheet for zero waste alumina manufacturing presented in Figure 44 below.

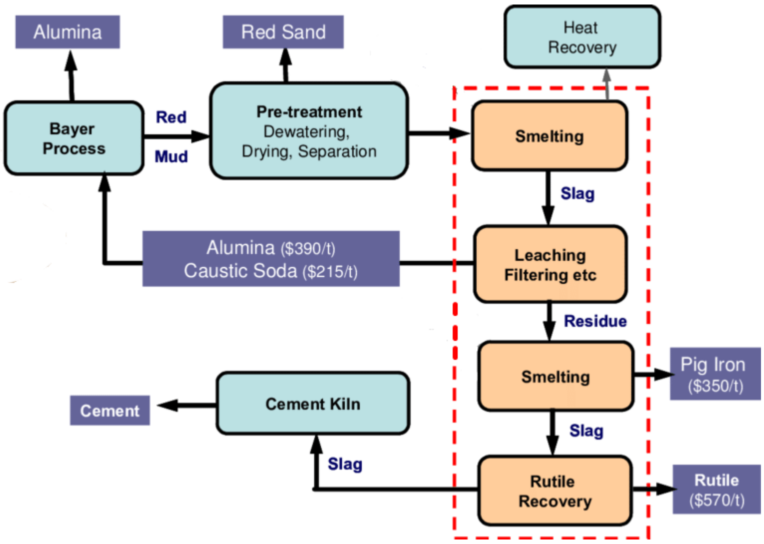


Figure 44: A conceptual flowsheet for zero waste - value recovery from red mud ((Jahanshahi, 2015)

Yet before any commercial application of neutralized BR can be considered, it will be essential for future research projects to perform all the steps needed to classify the material as non-hazardous and receive proper environmental permits (e.g., leachability tests, heavy metal content etc.). In particular, the ability of BIORECOVER to remove chromium during bioleaching would offer significant value, since this element is seen as a limiting factor in the bulk valorisation of Bauxite Residues in cement **(International Aluminium Institute, 2015)**.

Recommendations to valorise Bauxite Residues

In a future value chain scenario, the main activities related to extracting REE, and valorising Bauxite Residues would be conducted by alumina refiners such as Mytilineos. After research has indicated the optimal microbial consortia to selectively remove interfering compounds from Bauxite Residues, the exploiting partner would then need to find a partner from which to procure the tailored microbes. At this stage in the project, the optimal method of applying the microbes to BR has yet to be determined, but it is likely that they will need to be multiplied onsite in controlled conditions, such as in stirred tank bioreactors. During the Circular Value Proposition Workshop, partners also mentioned exploring the use of molasses (an available by-product of the sugar industry) as an energy source to nourish the microbes. After this stage in the value chain, the alumina refinery would have two commodities: a REE concentrate, and neutralized Bauxite Residues. Existing logistics infrastructure could be used to ship the REE concentrate offsite to a company providing REE separation and processing. Likewise, Mytilineos already has existing ties to a **cement manufacturer** operating near their alumina refinery in Greece and could orchestrate the **logistics of delivering the neutralized Bauxite Residues for bulk valorisation.**

5.5.5 Upgrading REE Processing

Drivers and Barriers to upgrading REE processing

As was explored in section 5.2, the vast majority of global REE processing is currently performed by Chinese actors. The European Commission has made the onshoring of REE processing a key element of its raw material strategy. Yet despite innovation in this sector being driven by public investments and policy support, at the moment only a few companies in Europe offer REE separation and refining at commercial scale.

This can be understood to be a result of the significant barriers facing European innovation in REE processing. The economies of scale and cost competitiveness offered by Chinese REE producers makes it economically challenging for European actors to compete on price at this link in the value chain. Technology transfer is another identified barrier to upgrading European REE processing. Without persistent collaboration among business, academia, and government laboratories to solve scientific and technological issues during scale-up, handing off innovations in this field is challenging. Generally, achieving and maintaining cost-competitiveness for new processes is a challenge. Obtaining intellectual property rights for manufacturing is another barrier. Moreover, given the relative lack of a European REE processing industry workforce development represents another barrier to upgrading. One of the greatest needs is reported to be at the technician level, where industry is already anticipating multi-generational workforce gaps. Qualified workforce shortages in developed economies are a rising problem that is amplified in this sector.

Value Proposition and key stakeholders for REE processing

Careful design of logistics and business models will be needed in order for BIORECOVER to deliver on its ambition of creating a novel European REE value chain. While the technical performance of BIORECOVER at selectively leaching and purifying REE remains to be determined, several recommendations can still be made for the design of an economically viable REE processing business within Europe.

- **Ensure the process can handle a diversity of feedstocks.** In order to achieve the economies of scale necessary to penetrate the REE market, a REE processor will need to be able to handle concentrates from multiple sources. Seeking to separate and refine REE onsite at each alumina refinery producing BR could entail major investments in capital equipment that may not be covered by the value of REE produced. Therefore, it is instead suggested that a REE concentrate be produced at alumina refineries in order to reduce bulk shipping costs, but that the separation and recovery stages of BIORECOVER be upscaled by a single larger scale REE processor offsite. This processor could license the BIORECOVER technology from project partners. By adopting a process flow that is flexible based on different feedstocks this company could lower costs in order to compete with Chinese manufacturers by targeting REE sources in challenging material streams that may not be logistically or legally feasible to ship to China. For instance, the Swiss REE processing startup REMRETEC has found a stable REE feedstock by targeting waste from fluorescent lighting that contains high quantities of REE but must remain in Europe under the terms of the Basel convention. A diversity of extractive wastes or post-use consumer goods also could be considered as potential feedstocks.

- **Consider a separation as a service business model.** As we have seen in this Chapter, the market volatility of REE commodities poses challenges to long term production planning and the economic stability of actors along the value chain. Therefore, in a novel EU REE value chain, the REE refiner should consider insulating themselves from market volatility through a service based economic model rather than one based on purchasing concentrates and selling REE commodities on the open market. In such a model, the processor never has ownership of the REE concentrate they treat. Instead, the REE concentrate would be "lent" to the processor, who takes a fixed fee to separate and refine REE within the feedstock. This economic model is more amenable to long term business contracts and could allow for upstream supply and downstream demand to meet without having to navigate volatile spot markets. Meanwhile the downstream consumer could pay the concentrate supplier (e.g., alumina refinery) for the market value of the REE in their feedstock. This would also allow the alumina refinery to maintain ownership of the Sc within their feedstock, which will be shipped back to them after separation for use in alloys.
- **Tailor REE commodities to downstream EU demand.** The numerous economic rents that Chinese REE processors possess will make it challenging for EU actors to compete on price alone. Therefore, European REE processors should also focus their production on specialty REE chemicals that are directly tailored to downstream demand. Since Chinese suppliers typically negotiate bulk sales of REE, there is a market opportunity for smaller scale producers shipping higher value specialty products. REE processors should consider client needs in terms of REE purity, as compared to oxides or specialty REE compounds. For instance, FAE chooses to source their REE from a non-Chinese supplier who is capable of producing small orders of specialized Yttrium Zirconium Oxides for tailored use in their production of oxygen sensors.
- **Facilitate long term contracts across the value chain.** This chapter has highlighted that one major barrier to the emergence of a European REE value chain, and particularly the Scandium market, is a "chicken and egg problem" where supply and demand struggle to align due to the lack of the other. As the intermediary between extraction and manufacturing, processors can help bridge this chasm between REE supply and demand. One strategy would be to pursue investments from upstream and downstream actors to build out the new processing facility, in exchange for transforming stable feedstock supply into consistent REE commodities for industry. This commercial strategy could be supported by long term B2B supply contracts and would ensure that all key economic stakeholders would have a shared interest in building out the novel REE value chain.

Adopting these changes, and upgrading European REE processing using BIORECOVER's results, will likely involve a major transformation in the stakeholders operating at this link in the value chain. There is currently only one commercial scale REE separation and refining facility in continental Europe, owned by Neo Performance Materials in Sillamäe, Estonia (Materials, 2022). Less Common Metals (LCM) in the UK also operates facilities for REE processing (Metals, 2022). There are also several start-up ventures at high TRL's nearing commercial operations in Europe, such as REMRETEC producing Yttrium, or SCAVENGER producing Scandium. If any one of these actors is interested in licensing the BIORECOVER process for REE separation and purification, and treating concentrate produced by alumina refiners, this would dramatically expand the amount of Sc and Y produced in the European market. Such a change would also decrease the reliance of European manufacturers on Chinese production. However, given the vertical integration of the Chinese REE value chain, Chinese firms would very likely continue to operate to supply their internal market. If a licensing agreement is not feasible for commercial or technical reasons, a new private company would then need to be created as a spinoff to upscale BIORECOVER and begin commercial REE production.

5.5.6 Upgrading Downstream Manufacturing

Drivers and barriers to upgrading manufacturing with REE

REE elements represent a proportionally small amount of the raw materials procured by downstream manufacturing in Europe. However, the unique material properties of REE enable them to be applied in small amounts to produce major performance gains across a tremendous diversity of end-use applications. Thus, ensuring stable supply of REE elements in Europe can help create far greater value than the raw materials themselves, by enabling the growth of high value industries. How then can BIORECOVER play a role in developing downstream applications using REE?

In order for BIORECOVER to penetrate the REE value chain and capture downstream demand, technical, relational, and economic barriers will have to be overcome. The largest barrier to changing industrial manufacturing systems is ensuring technical performance. Manufacturing systems are typically designed to operate with very specific material qualities (chemical composition, particle size, etc), and if the REE produced by BIORECOVER do not conform to the requirements of industry they will not be able to gain any market share. This technical specificity of REE procurement contributes to long-term, stable, relations between suppliers and consumers of REE. Beyond the need to ensure that raw materials and manufacturing systems are tailored to one another, EU manufacturers using REE also face challenges competing based on price with Chinese producers due to their economies of scale and the numerous economic rents detailed in section 5.2.

In addition to general barriers related to integrating REE into EU manufacturing, the Yttrium and Scandium markets each face particular barriers to long term procurement due to their evolving market dynamics. In the medium term, Yttrium is expected to be in oversupply due to its extraction as a by-product and decreasing demand in fluorescent lighting. This could drive prices lower to the benefit of manufacturers in the short term, however it may also lead to underinvestment in production over the longer term, potentially hindering the development of innovative products containing Yttrium. Meanwhile, the prohibitively high costs of Scandium have to date limited its application in mass produced consumer goods and led to an underinvestment in Scandium containing products. New technologies capable of cost effectively producing Sc, such as those proposed by BIORECOVER, are expected to transform this dynamic.

While transforming the procurement of REE towards EU supply faces several barriers, current events may also drive a shift towards relocalising REE supply chains via innovative production models. Notably, recent disruptions in global commodity flows due to the covid-19 pandemic and the war in

Ukraine have led many large manufacturers to rethink their raw material procurement strategies. This has been framed by commentators as a shift from "just in time" supply chains to "just in case" procurement (Shih, 2022). The shift in corporate procurement entails increasing strategic stockpiles of key materials and seeking to diversify suppliers to build supply chain resilience and avoid bottlenecks.

Value proposition and key stakeholders for downstream manufacturing

As has been mentioned, alumina manufacturers are the key exploiting partner of BIORECOVER's REE technology. The fact that Alumina refineries will also be the key consumer of the Sc produced industrially by the technology, means that they can also be considered the major stakeholders in downstream manufacturing. Their role in the upgraded value chain would be to produce high performance master alloys containing Scandium and Aluminium though casting or electrolysis. Being both the producer and industrial consumer of Sc offers specific competitive advantages to alumina refiners. If functional, the technology could allow them to control production costs through vertical integration of the value chain from mine to master alloy.

These alloys would then be sold to major industrials in the aerospace industry. Large aerospace industrials would then need to further tailor the chemical composition of the master alloys to suite the specific performance criteria required by their applications. The value these products offer is largely due to the strength increases they offer at lighter weights than conventional metals. For instance, Airbus has claimed that Al-Sc containing alloys they have developed in house could contribute to reducing the weight of large aircraft by between 10-15% (Djukanovic, 2017).

Cement manufacturers are another major industrial stakeholder working in manufacturing that could have their business model transformed by an upgraded REE value chain. Due to the low price of primary construction aggregates, it is unlikely that the construction industry would adopt neutralized BR as a feedstock if it required significant changes to their production processes. The major value added for actors such as cement manufacturers will be if the neutralized BR can be provided at a sufficiently low cost to outcompete primary aggregates. Other potential benefits could be provided to them if they can justify that cement or geopolymers produced using neutralized BR offer clear reductions in CO_2 emissions, which could lower their exposure to high expenses under the EU ETS carbon market.

5.6 Overall impact of the BIORECOVER technology on REE

This chapter has argued that BIORECOVER has the potential to bring significant value to a diversity of European industries by transforming BR into valuable industrial products. In contrast to the PGM value chain, BIORECOVER has the potential to enable value chain upgrading and relocate REE production onto the European continent. It has been argued that the largest potential impact of this technology is enabling the valorisation of BR as a bulk material through industrial symbioses between alumina refineries and the construction industry. Beyond providing a solution for the disposal of BR, BIORECOVER could unlock major improvements in the technical performance and sustainability of the mobility and aerospace sectors by enabling Sc-Al alloys to be commercialised affordably. Numerous other potential impacts on other sectors consuming REE could also become available as the technology reaches a more mature TRL.

6 ANALYSIS OF THE MAGNESIUM VALUE CHAIN

6.1 Introduction to Magnesium

Magnesium is a chemical element with symbol Mg and atomic number 12. It is a lustrous grey metal. Magnesium is the eighth most abundant element in the earth's crust and the fourth most common element on earth after iron, oxygen and silicon (Royal society of Chemistry, 2022). However, it does not occur uncombined[13] in nature. It is found in large deposits of minerals such as magnesite or dolomite and it also largely exploited from sea water.

Magnesium is 30% less dense than aluminium, and the alloy of the two is prized for its combination of lightness and strength. As a metal, one of its main uses is as an alloying additive to aluminium. As such magnesium is utilized in devices where weight can be critical such as cars, luggage, packaging, and power tools. It is also used to eliminate sulphur from molten iron and steel.

Processing

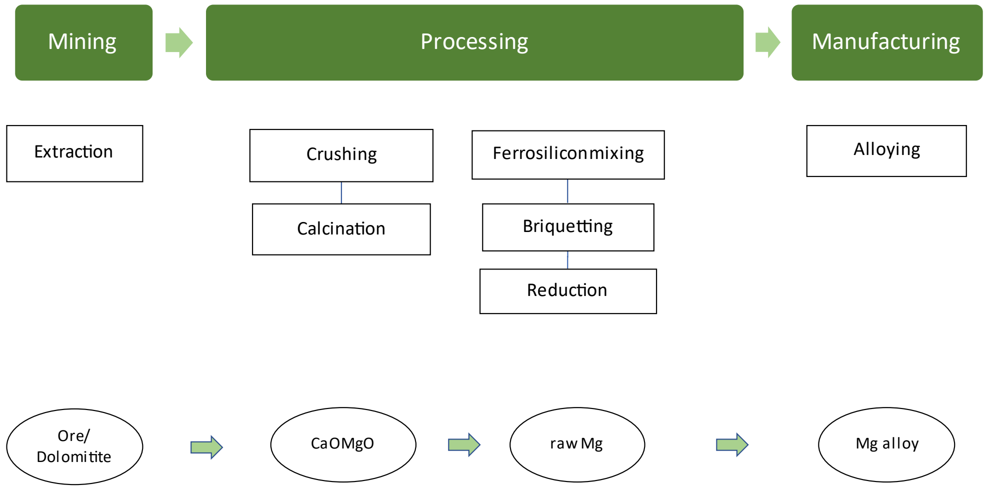
At present, there are two main magnesium production methods: the electrolytic method and the reduction method. The reduction method, known as the Pidgeon process, is the main process used in China, the main global supplier. Compared with the electrolytic magnesium smelting process, the Pidgeon process has the advantages of simple and mature process flow and small investment requirements. However, it displays low thermal efficiency, and intermittent production, requiring high labour intensity, consuming high energy, and is environmentally harmful (Wu, Han, & Liu, 2021). It takes 35-40 megawatt-hours of electricity to produce one ton of magnesium, equivalent to powering about ten to twelve thousand homes for an hour (Global Times, 2021).

Magnesium smelting via the Pidgeon process is a process where dolomite, the magnesium bearing ore, is thermally reduced to metallic magnesium using 75% ferrosilicon as a reducing agent. There are four main processes in smelting magnesium via the Pidgeon process: calcination, pelleting, thermal reduction, and refining.

- Calcination of dolomite: After the dolomite is crushed and screened it is heated to 1100–1200 °C in a rotary furnace (rotary kiln) to form calcined dolomite (MgO CaO)
- Batching and pelleting: The crushed calcined dolomite is then sent to a silo while ferrosilicon powder is also crushed and sent to the silo, fluorite is used directly in the batching process. The three materials are mixed in the batching machine according to the specific proportions, and then fed via a belt conveyor for grinding, and then pressed into pellets, spheroids of about 40 mm. The preparation of pellets is conducted to prepare raw materials for the reduction process.
- Reduction: The pellets are heated to 1200 ± 10 °C in a closed reduction tank and reduced by silicon to form metallic magnesium under vacuum to avoid oxidation. Magnesium vapor

[13] Uncombined elements are not found attached or combined with other elements. Instead, they remain in their pure elemental form.

forms crystalline magnesium in the tank condenser. This crude Magnesium is refined via flux to obtain commercial magnesium ingots at high purity (99,9%).



Production

As shown in the following figures, China is the main primary producers of Magnesium, with 800 kilotons per year, followed by Russia (60 kilotons per year), and Kazakhstan (22 kilotons per year.) (USGS, 2021)

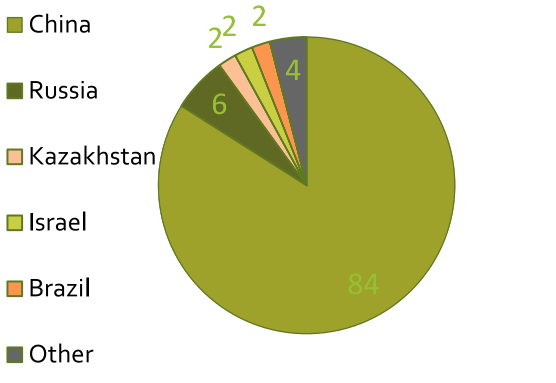


Figure 46. Global Magnesium Production (% t/t)

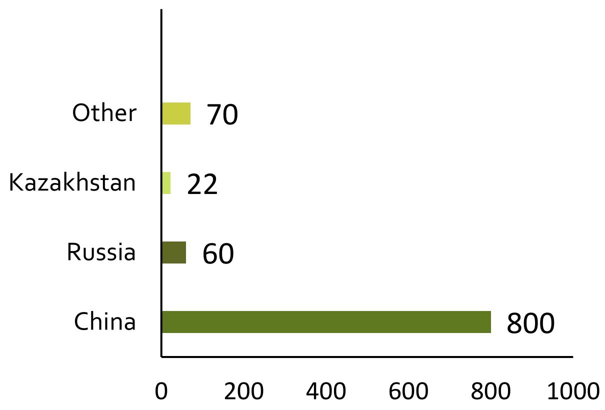


Figure 45. Production of Magnesium (Thousand Metric Tons)

Main Market

As shown by the following figure, the main applications of magnesium are transportation (63%) and Packaging (10%). Other applications include desulfurization for metallurgy and construction.

Magnesium alloys and aluminium alloys represent respectively 43% and 39% of magnesium use in the EU over the 2010-2014 period. Most of the magnesium alloys are used in transportation applications (EU Comission, 2020)

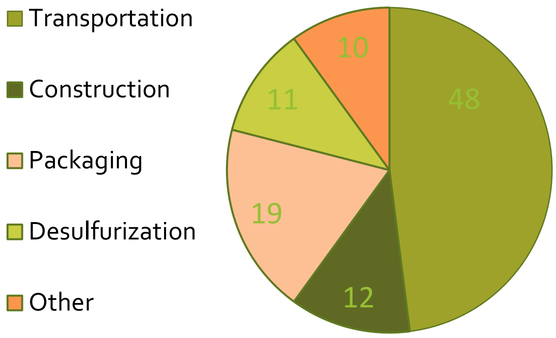


FIGURE 47. MAGNESIUM MAIN APPLICATIONS (%)

Main Players

As China is by far the biggest producer of primary magnesium, and the world's largest production companies are based there. Shanxi Yinguang Magnesium Industry (Group) Co., Ltd. is the largest primary magnesium producer in China, with a primary magnesium capacity of 100 kilotons in 2012. Its major subsidiary Shanxi Yinguang Huasheng Magnesium Industry ranked No.1 in China in terms of primary magnesium output in 2011. The company has formed a complete industrial chain covering every stage from magnesium ore exploitation to magnesium alloy processing. Nanjing Yunhai Special Metals is the largest producer of magnesium alloys in China, with a magnesium alloy capacity of 140 kilotons in 2012.

EU demand

The EU consumption of magnesium was 113 kt (annual average in 2012-2016) and was 184 kt in 2018 (EU Comission, 2020). Magnesium casting alloys and aluminium alloys represent respectively 43% and 39% of magnesium use in the EU. It can be considered that most magnesium alloys are used in transportation applications. The major end-uses of magnesium in the EU are in the transportation sector. Magnesium casting alloys is mainly used in vehicles to lower the overall weight and may also increase the strength of the material compared to various steel components (EU Comission, 2020).

6.2 Distribution of value along the chain

As part of the Magnesium value chain analysis the report will focus on how the value is captured or distributed along the various stages and chains of the magnesium value chain. To uncover this, there will first be a financial analysis of margins, prices and costs to have a clearer picture of the situation in the sector

6.2.1 Financial analysis

To better understand the distribution of revenue along the magnesium value chain, a solution can be to analyse the margins of some of the main actors of each sector of the said value chain, the table below represents targeted stakeholders of the sector from mining to end applications. The representative companies chosen for this analysis are large scale producers of magnesium and companies involved in its main application: the automotive sector.

Margins

Company	Sector	Profit margin TTM (2022)	Profit margin change (2017-TTM 2022)
Shanxi Yinguang	Mining/processing	No data publically available, limited information on this stage in value chain	
Nanjing Yunhai	Mining/ Processing	16%	-12%
Group Antolin[14]	OEM	35%	7%
ZF group[15]	OEM	15%	-16%
Volkswagen	Cars	19%	-4%

When analysing the table above, it seems relatively difficult to establish a clear point within the value chain where value is captured. Upstream magnesium actors do not seem to capture that much value compared to other raw materials producers, which might be a consequence of the active dumping policy of the past. The upstream actors, big and integrated Chinese corporations allow for only small competition and make OEM companies very dependent, the chosen companies within this analysis display very different margins. Magnesium use for OEMs are however not extensive as they don't produce frames, doors etc where magnesium is more used in general, this could explain the margin variations.

There is no primary Mg producer in Europe. The value chain in EU starts with imported pure magnesium 99.98% mainly through Al industry; alloys are imported and go into converters or for use through die cast and re injected into moulds for the automotive industry.

Price

Similarly, as with other industrial metals, there is no formal market for magnesium. The price for magnesium compounds is set based on price confrontation between producers and end users as most of the business takes place in China, the Chinese price for 99.8% magnesium metal and the European price set in Rotterdam are the most indicative (Berry, 2015).

[14] (Antollin, 2021) for the year 2020

[15] https://craft.co/zf-group/metrics

The pandemic wreaked havoc on magnesium exports, leading to overcapacity and a drop in price to 13 000 CNY / 2 000 USD per tonne at its lowest. The whole industry suffered great losses, and some Chinese companies halted or reduced production (Xinhua, 2021). However, Magnesium prices quickly bounced back and soared above 10 000 USD (63 000 CNY) per tons in the fall of 2021(400% increase compared to January 2021). As explained, the Pidgeon process in China necessitates FeSi, which also got much more expensive generating a magnified effect. The crisis can be traced back to missed electricity targets from aluminium smelters in China.

The price spike in magnesium during 2021, and subsequent concern from downstream users, is directly related to energy policy enforcement developments in China, adding to ongoing challenges from the COVID-19 pandemic. To meet annual emissions targets, northwest China's Shaanxi province reportedly reduced magnesium production in the early Fall as a result of the realization of the industry concerns voiced in 2020. Magnesium production in Yulin, which accounts for more than 60 percent of China's magnesium production, was reduced by half in September 2021 (Hume, 2021). Chinese magnesium producers have been working tightly with other industries to create a circular economy to minimise costs and waste but making it vulnerable to the aluminium market. The price used to move like base metals, but it seems now much more unstable.

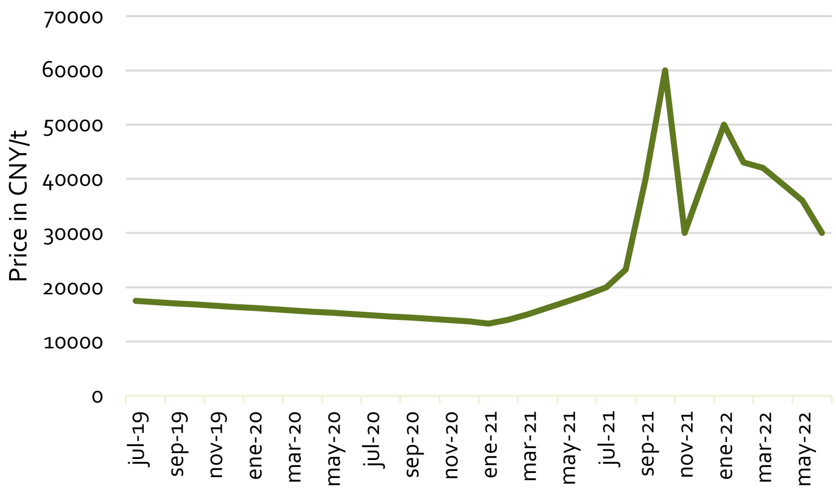


FIGURE 48: MAGNESIUM PRICE EVOLUTION (TRADING ECONOMICS DATA)[16]

Costs

One of the key elements to Chinese magnesium producers achieving a low cost is because they are co-located with coking ovens. This allows them to take advantage of waste heat energy associated with coal gas production needed for processing. Nevertheless, the pidgeon process necessitates important amounts of ferro-silicon (FeSi) meaning magnesium costs are strongly correlated with Fe-Si prices and steel prices (CME Group , 2020). Prices of raw coal and ferrosilicon, the two main materials for smelting magnesium, have risen from around 500 CNY[17] per tonne in 2020 to the rate

[16] 1 USD was valued at 6.3 to 6.7 CNY between June 2017 and July 2022 (1 CNY = 0.16 USD)

[17] CNY : Chinese Yuan

of about 2,000 CNY in end 2021 and from 6,000 CNY per tonne to 19,000 CNY, respectively (Xinhua, 2021).

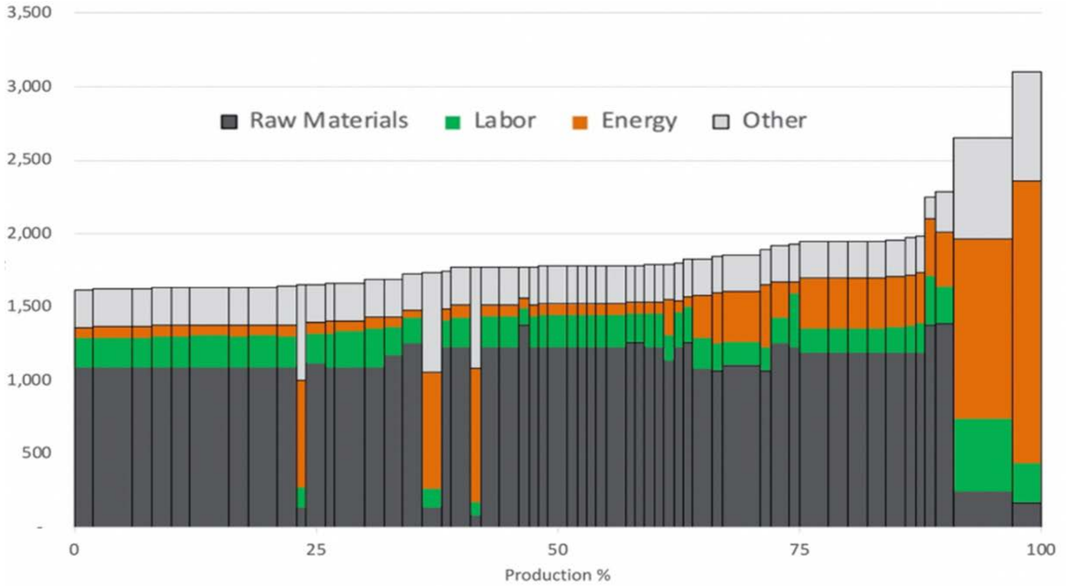


FIGURE 49: PRIMARY MAGNESIUM CASH COST CURVE , 2019 IN US$/T (CME GROUP , 2020)

On the figure above, Chinese producers are recognizable on the lower end of cash costs curve by their relatively high raw material costs while Australian, Brazilian and American producers sustain much heavier total costs specifically regarding energy despite more effective methods used.

In 2018, the average cost of Chinese pidgeon process was 1.8 USD/kg, with a free on board (f.o.b) Chinese price fluctuating at around 2.5 USD/Kg. After years of virtually no profits, and despite the recent raw materials price increases, Chinese primary Mg producers are enjoying healthy margins compared with any period over the past decade. Inventories have very low levels but increasing slightly since beginning 2022. Structural shift in costs structure remain high guided by the main curve but with a cost base 15/20% higher (Tauber, 2022).

Costs can vary from province to province in China with the average cash costs for Pidgeon producers in Shaanxi were at 1,949USD/t, compared with 2,646USD/t for producers in Shanxi. Costs increased by 15% in 2021, mostly because of higher FeSi and coal prices.

Capital investment expenses continue to be a substantial factor in favour of the present technical status quo of the pidgeon process. As we can see in the following table dating from a couple years back, the investment cost associated with electrolytic smelters is virtually unsustainable at current market prices.

Facility	Specific Capital Investment Cost (USD/t FeSi)	Specific Capex based on Mg (current)	Source of Data
Chinese Technology FeSi smelter (cost basis 300kt/y)	1,000	1,200	OM Holdings Sarawak project 2014 project investment report
Huayuan Shuizuizhan Pidgeon process facility (costs basis 8,000 kt/y)	3,370	4,540	Zang, TMS 2001 escalated for inflation
Confidential vertical Pidgeon facility Cost basis (50 kt/y)	5,600	6,310	Hatch study data, Western project escalated for inflation.
Electrolytic smelter (cost basis 50 kt/y)	15,000 – 20,000	15,000 – 20,000	Hatch data escalated for inflation.

TABLE 8: CAPITAL COST COMPARISON (BAKER, 2016)

Other factors to consider are the amount of idle capacity in China but with potential to increase it. The sometimes-aging plants increases risks on a province basis as missed targets can lead to have forced closures.

6.2.2 Economic rents

In addition to the more straightforward analysis of prices, costs and margins it is important to dig deeper into the specific rent seeking behaviour of Chinese magnesium companies.

Organisational rents

With fast development of cheap magnesium production in China in the 1990's many small-scale actors appeared. Indeed, magnesium in not a scarce resource and it necessitates little investment to start production, hence a profusion of smelters appeared in producing regions. With time however, the market consolidated with several large corporations growing through vertical and horizontal integration. The Pidgeon process in China being cheap but not extremely productive large plants and economies of scale became solutions. Nowadays, big actors like Shanxi Yinguang Magnesium the largest primary magnesium producer, which controls around 20% of the production. The company has formed a complete industrial chain covering every stage from magnesium ore exploitation to magnesium alloy processing. A high integration can lead to rent seeking behaviour, which is developing in the Chinese magnesium sector.

Moreover, geographically the production is also extremely concentrated as the Fungu county represents 50% of the world magnesium consumption (Xinhua, 2021). County is now building a magnesium ingot, magnesium-based new materials and magnesium alloy products industry value chain, aiming to lift its total magnesium ingot and alloy output capacity to 1 million MT/year by the end of the 14th Five Year Plan period (2021-2025) from the current more than 700,000 MT/year capacity. This fact only consolidates the rent seeking potential from large Chinese corporation.

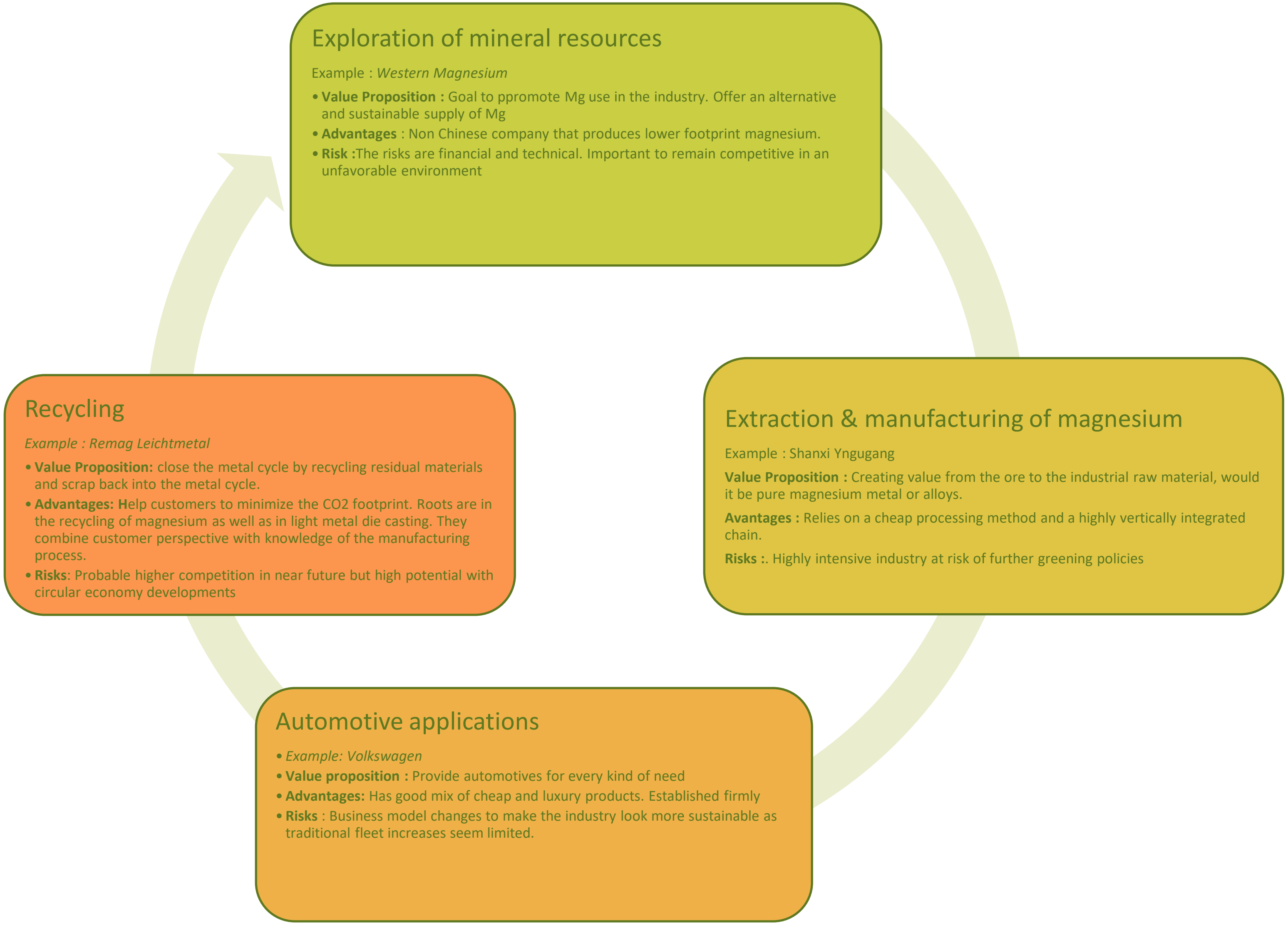
Policy rents

China has built a monopoly on the global supply of magnesium in the last two decades and they have managed to overcome their European rivals by what has sometimes been described as large-scale dumping[18] .This is due to Chinese government subsidies in the sector since 1990 as well as its flexible environmental standards.

Dumping can here be understood as when foreign firms dump products at artificially low prices in the European market. This could be because countries unfairly subsidise products or companies have overproduced and are now selling the products at reduced prices. In the case of Chinese magnesium, the policy of energy subsidies and other state help have help Chinese producers to almost control the whole magnesium market by selling at less than fair prices. The Chinese economic competitiveness of this production will surely remain higher than others. The extraction of raw materials and the production of magnesium in Europe remains much more expensive than in China.

6.2.3 Value chain example

[18] See the Notice by the US International Trade Administration on 11/26/2021: https://www.federalregister.gov/


Exploration of mineral resources
Example : Western Magnesium
• Value Proposition : Goal to ppromote Mg use in the industry. Offer an alternative and sustainable supply of Mg
• Advantages : Non Chinese company that produces lower footprint magnesium.
• Risk :The risks are financial and technical. Important to remain competitive in an unfavorable environment
Extraction & manufacturing of magnesium
Example : Shanxi Yngugang
Value Proposition : Creating value from the ore to the industrial raw material, would it be pure magnesium metal or alloys.
Avantages : Relies on a cheap processing method and a highly vertically integrated chain.
Risks :. Highly intensive industry at risk of further greening policies
Automotive applications
• Example: Volkswagen
• Value proposition : Provide automotives for every kind of need
• Advantages: Has good mix of cheap and luxury products. Established firmly
• Risks : Business model changes to make the industry look more sustainable as traditional fleet increases seem limited.
Recycling
Example : Remag Leichtmetal
• Value Proposition: close the metal cycle by recycling residual materials and scrap back into the metal cycle.
• Advantages: Help customers to minimize the CO2 footprint. Roots are in the recycling of magnesium as well as in light metal die casting. They combine customer perspective with knowledge of the manufacturing process.
• Risks: Probable higher competition in near future but high potential with circular economy developments

6.3 Factors structuring/governing the value chain

This part will offer an overview of the most impactful parameters of the magnesium market. An analysis of logistics and trade policies are also being added

6.3.1 Aluminium & Magnesium

Aluminium and magnesium have closely related markets, and aluminium alloying is the single largest market sector for primary magnesium. Indeed, about 75% of all final applications created from primary aluminium wouldn't be appropriate for their intended uses without Magnesium, since magnesium cannot be substituted in most aluminium alloys.(CME Group , 2020).

The synergies between the two value chains can even be seen in its more upstream links. Indeed, the energy crisis that affected the magnesium sector can be traced back to missed electricity targets from aluminium smelters in China (Tauber, 2022).

6.3.2 Chinese governance

The magnesium sector is of the many industries that left Europe for China since the 1990s. By the early 2000s the European production of magnesium in France, Italy and Norway had ended due to the low prices of Chinese imports. The tertiarization of Europe and its new environmental standards have therefore caused a relocation of magnesium production. For instance, companies like Norsk Hydro used to produce magnesium but stopped because they could not compete with Chinese producers[19]. The primary cause of the global Magnesium industry's relocation to China is rather straightforward. Chinese producers have had low capital costs and available resources for their highly labour and energy intensive process. With these attributes of the Pigeon process, Chinese companies have thus been able to produce at lower prices than other market participants using the more environmentally sound electrochemical processes.

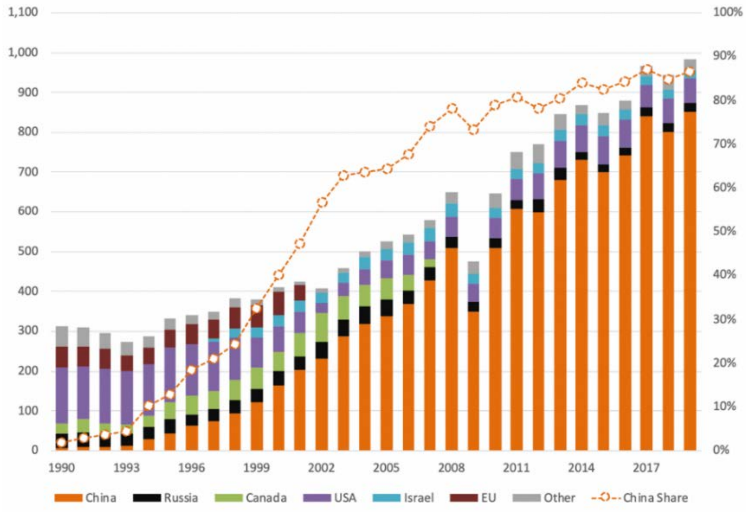


FIGURE 50: CHINESE MAGNESIUM MARKET SHARE EVOLUTION (CME GROUP , 2020)

[19] (Norsk Hydro, 2001) : "*Fundamental changes to the global magnesium market necessitate an extensive restructuring of Norsk Hydro's magnesium operation in order to restore profitability*".

Another important factor in the primary magnesium industry's pivot to China was that between 1995 and 2005 multiple new western electrolytic projects initiated by new participants spurred by forecasted increasing demand generated by the car industry's need for light weighting to fulfil CAFE[20] criteria (Baker, 2016). This resulted in major investments for little return, which deterred further investment in the Western world.

European primary aluminium production alone has lost more than 30% of its capacity since 2008. In parallel, China continuously increased production capacity to meet the steady increase in European and global demand for both aluminium and magnesium (European Aluminium, 2021).

Last year events on the magnesium market perfectly showcased the outstanding importance China occupies in the value chain. In the second half of 2021, the supply of magnesium coming from China either stopped or substantially decreased due to the Chinese government's efforts to cut domestic power usage, creating an unprecedented global supply crisis. In Shanxi, a major magnesium producing region, was impacted by policies and industry maintenance; as a result, magnesium ingot production started to decline since August 2021. The gradual clarification of the double control policy of energy consumption, various localities have issued policies for high energy consumption industries, such as coal supply reduction, shutdown, and other policies (European Aluminium, 2021).

6.3.3 Logistics

Global trade of magnesium and Aluminium-Magnesium alloys is hundreds of thousands of tonnes, which is several orders of magnitude greater than trade in Scandium, Yttrium, and PGMs. Thus, the logistical aspects of the Magnesium value chain needs its own assessment.

The pandemic impacted metal production due to lock downs but only marginally. The pandemic-driven supply disruptions in metals were less than 2% for the full year of 2020 on our calculations. However, demand grew through the year due to the massive credit impulse unleashed by China during March 2021 through October 2021. Higher freight and shipping costs has been one of the main areas where supply chain constraints have hit the cost of production of the metals and mining companies (Sheet, Krause, & Khaliq, 2021).

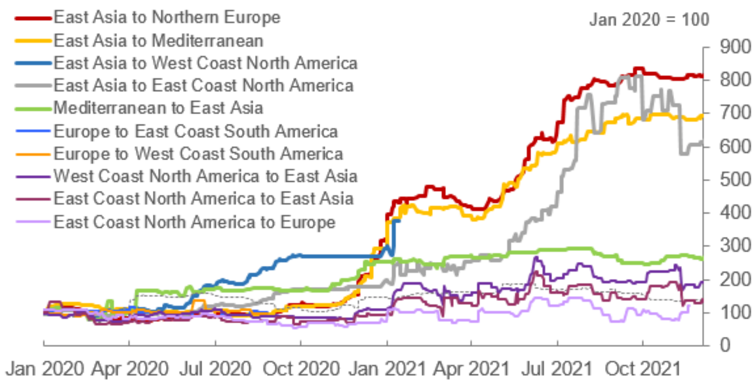


Figure 51: Index price of freight routes (Vehbi, Sengul, & Christen, 2022)

[20] The Corporate Average Fuel Economy (CAFE) standards are regulations in the United States.

Congestion at Asian ports was up 30% by the end 2021 and globally congestion is up 10% over the same period, with 37% of the global containership fleet waiting at dock in November 2021. Signs of congestion filter through the global supply chain in the form of higher rates. Ocean rates from Asia to Northern Europe or the Mediterranean are the first and third most impacted with an increase of 600% to 800%

Tianjin port is the major export port for magnesium and has been affected by COVID-19 indirectly as freighting was slowed. For single route between the port of Tianjin and Inner Mongolia, delivery costs have risen by around 20 yuan per tonne to 130-140 yuan ($20-22) per tonne in January 2022 (Zhang, Liu, & Zong, 2022)

To grasp the extent of the breakdown of supply chains, we can have a look at shipping companies. Container shipping pre-tax profit for 2021 and 2022 could be as high as $300 billion (Goodkind, 2021). In 2021, the industry was estimated to make $150 billion in profits while in 2020, the industry brought in $25.4 billion. This part of the value chain seems to be taking advantage the most from strong demand in ports bringing freight prices to new highs. This is because container and shipping line companies continue to charge fees as they wait to dock and leave port. Additionally, a greater demand for containers and shipment has led to rapid fee increases.

6.3.4 Trade Policies

No main magnesium producer or importer has set up a specific tax or tariff on that material outside of Russia. The countries with the highest import tariffs for Magnesium unwrought > 99.8% pure are Bahamas (40.2%), Bermuda (25%), Cayman Islands (22%), and Sudan (21.9%) according to the OEC institute (OEC, 2022)

In the EU, the regulation targets for magnesium, for which a 4% import tariff used to be in place has been suspended in 2021. Europe has tariffs, 4% on alloys, a free tariff quota of 120 000t and a quota on powder too (Tauber, 2022).

In the EU, the Council Regulation No 2402/98 of November 1998 imposed a definitive anti-dumping duty on imports of unwrought unalloyed magnesium originating from China. The regulation expired in 2010 when the domestic industry had gone extinct. Similarly, the US issued in 2005 an anti-Dumping order to the U.S. Customs and Border Protection. The product covered by the order is magnesium metal from China, which includes primary and secondary alloy magnesium metal, regardless of chemistry, raw material source, form, shape, or size. The USITC completed its sunset review of Pure Magnesium from China and ruled to continue the US antidumping duties at 141.49%.

6.4 Emerging changes to the value chain

The IEA estimates that the scaling up of green technologies necessary to meet the Paris Agreement goals would increase the global demand for magnesium by 21 times.

The global magnesium metal market is estimated to surpass US$ 6.5 billion by the end of 2027, in terms of revenue, growing at CAGR of 7.2% during the forecast period (2019 to 2027). More specifically, the magnesium alloys market will witness a CAGR of 11.68% for the forecast period of 2022-2029 and is expected to reach USD 4.25 billion by 2029 (Data Bridge, 2022).

This global increase in the magnesium market will inevitably come along with changes to its value chain.

6.4.1 E-mobility

Even though magnesium can reduce component weight by more than 60 %, its use is currently limited to less than 1 percent of the average vehicle by weight (US Energy Department).

As technologies using magnesium progress from research and development to market launch, possible new downstream demand can appear in addition to existing uses for the element. The ability to lighten aluminium products helps to improve mileage and efficiency, a particularly important element for fuel-efficient vehicles and EVs.

Moreover, rechargeable batteries based on magnesium, rather than lithium, have the potential to extend electric vehicle range by packing more energy into smaller batteries (Casey, 2021). Additionally, magnesium is substantially more abundant than lithium, allowing for the batteries to be cheaper and more sustainable. Cathode and electrolyte issues are yet to be solved for magnesium-ion batteries but are posed to be a ground-breaking technology potentially revolutionizing the vehicle industry (Shah, Mittal, & Matsil, 2021).

E-mobility in its broad sense could see the application of Mg alloys to produce weight, vibration and noise reduction, and improve running safety and higher energy efficiency for high-speed train. Meanwhile, there have been some indications of industry interest in using magnesium-alloyed aluminium in commercial aircraft designs.

6.4.2 Carbon intensity of the pidgeon process driving search for new production

China GHG decrease by 2030

In October 2021, China officially pledged for CO_2 emissions to peak before 2030 and to achieve carbon neutrality before 2060 by mainly reducing coal power consumption. With an aggressive policy it is even expected for China to achieve a 67% reduction in carbon intensity below 2005 levels by 2030 (Lui, 2021). One of the primary strategies the Chinese government uses to assist achieve its energy and climate goals is "dual control," which aims to lower energy intensity while also limiting total energy usage.

The dual control program has effectively created a "policy squeeze" against underperforming provinces, forcing them to use power rationing to fulfil dual-control objectives (Dong & Feng, 2021). Energy consumption management is now a high priority national campaign. This coincided with a recent wave of power outages that affected two-thirds of regions, which are thought to have been primarily caused by a shortage in coal supplies and added to their intensity and extent.

If we take the example of the magnesium sector, metal companies in Fugu County, Shanxi Province, suspended production for ten days in September 2021, resulting in a shortage of magnesium supply and higher prices on the world market (Xinhua, 2021). The aim of the suspension was to achieve energy savings and emissions reductions. Throughout the end of 2021, some energy-consuming companies, such as Fugu's magnesium smelters, had to curtail production to meet these goals. Because Fugu's magnesium industry is of global importance, a balance had to be struck between energy savings and production to ensure stability in the global supply chain while protecting the environment. Limiting production is said to be beneficial to the industry as a whole. In the long term, increasingly stringent environmental regulations are an incentive for energy-consuming companies to reduce pollution and make changes.

In China, the consolidation of the mining sector is continuing, the number of plants will be reduced, but producing plants will become bigger (EU Comission, 2020). New projects are under development, for instance Qinghai Salt Lake in China, 100 kt/y as first stage, is scaling-up its production slowly.

CBAM

The European Union has committed to become carbon neutral by 2050 with the help of different carbon regulations (EU ETS). However, carbon leakages through free allocation partially "mutes" the carbon price along the value chain, reducing incentives for the use of lower carbon alternatives. To combat this, the EU Commission has committed to implement a carbon border adjustment mechanism (CBAM), a mechanism that ensures that imported products sold to consumers face similar levels of carbon pricing in the European Union as similar domestic products (EU Commission, 2021). The CBAM charge would cover imports of these goods from all third country. The CBAM would initially apply to imports in five emissions-intensive sectors deemed at greater risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, and electricity. For now, magnesium is not included in the scheme, but its potential future inclusion may affect a very concentrated market.

According to the European Commission proposals, the CBAM will be introduced in 2023 in advance before becoming fully functional in 2026.

New interest in having Mg

On the supply side, leading players in the magnesium metal market, aside from China, are expected to continue expanding in the coming years including Brazil, Australia, the US and Turkey.

In Turkey, for example, the Esan site will initially have a production capacity of 15,000 megatons. However, according to the International Magnesium Association (Rossignol, 2022), production sites are expected to reach 30,000 to 45,000 megatons of capacity in the future. More reliable partners and domestic magnesium production will serve to stabilize the metal's supply and price. Nevertheless, this project is not without its challenges

The bulk of non-Chinese plants produce liquid magnesium from magnesium chloride via electrolytic processing. Magnesium may be found in seawater, salt, dolomite, magnesite, and carnallite. Despite being quite clean, electrolytic processing is often expensive. On average, the electrolytic process has a specific energy consumption less than half that of the typical China Pidgeon process plant (Baker, 2016).

Numerous projects attest the interest in magnesium development. For instance, the Austrian project on magnesite. The project goal is to reach 15% of European needs or 30 000t with the main issue being cost. The production is more expensive in Europe for magnesite. There exists also Tyrol Magnesia in Austria who built pilot plants for 20 years (10 000t) using fly ash tech. Overall, it is expected that global primary capacity will expand in line with over 42% of underutilised capacity in China and other Western smelters expanding capacity or creating new plants.

6.5 Upgrading the value chain

6.5.1 Value Proposition of the BIORECOVER project : enabling new, high-value products for magnesite mining

As with the other value chains analysed in this report, partners were invited to co-create a circular value proposition for the BIORECOVER technologies related to the Mg value chain. After several hours of discussion about the different facets of the technology and the way they can capture lost value in the Mg value chain partners synthesized their outputs into the following value proposition:

"BIORECOVER provides an innovative, cleaner, safer, and more sustainable source of CRMs. This low-cost solution uses bio-based technologies to recover many metals from waste streams, obtaining high added value elements at high purity from currently underexploited materials. Through collaboration, we generate new knowledge and economically viable solutions."

Several aspects of this value proposition are particularly key when thinking about how BIORECOVER can upgrade the Mg value chain. Key among these points is the ability to obtain **high added value elements**, and in particular pure Mg (either in metal or nanoparticle form). Conventional Magnesite mining to produce MgO is an industry that works to produce large quantities of relatively low value, bulk material. **If BIORECOVER can economically purify Mg from magnesite deposits this could unlock significant new markets for MgO producers and help them diversify their role in the value chain via product upgrading**.

At this point in the project, the optimum method for extracting and purifying Mg either in metal or nanoparticle form using BIORECOVER has not been established at lab scale. This has made it challenging to describe precisely the strategic route that should be taken to upscale the technology. The following analysis thus remains at a high level and assumes that project research will succeed in successfully recovering pure Mg from low grade ores at a commercially viable rate.

6.5.2 Strategically positioning the Biotechnologies: a complementary technology for Magnesia producers

In a second collaborative workshop with the key partner exploiting BIORECOVER for Mg recovery, Magnesitas Navarras (Magna), three scenarios for how BIORECOVER could impact the Mg value chain were considered as potential options.

The first involved BIORECOVER being used as a treatment process for waste rock from Magnesite mines, only after **mine closure**. This would entail BIORECOVER either reducing the cost of remediation or generating new revenue streams to cover the cost of mine closure.

The second scenario would be the deployment of BIORECOVER at active Magnesite mines, as a **parallel processing** route to the production processes for MgO. This would involve conventional, high-grade, magnesite being processed as normal via calcination. Meanwhile lower grade Magnesite could be treated with BIORECOVER to extract additional value by producing pure Mg as a by-product.

The final scenario would involve Magnesite miners such as Magna entirely **shifting their business model** away from MgO production and towards the production of pure Mg via BIORECOVER.

Ultimately, it was decided that the most viable path for BIORECOVER to enter the Mg value chain was the second scenario, where the **project's results could be used as a complementary processing route for low grade magnesite, alongside conventional processes to produce MgO.**

This approach was considered optimal for several reasons. Magnesite mines produce significant quantities of low grade, ores that can serve as a feedstock for BIORECOVER during the life of mine, and don't necessitate waiting until mine closure. However, given the factors analyzed throughout this chapter, it will be challenging for pure Mg produced from Magnesite to be cost competitive with Chinese Mg. Moreover, MgO producers have major fixed capital investments, as well as long term clients and business relationships that would be costly to abandon if they shifted their production entirely to a different commodity (pure Mg). Thus, producing Mg as a by-product of MgO production was considered the most viable route to generate additional value using project results.

6.5.3 Upgrading Mg Exploration and Process Design

The BIORECOVER process would have little impact on exploration. Conventional assaying done at Magnesite mines should be sufficient to design a bioleaching process flow for a given mine. The data produced within the project related to low grade ores at Magna's operation would be sufficient to upscale the process at an initial site.

With respect process design, project coordinator **CETIM** will have a key role in providing the scientific knowledge to tailor bioleaching to a specific orebody. Meanwhile, **Tecnicas Reunidas** experience designing and building out industrial facilities also makes them a key partner in implementing a bioleaching process at scale.

6.5.4 Upgrading Mg extraction

To date the optimum method for extracting Mg from low grade ores has not been established by the project. Yet initial research with numerous bacteria strains have demonstrated effectiveness at removing iron and silicon from low grade ores, and at leaching high rates of Mg from the ore.

As research continues to advance, several factors will be key in justifying BIORECOVER's capacity to add value at the extraction stage in the Mg value chain.

Key among these will be **the environmental impact of the BIORECOVER process**. As governments around the globe, and particular the EU, ramp up their decarbonization targets, it will become increasingly essential for Mg producers to have a low emission production technology. The very high carbon and energy intensity of the pidgeon process makes it poorly suited to the broader environmental transition. Therefore, if BIORECOVER can demonstrate a capacity to extract Mg from ores with limited CO_2 emissions it is well placed to garner interest from mining companies looking to position themselves towards a sustainable future.

Economic factors will also be key in determining BIORECOVER's ability to upgrade Mg extraction. Since the bioleaching process is targeted towards low grade ores, it will be challenging for the sale of Mg to cover the cost of the process. Designing the bioleaching process so that it requires minimal CAPEX and OPEX will thus be a key driver of its viability. In this case, heap bioleaching offers one potential model that could be pursued for upscaled extraction using BIORECOVER, because of the minimal investments required to build and operate this production route.

6.5.5 Upgrading Mg Processing

At the time of this deliverable's submission, a final and optimal method to refine pure Mg metal from BIORECOVER has not been determined. Once a bio leachate has been produced, with minimal interfering compounds such as silicone and aluminum, several conventional routes are available to recover pure Mg.

The first of these would be **electrolysis** of Mg metal from a leachate. Electrolysis is a widely used technique for refining numerous industrial metals and was the dominant form of Mg production globally before the emergence of the pidgeon process in Chinese refineries during the 1990s (EU Comission, 2020). It involves the passage of an electrical current through an electrolyte to facilitate the decomposition of Mg compounds into pure metal, which can be commercialized as Mg ingots.

Another route being considered for the purification of Mg is **carbon reduction**. This involves heating Mg compounds in the presence of carbon to facilitate the decomposition of the compound into pure Mg and CO. This process could be used to produce pure Mg nanoparticles in powder form.

6.5.6 Upgrading downstream Mg manufacturing

The final efficiency of the BIORECOVER process will of course determine its capacity to increase European supply of Mg. If high recovery rates are achieved, Magna estimates that its low-grade ores alone, which are currently treated as waste rock, could supply between **fifteen and thirty thousand tons of Mg per year**. Based on EU consumption figures in 2018 (EU Comission, 2020), this represents roughly **8-16% of total EU Mg demand**.

The industrial application of Mg will depend on the form it is refined into, and whether it is commercialized as ingots or powder. All commercial applications will require the BIORECOVER process to produce a high purity Mg product (99,9%) with minimal manganese and silicon impurities. Magna has existing transportation infrastructure in place to handle the logistics of its MgO business, which could effectively operate to transport refined Mg as well.

Given that the largest application of Mg metal is in the form of aluminum alloys, it could be interesting for commercial arrangements to be explored between magnesite and bauxite miners in Europe, such as Magna and Mytilineos. If Magna is able to produce a consistent supply of Mg metal, Mytilineos expertise in the lightweight cast alloy industry, and existing business relationships within that sector, could prove a valuable distribution channel to scale up European Mg supply. However, at this stage in the project, it remains too early to determine if commercial partnerships should be pursued since technical results would first be needed.

6.6 Overall Impact of the BIORECOVER technologies on Mg

This section has explored the Mg value chain to understand how BIORECOVER could create added value for the European Mg industry. It's been argued that ultimately BIORECOVER could offer a supplemental form of revenue to magnesite miners in Europe, who would be able to add Mg production alongside their existing MgO offer. If the BIORECOVER project can demonstrate that pure Mg can be recovered from low grade magnesite ores, it could offer a major resource to European industry, which is currently highly dependent on carbon intensive Mg imports from China. The sustainable transition is expected to simultaneously drive demand growth for Mg as an enabler of e-mobility, while also requiring producers to identify more sustainable production methods than the pidgeon process. This presents a major commercial opportunity for the project if it can demonstrate viable Mg recovery pathways.

7 CONCLUSIONS AND RECOMMENDATIONS FOR STRATEGICALLY POSITIONING THE BIORECOVER TECHNOLOGY

7.1 Technological advances to the new PGM & REE value chains

7.1.1 Technological advantages

The technological advantages offered by BIORECOVER are to be found in its use of Biotechnologies. Biotechnology could provide innovative alternatives for metal recovery and production as Micro-organisms can be used to concentrate or separate wanted elements. As more easily recoverable high-grade South African PGM-reserves face depletion, new resources (i.e. residues) are to be exploited using viable and innovative means. Concurrently, the absence of large-scale reuse of bauxite residues despite being both a source of useful metals and a potential ecological threat exhorts to technological innovations.

BIORECOVER is developing different protocols that are providing solutions to above listed issues. More specifically, improved biomining techniques will improve metal leaching results, the use of bio absorbent agents will enhance the toxic element removal processes while allowing for better concentration of targeted metals thanks to genomic innovations.

Those innovations cannot be only compared to traditional techniques on specific metal recovery metrics but also need be seen as important ecological improvements for the sector.

7.1.2 Environmental advantages

Environmental advantages first concern the very operation scope in which BIORECOVER is expected to be used. Indeed, the main environmental advantage provided by BIORECOVER is its valorisation of waste and especially toxic mine residues as well as other processing scenarios that minimise the water consumption and wastewater generation to achieve a zero liquid discharge (ZLD).

Traditional mining techniques of pyro and hydrometallurgy used by the mining sector are among the most energy intensive activities. BIORECOVER is providing alternative options that allow for lower energy consumption while implementing circular economy models. BIORECOVER thus promotes efficiency, so to allow for a double advantage both environmental and also economical.

7.2 Building new Economic Models

7.2.1 Transforming value negative materials into revenue streams

Reprocessing of Bauxite Residues & PGM low grade ores

Reprocessing mining waste, such as Bauxite residues and PGM low grade ores, can enable save costs for disposal waste. Moreover, the reprocessing can generate additional value while contributing to the environmental remediation of the mine site.

Moreover, in the case of reprocessing Bauxite Residues, the remaining waste can be used as a cement for the construction industry.

Reprocessing industrial waste streams for PGM

Reprocessing a diversity of feedstocks produced as by-products when consumer or industrial products containing PGMs would mean that the technology would have to extract enough PGMs from the feedstocks to justify the cost of deploying them.

7.2.2 Building a new REE value chain vs reinforcing existing PGM value chain

Partnerships could be built to foster circular economy, while marketing a technology from the mine to the metal recovery.

Diversification of partnerships is important to reduce supply risk of critical raw materials, and secondary resources constitute an opportunity.

Eco-design constitutes an important long-term perspective of the value chain of BIORECOVER: catalysts, brake pads, … could be designed to be remanufactured, and processes should be designed to make sure the maximum of resources can be extracted.

Cross-industrials partnerships among the aluminium, rare earths, and construction industry

There is a need to build a strong partnership between the alumina/aluminium industry and the rare earths industry in order to secure flows of bauxite residues & their valorisation into rare earth metals. Technical parameters need to be taken into account in order to deliver the right quality.

Moreover, the construction industry could also benefit from a partnership with the alumina/aluminium industry, as the processing of bauxite residues could be valorised as a cement for the construction industry.

As quantities of bauxite residues would be important, having local players could be of tremendous help to generate a rare earths concentrate and a cement for the industry.

Partnerships within the same industry (closed loop)

Having a closed loop partnership will be easier since stakeholders already know each other and can have access to all flows.

7.3 Creating stability of supply

7.3.1 Need to work directly with clients to produce niche materials directly tailored to their needs – Yttrium and Scandium

While aiming at bringing closer home the value chains of strategic industrial metals, BIORECOVER also aims at developing on European soil new value chains for certain metals like Yttrium and Scandium.

Some minerals are facing low use despite high potential due to a mismatch between demand and supply of said minerals. BIORECOVER being a project build around different industrial partners has the ability to push forward a targeted and tailored supply to satisfy their needs and break the so called " chicken egg" problem where low demand implies low supply and vice versa, hence hindering the use of the target element (i.e., Scandium) that could lead to further industrial innovations .

7.3.2 Less dependence towards other countries

BIORECOVER will help to reduce the import dependence by exploitation of alternative EU resources, improving the resource efficiency and supply.

In fact, according to the DOA, the project objective is to unlock unexploited ore reserves: 863 t/yr. of REEs from BR, 69,000 t/yr. of Mg and 3.3 t/yr. of PGM from scrap metals, which will allow to reduce the dependency of EU from critical raw materials importations by promoting sustainable self-production (Biorecover, 2018). A lower dependence of Europe regarding critical raw materials implies being less economically vulnerable when highly stretched supply chains get disrupted and avoiding diplomatic and strategic complications when over reliant on specific countries.

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