ION4RAW

Research and Innovation Action (RIA)

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Market analysis final report: trends in applications using materials targeted by Ion4Raw processand assessment of the process impact on EU supply criticality

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Summary

This report represents a final market analysis for the EU Research and Innovation project, ION4RAW. The innovations developed by the project aim to recover by-product metals in an integrated iono-metallurgical processing circuit. The five metals that are targeted for recovery as co-products using the ION4RAW technology are antimony, bismuth, indium, silver, and tellurium, which can be sourced from sulphide minerals extracted at copper and gold mines. The report presents a global analysis of the sectorial demand for the target metals, as well as the factors expected to drive future growth in their demand. The market for each individual metal is also considered in the analysis. The report also seeks to chart a path to market for the ION4RAW process by analysing its potential impact on the European metal supply. An analysis is presented of the major economic factors influencing by-product metal supply. This is complemented by cartographic work using data regarding known deposits of target metals to identify all active mines in Europe that may have the potential for by-product recovery due to their proximity to a deposit. The final chapter of the report builds upon interviews with experts in the mining industry to propose a strategic path to bringing ION4RAW to market. Three technical exploitation scenarios are laid out, which would allow ION4RAW to recover by-product metals alongside standard processing routes for recovering more valuable main metals such as copper or gold. The report also lists all candidate mines for adopting the technology according to several strategic criteria.

Approval

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ION4RAW: Ionometallurgy of primary sources for an enhanced raw materials recovery

Project type:	Research and Innovation Action
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D7.3 – Market Analysis Final Report

WP n° and title	WP7 – Sustainability assessment and exploitation
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EXECUTIVE SUMMARY

This report represents a final market analysis for the EU Research and Innovation project, ION4RAW. The innovations developed by the project aim to recover by-product metals in an integrated iono-metallurgical processing circuit. The five metals that are targeted for recovery as co-products using the ION4RAW technology are **antimony, bismuth, indium, silver, and tellurium**, which can be sourced from sulphide minerals extracted at **copper and gold** mines. The report presents a global analysis of the sectorial demand for the target metals, as well as the factors expected to drive future growth in their demand. The market for each individual metal is also considered in the analysis. An overview of **current and future sectorial demand** for the target metals is summarised below.

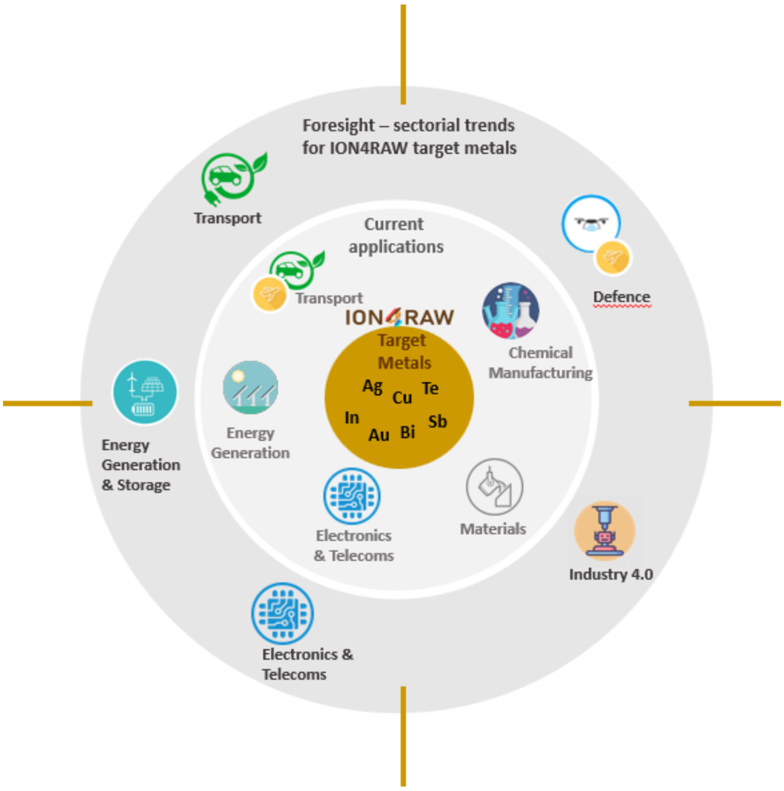

Figure 1. Overview of current and future sectorial demand

The report also seeks to chart a **path to market for the ION4RAW process** by analysing its potential impact on the European metal supply. An analysis is presented of the major economic factors influencing by-product metal supply. This is complemented by **cartographic work using data regarding known deposits of target metals to identify all active mines** in Europe that may have the potential for by-product recovery due to their proximity to a deposit.

The final chapter of the report builds upon interviews with experts in the mining industry to propose a strategic path to bringing ION4RAW to market. **Three technical exploitation scenarios** are laid out, which would allow ION4RAW to recover by-product metals alongside standard processing routes for recovering more valuable main metals such as copper or gold. The report also lists all **candidate mines for adopting the technology** according to several strategic criteria. At this stage in the Project, **active copper, gold and silver mines** with **complex ore bodies** and **high rates of production** and a record of **Environmental, Social and Governance** performance are considered the most viable candidates for by-product recovery using ION4RAW.

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KEYWORDS

Critical raw materials, market analysis, mining, by-product, technology, applications

ABBREVIATIONS

APR	Ammonium Perrhenate
ATO	Antimony trioxide
CdTe	Cadmium-Telluride
CZT	Cadmium-Zinc-Telluride
CIS	Copper Indium diSelenide
CIGS	Copper Indium Gallium diSelenide
CRM	Critical Raw Material
DES	Deep Eutectic Solvent
EI	Economic Importance
EU	European Union
EV	Electric Vehicles
FPD	Flat Panel Displays
GA	Grant Agreement
GDP	Gross Domestic Product
ICT	Information and Communications Technology
ITO	Indium Tin Oxide
LED	Light Emitting Diodes
LCD	Liquid Crystal Display
MCT	Mercury-Cadmium-Telluride
Partners	
BRGM	Bureau de Recherches Géologiques et Minières
LGI	LGI Sustainable Innovation
PET	Polyethylene Terephthalate
OECD	Organisation for Economic Co-operation and Development
Target Metals	
Ag	Silver
Au	Gold
Bi	Bismuth
Cu	Copper
In	Indium
Sb	Antimony
Te	Tellurium
SR	Supply Risk
TIM	Thermal Interface Material
TCO	Transparent Conductive Oxide
TMO	Technical Molybdenum Oxide MoO_3
TRL	Technical Readiness Level
PET	Polyethylene Terephthalate
PV	Photovoltaics
PGM	Platinum Group Metal
Project	The ION4RAW Project
USGS	United States Geological Survey
WP	Work Package

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1 INTRODUCTION

Raw materials are the physical foundation of the global economy, and yet extractive industries also contribute to numerous intersecting environmental crises unfolding across the planet (The Guardian, 2019). Ensuring a supply of raw materials that is both secure and sustainable is thus key to achieving Europe's economic and environmental ambitions. However, Europe is currently highly dependent on imports to obtain many of the raw materials used across all sectors of its economy. In particular, the global supply of many minor metals used in rapidly expanding technologies (such as renewable energy and e-mobility) is highly concentrated in countries with politically unstable and/or authoritarian governments.

The European Commission has responded to this challenge since 2008 via the "Raw Materials Initiative". The initiative emphasises three pillars and seeks to ensure: 1. A fair and sustainable supply of raw materials from global markets; 2. Sustainable supply of raw materials within the EU; 3. Resource efficiency and supply of 'secondary raw materials' through recycling (European Commission, 2008). The ION4RAW Project (Project) is working to develop novel mineral processing technology in response to this three-part ambition by developing a sustainable processing technology that could recover by-product metals that are currently not valorised, both in the EU and globally. This report will provide an overview of the market for the ION4RAW technology and begin charting a path to introduce the novel technology in the European market.

1.1 The ION4RAW Project

The ION4RAW Project is dedicated to developing a cost-effective and environmentally friendly mineral processing technology to recover by-product metals from primary sources. The project proposes to use novel deep eutectic solvents (DES) to leach and jointly recover by-product metals alongside primary metals belonging to the Cu-Ag-Au deposits. Most of the targeted by-product elements are defined by the European commission as Critical Raw Materials, including bismuth (Bi), indium (In), and antimony (Sb). The project is also working to ensure that it fits within a system capable of recovering major product metals, notably copper (Cu), silver (Ag) and gold (Au). Other non-critical by-product metals may also be recovered, including tellurium (Te).

The Project runs for four years and involves thirteen partners from six countries across the European Union as well as the United Kingdom and Peru. The consortium brings expertise spanning technical research institutes and universities, companies from the mining sector and consultancies.

1.2 Deliverable Objectives

This deliverable falls within Work Package 7 (WP7) of the Project, which focuses on the Sustainability Assessment and Exploitation of the Project. The ambition of the Market Assessment task is, therefore, to strategically position the results of the Project within the metallurgical market such that the technology can best be exploited by project partners in a sustainable and economically viable way after the Project concludes.

1.2.1 Task overview

In keeping with its ambitions of boosting the sustainable exploitation of project results, this market assessment has two major goals.

Firstly, the task **assesses the demand for the raw materials** that can be produced using the Project's iono-metallurgy. This entails a global assessment of the major factors that influence demand for these raw materials, including their price trends and substitutability. Drawing upon previous work done to

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explore demand trends of CRMs in Europe (Monnet, 2018) (Bobba, 2020), a focus is also placed on how target metals are used within rapidly emerging technologies driven by strong social, economic, and political headwinds. For each of the Project's potential target metals, an individual assessment is provided to offer a summary of the current demand for the metal and strategic considerations in applying the ION4RAW technology for its recovery.

Secondly, the task **explores the potential of ION4RAW to boost the EU supply of target metals**. Since most target metals are currently produced as by-products during the processing of bulk metals, the most viable path to increasing their production in the near term is to increase their rate of recovery from active mines. As such, there is a focus on identifying the most promising active mines in the European Economic Area that are likely to be able to recover target metals from their ores. This task is realised in parallel to an "Assessment of selected critical raw material potential in Europe" (D2.1) and draws upon data produced by BRGM in their predictive study applied to the European database for the target metals.

The results of the task are presented in two separate reports, an intermediate and a final market analysis. The ambition is that the two reports build upon one another. The **intermediate report** (D7.2) was more global in scope and aimed to provide a *general overview of the market for all possible metals* that could be recovered using the ION4RAW technology.

This report is the **final report** (D7.3) that builds upon D7.2 through consultation with experts working in the metallurgy sector to provide a more targeted assessment of the strategic considerations necessary for successfully bringing project results to market. Since this report is arriving at a stage in the project when the technical performance of the DES has been more established, its focus is narrowed to the five metals with the highest rate of recovery by the process, as well as gold and copper, which are the primary metals driving extraction of the five other metals.

1.2.2 Target metals for this analysis

Seven target metals are considered in this market analysis report: **Sb, Bi, In, Te, Ag, Au, and Cu.**

The decision to target these specific metals, which occur in sulfidic ores, was confirmed with all partners of the project during a General Assembly meeting and is based on research at a lab scale indicating that they can be solubilised by DES, leaving behind their insoluble accompanying gangue material. This has a notable economic potential to improve the rate of recovery of these metals, many of which are considered by-product metals and are currently very often lost to tailings or during refining in conventional mineral processing systems.

As the ION4RAW project has advanced the TRL of its iono-metallurgical technology, it has become more apparent which of the original thirteen metals considered at the onset of the project are most amenable to full-scale production using DES leaching and recovery. Therefore cobalt, germanium, molybdenum, platinum, rhenium, and selenium have been dropped from this second market analysis since their recovery rates were not significant. The ultimate commercial viability of the ION4RAW process will depend largely on technical performance metrics (e.g., rate of recovery, rate of purity) and economic factors (e.g. cost of materials, energy requirements, solubility time). These factors will be fully covered in Task 7.3 and Task 7.4 of the project, and an initial approach to aligning across these tasks based on feasible "exploitation scenarios" is put forward in section 4 of this report.

All of the target metals have been considered as part of the European Commission's assessment of **Critical Raw Materials** (CRM). The assessment ranked these materials according to two criteria:

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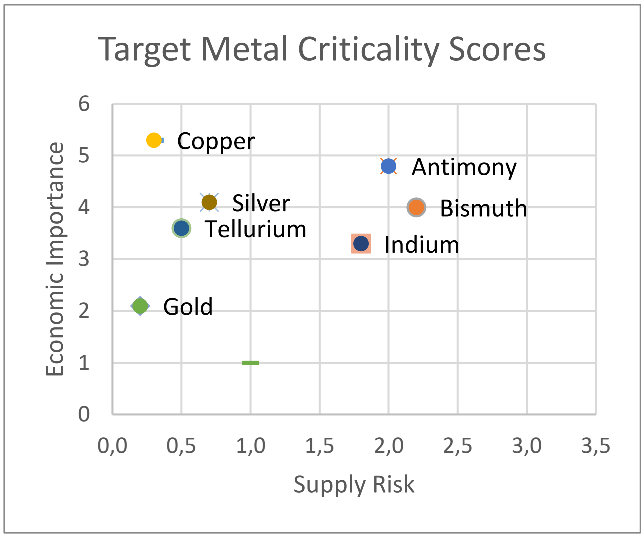
- **Economic Importance (EI):** determined according to the end-use application of raw materials and the value-added for the EU industry. The ability to substitute a given raw material in its applications was also assessed.
- **Supply Risk (SR):** determined according to the likelihood of EU supply disruptions. This considered the concentration of supply across the production value chain, with a specific focus on the EU's import reliance from different countries while accounting for their governance and trade factors.

Figure 2 provides an overview of the target metals and their criticality scores as defined by the EU in 2020. The list of CRM is updated regularly by the EC and reflects Europe's geostrategic considerations, making it unique from the raw materials considered critical by other countries such as the US.



Raw Material	Supply Risk	Economic Importance	Criticality
Antimony	2,0	4,8	CRM
Bismuth	2,2	4,0	CRM
Indium	1,8	3,3	CRM
Gold	0,2	2,1	Non-critical
Copper	0,3	5,3	Non-critical
Silver	0,7	4,1	Non-critical
Tellurium	0,5	3,6	Non-critical

Figure 2. Overview of the Target Metals and their EU Criticality Scores

1.3 Methodology and limits of data

This report seeks to build upon existing work done in European projects related to CRMs and the SCRREEN expert network in order to provide a focused analysis of the seven metals targeted for recovery using the ION4RAW technology.

Two reports published by the Commission, the "*Report on major trends affecting future demand for critical raw materials*" (Monnet, 2018) and "*Critical Raw Materials for Strategic Technologies and Sectors in the EU – A Foresight Study*" (Bobba, 2020) helped to inform and frame this report's assessment of current and future demand for target metals. Both reports adopt an approach to demand forecasting that considers the **strategic sectors** of the European economy where there is expected to be a significant need for CRMs in the upcoming decades. Each report also identifies individual technologies where innovation is expected to occur, which are expected to drive the macro-level change taking place across these strategic sectors.

Economic theory produced by the World Bank is also drawn upon in Section 2 of this report to assess how ION4RAW's target metals and technology will respond to the macro-level factors that influence metal supply and demand. In this way, section 2 seeks to provide a general overview of the market size and structural factors affecting all target metals. Inspired by this research, section 2.1 of this report categorises the target metals' current and future demand according to end-use applications and the sectors that the metals are applied. Section 2.2 meanwhile looks at ION4RAW's ability to influence the supply of its target metals.

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Section 3 of the report then seeks to provide a tailored assessment of the market for each target metal. Here, the Mineral Commodities Summary from USGS and European Commission **Raw Materials factsheets** from 2020 are drawn upon to provide information regarding the current European demand, supply, and market conditions for each of the individual metals. This is complemented by a cartographic assessment of the by-product supply potential for each of the metals in Europe.

Initially, this task had envisioned assessing how the ION4RAW technology could bolster the European supply of target metals and the impact this would have on the **criticality scores** for all concerned metals. However, it became apparent that there is currently no comprehensive data regarding the size of Europe's geological reserves for many of the metals targeted by ION4RAW. Moreover, the ability of ION4RAW's novel technology to improve European by-product metal supply will be dependent on numerous economic variables, including mineral grade and production cost, which are variable and may not yet be determined at this stage of technological advancement.

Therefore, the current, **more tailored approach to assessing ION4RAW's impact on EU metal supply** was proposed. To identify candidates for implementing the Project's iono-metallurgical technology, geographic data regarding all known deposits of target metals was provided by BRGM. This data was then crossed by LGI with the geolocation of all known mines in Europe, drawn from a dataset published by the United States Geological Survey (USGS). Spatial queries were then performed to locate all active mines in the European Economic Area and the United Kingdom that are located within 50 km of a known deposit of a target metal.

Since the Project targets metals from **sulphide ores**, only mines producing copper, gold, silver, lead, or zinc were considered for this analysis. Because the USGS dataset was published in 2007, an extensive process of cleaning and updating the data regarding active European mines was required. The USGS dataset was then supplemented with data concerning active EU mines sourced from S&P Global. Yet despite the authors' best efforts, certain mines listed as candidates for exploiting ION4RAW's process may no longer be active, and other European mines that were opened after 2007 may be overlooked.

Section 4 of the market analysis seeks to develop the path to market for the ION4RAW project results and feed into work carried out as part of WP7 on both technical and economic exploitation of results. In this final report, D7.3, an initial **overview of all identified mining candidates** for expanding the technology in Europe is presented. This is accompanied by strategic recommendations to help ION4RAW reach the European market. These recommendations are based on the results of interviews conducted with technical experts in the mining industry, listed in the annex.

The research in this report informed the design of three "exploitation pathways", which are scenarios for the deployment of ION4RAW presented in Section 4, that will be elaborated in tasks 7.3 Roadmap and technical recommendations, 7.4 Economic assessment and sensitivity analysis and 7.6 Exploitation plan, to establish the most suitable way to upscale project results in a technically and economically viable manner. Each of these scenarios has the potential to offer value to European industry but also faces commercial barriers, which are detailed in Section 4.

2 Global Overview of Supply and Demand Trends for Target Metals

2.1 Global Determinates of Demand for Target Metals

The world's demand for metal has been consistently growing alongside total economic output and population since the industrial revolution. The Organisation for Economic Co-operation and Development (OECD) projects that this steady growth in demand will continue and that by 2060 the world will use 19 Gt of metal annually (up from 7 Gt in 2011) (OECD, 2018).

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While this rapid growth in overall metal demand is expected to be particularly driven by countries with developing economies, largely due to their high rates of population and Gross Domestic Product (GDP) growth, OECD member countries are also expected to see a 1,5X increase in total demand for metal between 2017 and 2060. Yet not all target metals will see the same growth in demand. Instead, demand for certain metals is expected to increase dramatically while demand for other metals may stagnate due to changing structural factors.

Considering the World Bank's list of seven major determinants of demand for mineral products can help to clarify the varied ways in which demand is expected to change for the 7 metals targeted by the ION4RAW process.

2.1.1 Economic Growth and Key Sectors of Current Demand

Income and economic activity are the first determinants of demand. Mineral products are most often consumed as intermediate products used to produce consumer goods. Therefore, changes in demand for consumer goods will also change the direct demand for mineral products, including the project's 7 target metals. Based on the European Union's average rate of GDP growth between 1971 and 2019, which was 2.19% (The World Bank, 2020), it can be assumed that despite the current recession induced by the Covid-19 crisis, on average in the medium to long term, European economic activity will continue to grow, leading to an overall increase in demand for raw materials.

The metals targeted by ION4RAW are currently used in numerous products across the EU economy. An analysis of the leading economic sectors with demand for each metal produced five major sectorial categories driving the current market for the target metals: **energy generation, transport, chemical manufacturing, electronics and telecoms, and materials**. Within each of these sectors, several consumer products are included, which can be seen in Figure 3.

	Energy Generation		Transport			Chemical Manufacturing				Electronics & Telecoms			Materials				
	Solar Panels	Thermoelectric devices	Auto-catalyst	Batteries	Auto & Aerospace	Chemical	Catalyst	Paints & Pigments	Medical & Bio	Wiring	Displays	Electronics	Alloys	Coins & Jewellery	Glass & Ceramics	Metallurgy	Petrol. Deriv.
Antimony				x	x	x	x	x	x	x		x	x		x	x	x
Bismuth						x		x	x				x			x	
Indium	x	x		x						x	x		x				
Tellurium	x	x				x										x	
Copper	x	x		x	x	x				x		x	x	x		x	
Gold			x		x	x			x	x		x		x			
Silver	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x

Figure 3. Current major applications for the ION4RAW target metals

2.1.2 Price of Target Metals

The price of the mineral product is the second major determinant of its demand. Generally, as the price increases, demand for a given metal decreases. This is because consumers will demand less of higher-priced goods containing the more expensive metal, and producers will look to reduce or substitute higher-priced metals where possible.

However, as indicated in Figure 4, the price elasticity of demand for metals varies according to different timescales. In the very short term, the fixed costs of production systems and barriers to changing

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existing technologies tend to lock in demand, meaning that major fluctuations in price can have little impact on the quantity of a metal that is demanded. Over the very long term, however, manufacturers will push to substitute or reduce higher-priced metals, leading to higher price elasticity of demand.

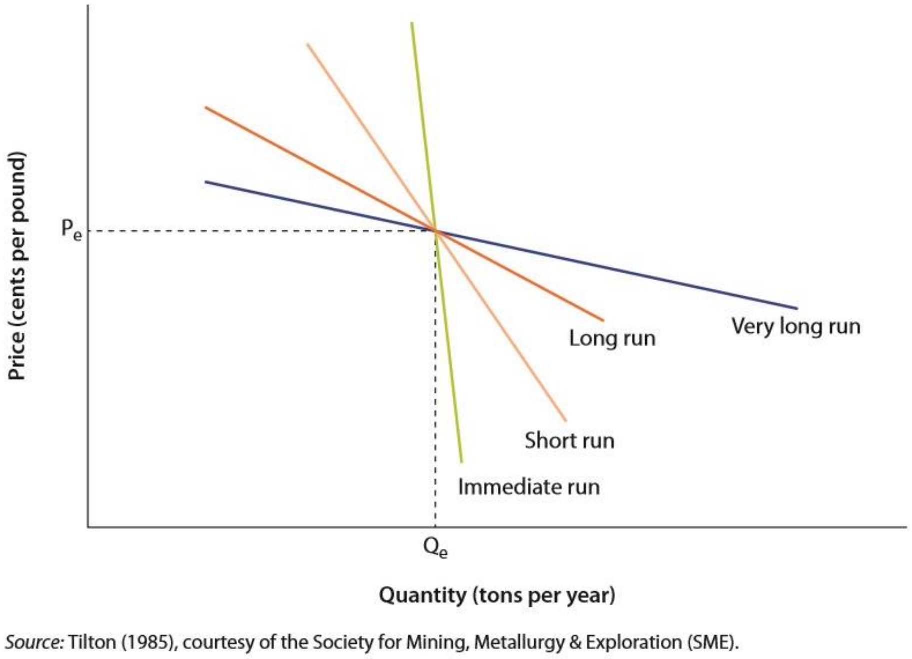

Figure 4. Illustrative Demand Curves in the Immediate, Short, Long and Very Long Run, reproduced under Creative Commons Attribution 3.0 IGO license (Halland, Lokanc, & Nair, 2015).

Given the time it takes for demand to respond to changes in price, this report will base its analysis of metal prices over 5-year periods. An overview of the price in USD per Kg of the Project's target metals is available in Table 1 and Figure 5.

Table 1. Recent Global Prices for Target Metals (in USD/ KG) (USGS, 2022)

Raw Material	2018	2019	2020	2021	2022
Antimony	8,382	6,688	5,874	11,682	13,86
Bismuth	10,142	6,996	5,984	8,228	8,58
Copper*	6,512	5,984	6,1556	9,284	8,8
Gold	40894,8	44849,25	57034,1	57902,15	57870
Indium**	281	177	158	217	250
Silver	505,7195	522,116	661,647	811,1445	675,15
Tellurium	73,67	60,45	56,05	67,26	66

**Price at London Metal Exchange, **Price at Rotterdam Warehouse*

As can be seen in Figure 5, which presents the USGS price data, there is a tremendous range of values for the metals targeted by the Project. The recent price value of the metals can be considered according to price ranges of three different orders of magnitude, with highly precious target metals

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(Au) at the upper end, semi-precious metals (In, Ag, Te) in a middle price range, and non-precious metals (Sb, Bi, Cu) priced well under 20$ per Kg. The high volatility in the price for several metals constrained by unstable supply chains is particularly notable.

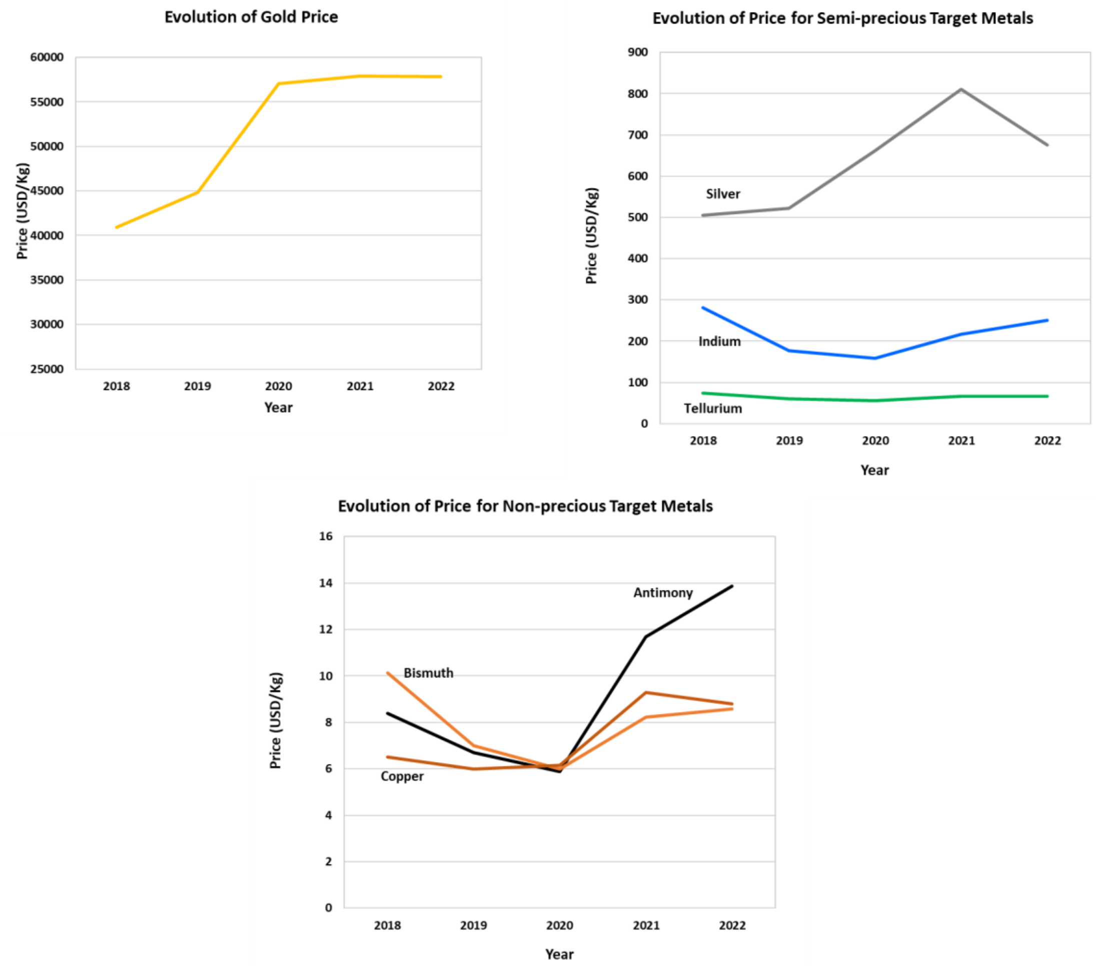

Figure 5. Evolution of Price between 2018-2022 for ION4RAW target metals (USGS, 2023)

The *price of substitutes* is the third major determinant of demand for a given metal. Since most metals used as intermediate products compete with other materials that can fulfil similar properties, a drop-in substitute material price will lead to a decrease in the demand for the metal in question. For instance, there is a strongly established relationship between copper and aluminium demand since these two metals compete for usage in pipe manufacturing. However, one of the peculiarities about many of the seven target metals in question, particularly the CRMs, is the inability or difficulty to find adequate substitutes for many of their functions.

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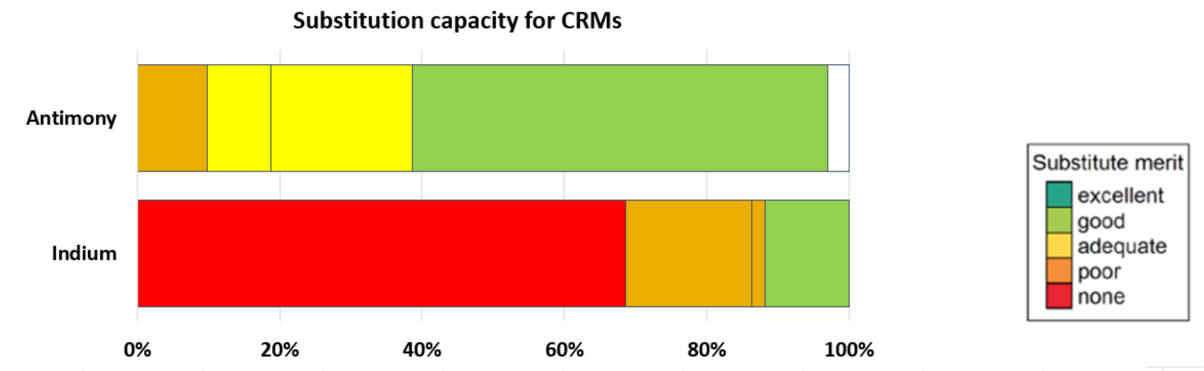

Figure 6. Substitution capacity for the CRMs examined in ION4RAW and in SCRREEN D5.1

The price of complements is the fourth key determinant of mineral resource demand. In certain cases, a decrease in the cost of a complementary material that is commonly used alongside a particular metal will drive an increase in demand for that metal. For instance, a decrease in the price of Iron will drive increased demand for steel and, consequently, an increase in demand for metals that are often alloyed with steel (including Bi and Cu). Thus, when assessing demand for a given target metal, the major uses of that element will be listed to indicate how demand could evolve in correlation with accompanying metals.

2.1.3 Emerging Technologies as Drivers of Demand Growth

Technology is the fifth global criterion influencing demand for metal. Innovation and technological change can influence demand in several ways. Notably, as technology improves, there is a tendency towards increased efficiency of material use. According to the OECD, this trend is expected to accelerate in the upcoming decades, leading to a decreased material intensity of the global economy and partially offsetting the increased demand for metal from economic growth. However, the decoupling of economic growth and material usage will not be complete (OECD, 2019).

In fact, the emergence of new technologies often drives rapid increases in demand for mineral products. This is expected to be the case for the ION4RAW target metals, all of which are currently used in one or various emerging technologies that are at the core of Europe's ambitions to decarbonise its economy and spark a 4th industrial revolution. These rapidly emerging technologies with demand for the Project's target elements have been divided into five categories: **energy generation & storage, transport, electronics & telecoms, industry 4.0, and defense**. An overview of which target metals are foreseen to be used by these strategic and emerging fields of technology can be seen in Figure 7 and Table 2 (Bobba, 2020).

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	Energy Generation & Storage	Transport	Electronics & Telecoms	Industry 4.0	Defence
Antimony		X	X	X	X
Bismuth			X	X	X
Indium	X		X	X	X
Tellurium	X			X	X
Copper	X	X	X	X	X
Gold	X	X	X	X	X
Silver	X	X	X	X	X

Figure 7. Overview of foreseen sectorial applications for the ION4RAW target metals

Table 2 below elaborates on the specific uses of each target metal within these strategic sectors for the European economy. As the technologies listed below continue to scale up, the material composition of dominant technologies may evolve rapidly, which is likely to lead to fluctuations in demand for target metals.

Table 2. List of foreseen target metal uses for major sectors and applications

Sector	Application	Target Metals Used
Energy generation and Storage	**Wind turbine**	**Cu**: widely used in generator windings, cables, inverters, control systems
	Solar PV	**Ag:** as a conductive paste on the front and back side of[i] the crystalline solar cells **Cu:** highly used for wires, cables, inverters, also in CIGS technology **In:** as ITO conductive layer or in CIGS technology **Te:** in thin-film cadmium telluride (CdTe) based PV technology
	Fuel Cells	**Ag:** alternative cathode to Platinum **Au:** used as a coating for bi-polar plates **Cu:** in alloys with Ni for anode catalyst, in wires and conductive parts
	Li-ion Batteries	**Cu:** as current collector foil at the anode side, in wires and other conductive parts

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Sector	Application	Target Metals Used
Electronics and Telecoms	**Smartphones & computers**	**Ag**: soldering and brazing alloys, electrical contacts and printed circuit boards **Au:** connectors, switches, relay contacts, solder joints, connection wires and strips, memory chips and circuit boards **Cu:** main conductor in electronics, connectors, printed circuits, wiring, contacts, integrated circuits, semi-conductors, etc. **In:** in screens as indium-tin-oxide **Bi**: non-toxic substitute in new classes of semiconductors, thermoelectric materials, topological insulators & low-temperature solders **Sb**: Sn-Pb-Sb alloys used extensively in the electronics industry
	Displays	**In:** in LCD screens as indium-tin-oxide
Transport	**Traction motors for electric vehicles**	**Cu:** widely used in windings, cables, inverters, control systems
	Jet engines	**Sb**: in low-load bearings used in the sector
Industry 4.0	**Robotics**	**Cu:** widely used in wire or axles or in corrosion-resistant alloys **In:** in compounds for electro-optical systems, sensors and stretcher skin **Sb, Te, Bi:** used in producing advanced materials
	3D Printing	**Cu:** alloying element in Ni and super-alloys
Defence	**Drones**	**Au:** Used in electronic components **Cu:** alloying element in super-alloys and CuBe alloys, communication equipment **In:** in compounds for electro-optical systems **Sb**: in radiation shields and ammunitions

The emergence of entirely new technologies is often accompanied by the total elimination of the demand for other consumer products and the materials used within them. For example, among the Project's target metals, silver has seen demand stagnate due to a massive decline in demand for its use within film cameras (Monnet, 2018).

Consumer behaviour is the sixth major determinant of demand for metals. It is important to note that technological transformations are always socially and economically embedded. Therefore, the emergence of new consumer goods containing a given target metal will only drive demand to the

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extent to which consumer demand for the consumer goods increases. New modes and preferences of consumption are emerging that may disrupt current demand trends for many of the metals targeted by ION4RAW. For instance, the widespread adoption of the sharing economy and *Mobility as a Service* business models within the transportation sector could significantly limit demand for personal Electric Vehicles (EV). This, in turn, could reduce the overall demand for the target metals used within the mobility sector (Ag and Cu). An overview of the major socio-economic factors influencing consumption of the technologies driving demand growth for target metals is presented in Table 3.

Table 3. Economic and Social considerations for strategic applications of target metals (Monnet, 2018) (Bobba, 2020)

Application	Target Metals Used	Economic	Social
Wind turbine	Cu	Increasingly low cost per MWh of both onshore and offshore wind power (high certainty - upward trend) Development of electric mobility drives increased demand for electricity (medium certainty – upward trend)	Not in my backyard perception (medium certainty – downward trend)
Solar Photovoltaics (PV)	Ag, Cu, In, Te	Average cost of MWh produced by solar installations (high certainty - upward trend)	Willingness to adapt power consumption during the day – demand response (low certainty – upward trend)
Fuel Cells (FC)	Ag, Au, Cu	Platinum currently represents 50% of the cost of an FC stack. Consequently, their high cost means that without technological innovations, they risk remaining dependent on public subsidies and never reaching mass commercialisation for stationary use. (Low certainty - downward trend)	Preference of consumers for battery EVs over Hydrogen FC vehicles (low certainty - downward trend)
Li-ion Batteries	Cu	Cost of raw materials in Li-Ion batteries (medium certainty, strong variable trend) High electricity price for households along with cost reduction for battery storage solutions (high certainty, upward trend)	Expansion of residential power generation and incentives for domestic energy storage (low certainty, upward trend) Use of EV for residential energy storage (medium certainty, downward trend)
Smartphones & computers	Ag, Au, Cu, In, Bi, Sb	Impact of material costs, competition between manufacturers, and renewable rates on sales (low certainty – slight downward trend)	Growth of demand related to social needs (high certainty – strong upward trend)
Displays	In	Economics of Zinc – Indium is almost entirely produced as a by-product of Zn (high certainty, variable trend)	Shift in user experience design toward display interaction (high certainty, upward trend) Demand for flexible electronics (low certainty, downward trend)

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Application	Target Metals Used	Economic	Social
Fibre optics	Cu	Emerging middle class, especially in rapidly growing Asian and Latin American countries (high certainty, high upward trend)	Digital content of higher quality (sound, video) and new ways to access it and higher expectations on content availability (high certainty, upward trend)
Traction motors for electric vehicles	Cu	Rapid decline in the price of Li-ion batteries is expected to make the purchase cost of electric vehicles less than combustion engine vehicles by 2023, while the cost of maintenance is already lower for electric vehicles (high certainty - upward trend)	Continued increase in shared mobility/ mobility as a service will reduce demand for personal vehicles (medium certainty - downward trend)
Robotics	Cu, In, Sb, Bi, Te	While currently only representing 20% of the robotics market, service robots for commercial and consumer use are expected to grow at a >20% CAGR in coming decades and overtake industrial robots as the largest portion of the robotics market (medium certainty - upward trend)	Uptake of robotics in the service sector may pose major challenges to employment and potentially face consumer backlash (medium certainty - variable trend). The uptake of exoskeletons is expected to progress rapidly in the biomedical and defence sectors (medium certainty - upward trend)
3D Printing	Cu	3D printing is expected to disrupt conventional manufacturing supply chains by opening new possibilities for reduction, substitution, recycling and mitigation in the use of raw materials and traditionally manufactured components (high certainty - upward trend)	The aerospace, automotive, and medical industries will account for a majority of the 3D printing market by 2025. Meanwhile, 3D printing in medical devices is also expected to grow rapidly between 2015 and 2025 (High certainty - upward trend)
Drones	Au, Cu	The current market is dominated by large, unmanned vehicles for use in defence. This segment is expected to continue to grow as Europe increases investment in defence (medium certainty - upward trend). The use of drones for sensors in commercial applications such as precision agriculture is expected to drive growth in the civilian market for unmanned vehicles (medium certainty - upward trend)	The use of drones for commercial tasks, including the delivery of goods, could dramatically reshape consumption patterns and potentially labour markets as well (medium certainty - upward trend). The growth of unmanned urban air mobility is envisioned as a strong sector of growth in the medium to longer-term (medium certainty - upward trend)

Government policies are the final major determinant of metal demand, according to the World Bank. The EU's new industrial policy, announced in 2020, will have an impact on all of the sectors with demand for target metals, in particular by increasing the demand for modes of production reliant on digital and Information and Communications Technology (ICT) infrastructure, as well as the technologies required to decarbonise European industry (European Commission, 2020). Likewise, the EU's new trade and investment policy, 'trade for all', will have crosscutting effects on demand across

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all the sectors using Project target metals by providing a framework for global value chains (European Commission, 2015). Sector-specific policies, both at the European and national levels, will also play a strong role in determining the demand for target metals in the coming decades by structuring how the transition toward a carbon-neutral and digital economy unfolds.

Table 4 summarises the key policy factors that will be driving and structuring the growth of European demand for strategic technologies using target metals.

Table 4. Summary of key policy factors driving the growth of European demand for strategic technologies using ION4RAW target metals

Application	Target Metals Used	Legal and Political Drivers
Wind turbine	Cu	EU & national policies in terms of CO_2-free power production (high certainty – upward trend) Protection of on-shore and off-shore landscapes and biodiversity (high certainty - Strong downward trend) Obligation to recycle products containing CRM used in wind turbine manufacturing (low certainty – downward trend)
Solar PV	Ag, Cu, In, Te,	EU & national policies in terms of CO_2-free power production (low certainty – upward trend) National/EU funding to the R&D&I sector – impact on material efficiency (medium certainty – downward trend) Feed-in tariff for solar PV electricity production (low certainty – variable trend)
Fuel Cells	Ag, Au, Cu	Achieving climate neutrality by 2050 will drive the growth of alternative sources of energy for industry and transport (high certainty - increase) European support through funding of innovation outlined in EC Hydrogen Strategy for EU (2020) Strategic Energy Technology Plan (2019) & EU Green Deal (2019)
Li-ion Batteries	Cu	Incentives for distributed energy generation involving households and incentives for domestic energy storage (medium certainty, upward trend) Growth of renewable energy production to cut CO_2 emissions resulting in high variability of power supply (high certainty, high upward trend) Implementation of the EU circular economy package (medium certainty, downward trend)
Smartphones & computers	Ag, Au, Cu, In, Bi, Sb	Political measures against planned obsolescence (low certainty – slight downward trend) Legal barriers outlined in the Circular Economy Action Plan (2020) to disposal and incentive measures in favour of reuse, repair and refurbished items (high certainty – downward trend)
Displays	In	Countries such as China banning the import of e-waste from the EU (high certainty, downward trend)

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Application	Target Metals Used	Legal and Political Drivers
Fibre optics	Cu	EU policies and certifications taking into account the environmental impact of electronic manufacturing from the design phase, even for imported products (high certainty, downward trend) Cyber-security threats related to submarine cables (medium certainty, variable trend)
Traction motors for electric vehicles	Cu	EU & national policies to cut GHG emissions in the transport sector (high certainty, upward trend) European threshold for particulate matters and policies to ban ICE vehicles from city centres (high certainty, upward trend)
Jet engines	Sb	GHG emissions reduction and air quality concerns (medium certainty, downward trend) Potential new Chinese competitor among civil airplane manufacturers (low certainty – low variable trend) Development of alternative high-speed transportation modes (high-speed trains, hyperloop,…) (medium certainty, slight downward trend)
Robotics	Cu, In, Sb, Te	The New EU Industrial Strategy (2020) and the SPARC public-private partnership are initiatives undertaken by the European Commission to promote the development of Europe's robotics industry (high certainty - upward trend)
3D Printing	Cu	Europe is well placed to capitalise on 3D printing technology to bolster domestic industry due to the relatively higher share of raw materials for this technology it can source domestically, and the strength of its aeronautics and automotive sectors (medium certainty - upward trend) 3D printing may challenge conventional intellectual property law by enabling the rapid duplication of creative/ manufactured works and legal liability law when a 3D-printed product is found to be defective or dangerous. New regulations are expected to confront these challenges (medium certainty - downward trend)
Drones	Au, Cu	The EU drone policy was updated in 2019 to specify the regulation of where drones are legally permitted or not and the requirements for flying them. They are regulated by the EASA (high certainty - medium trend)

2.2 Potential Impact of ION4RAW on Supply of Target Metals

The ION4RAW mineral processing technologies are innovations that will influence the supply of metals from primary production (metals extracted from the earth). **Technology** is one of six major determinates of mineral product supply listed by the World Bank, with the others being**: price, input costs, labour and other disruptions, government activities, and market structure**.

2.2.1 Influence of Price on Supply and Companionality

Price is the key determinant of supply in a market economy since profit-maximising firms are expected to increase their production of a given metal until marginal costs equal marginal revenue. In the short

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run, mining firms will face constraints at the limits of their production capacity (ex. mining and processing equipment size, geological deposits on-site, labour) that prevent them from expanding supply in response to the increased price. However, a sustained increase in price over the long term can be expected to drive firms to expand production, for instance, by exploiting lower-grade reserves or investing in mineral exploration. This increased price elasticity of supply (meaning the ability of supply to respond to changes in market price) for metals can be visualised in Figure 8.

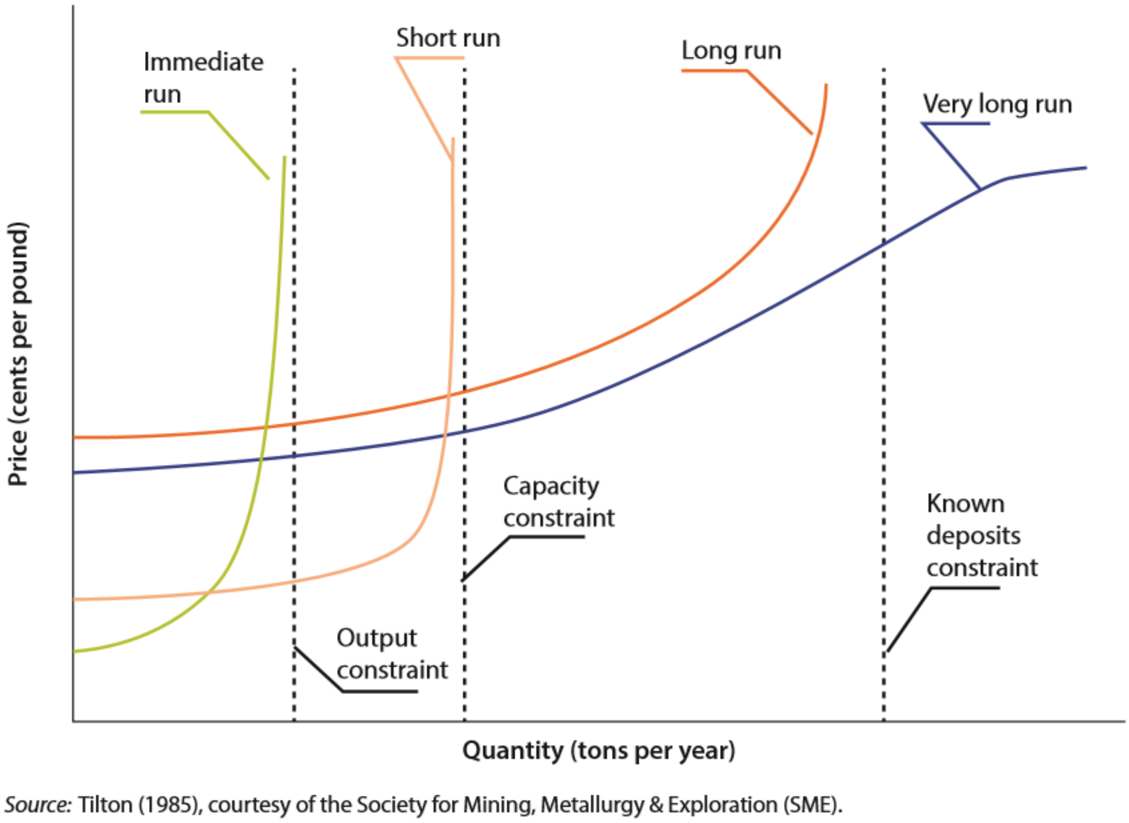

Figure 8. Illustrative Supply Curves in the immediate, short, long and very long run, reproduced under Creative Commons Attribution 3.0 IGO license (Halland, Lokanc, & Nair, 2015).

From the supply side, two major factors tend to influence the cost of production of a metal and, in turn, its market price. The **crustal abundance** of a metal represents a physical constraint on supply. For instance, the tremendous difference in geological prevalence between aluminium and gold largely explains their enormous price difference. The second major factor differentiating metals' production costs is the **input energy** it takes to separate a given metal from its ore. For instance, the high energy requirements for extracting and refining titanium largely explain its high cost (T.E., Gus, & Luis Tercero, 2014).

Energy costs have become a particularly acute issue impacting European metal producers since the invasion of Ukraine by Russia in early 2022 due to the subsequent disruptions in the European energy supply that resulted from the war. As shown in Figure 9, 2022 witnessed an unprecedented spike in EU electricity prices, which was accompanied by sharp price shocks in European natural gas as well. The high cost of energy led to dramatic reductions in European metal production as refineries across the continent went offline to avoid economic losses. By September 2022, over 50% of European zinc and aluminium refinery capacity was offline, with major disruptions in EU steel, copper and nickel production as well (Eurometaux, 2022).

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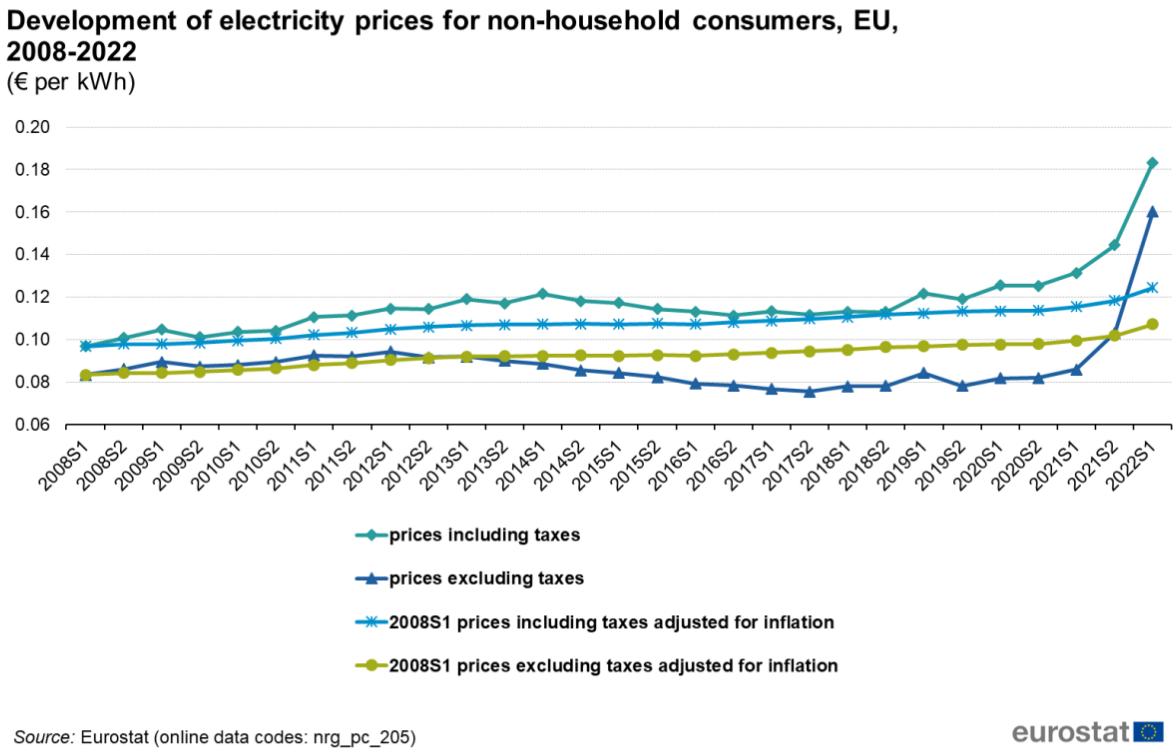

Figure 9. Development of electricity prices for non-household consumers, EU 2008-2022

To support European industry in the face of the energy crisis, the European Commission took a series of emergency actions to stabilise energy prices. As of early 2023, these emergency interventions succeeded in preventing the total collapse of the European metal industry. However, the ongoing geopolitical realignment provoked by the war in Ukraine has underlined the interdependence of European metal and energy markets.

In the medium term, European metal producers face a pressing need for energy-efficient processing technologies that can insulate them from fluctuations in the price of electricity and fossil fuels such as coke and natural gas. The ION4RAW project should therefore highlight results from the lifecycle assessment in T7.1 and economic assessment in T7.4 if they indicate the process is able to produce target metals at a lower energy intensity than standard processing routes.

The dynamic relationship between production costs and metal price is thus the key driver of metal output from mining firms. Based on this relationship, metal supply is typically placed into one of three categories.

Main supply refers to the output of metal that is essential to the economic viability of a given mine, whose price alone determines the project's output. This metal, also referred to as **bulk metal** or **carrier metal,** is relied upon to cover the fixed and variable costs of exploiting the mine. Copper is the primary carrier metal targeted by ION4RAW. In addition, despite its scarcity, due to its high price, gold is also often a financially viable main supply for mines.

A **co-product** metal exists when the costs of operating a mine are shared between multiple different commodities. The metal targeted by ION4RAW, which is typically mined as a co-products, is silver.

Finally, a **by-product** metal is one whose price and rate of recovery have no impact on the amount of production from a mine. Among the metals targeted by the Project, antimony, bismuth, indium, and tellurium are typically considered by-products. The fact that these metals are typically present in only trace amounts, and have market prices that are typically below their cost of recovery, means that

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globally most of the by-products which are extracted during mining operations are currently lost to tailings or during refining (T.E., Gus, & Luis Tercero, 2014).

An overview of the companionability of metal supply can be seen in Figure 10, depicting major bulk metals and the co- or by-products typically recovered from the same ore. In this market analysis, the terms *co-* or *by-products* are used interchangeably to refer to *companion metals*, as opposed to the main *carrier metal* in the ore. The ION4RAW process is designed to target sulfidic ores.

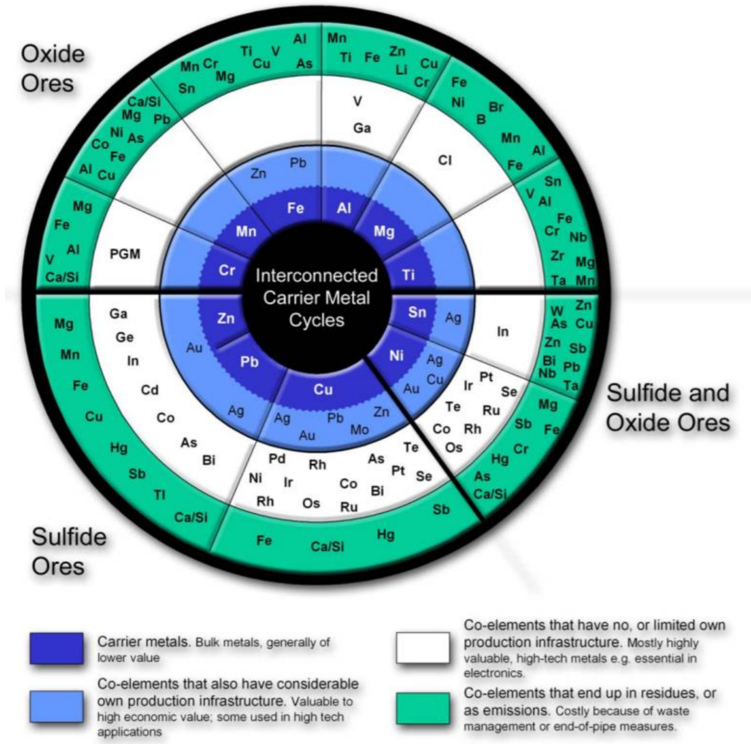

Figure 10. The metal wheel identifying between main carrier metals and by- or co-product metals: Reproduced with authorisation from (European Commission, 2010).

The goal of the Project is to increase the supply of by-product metals by acting on both levers of mineral production cost. By allowing producers to recover by-products at the mine site through an integrated mineral processing circuit, the ION4RAW technology is expected to reduce the energy requirement of extracting by-product metals compared with conventional pyrometallurgical processes.

Thus, given the dynamic relationship between by-product metals and their carrier metals, the Project seeks primarily to increase the supply of target metals in the medium term by increasing the recovery of by-products that are *already* being extracted and are currently lost to waste streams rather than proposing new mining operations that would likely not be viable due to the low grade in which most target metals are found. Research exploring the market dynamics of companion metals has argued that, indeed, this approach to tackling supply risk by increasing recovery rates is the most viable path forward (Nassar, Graedel, & Harper., 2015). Recycling several of these critical raw materials is often difficult because they are used in small amounts in complex mixtures or alloys for high-tech appliances. Moreover, even when technically feasible, the substitution of companion metals often just displaces other companion metals.

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2.2.2 Current Global Supply of Target Metals

Among metals targeted by ION4RAW, the tremendously disproportionate amount of global copper supply (as a bulk metal) over the other companion metals can be clearly seen. Figures for the total global mining output in 2022 are listed in tonnes in Table 5 below.

Table 5. Global Production in 2022 Target Metals in metric tonnes (USGS 2023)

Raw Material	World Mine Production (Tonnes) (2022)
Copper	22000000
Antimony	110000
Silver	26000
Bismuth	20000
Gold	3100
Indium	900
Tellurium	640

The significant difference in scale between copper supply and all other target metals is particularly notable. The massive disparity in supply between copper and all other target metals is also be seen in the number of known reserves around the globe. Notably, due to the lack of liquidity and the small size of the market for most by-product target metals, there has been little effort to classify known geological resources of these metals as reserves. In fact, no data is available regarding known reserves for bismuth and indium. Data on the size of identified global reserves for the other five target metals can be seen in table 6.

Table 6. Known global reserves in 2022 (USGS 2023)

Raw Material	Known Global Reserves in 2022 (Tonnes)
Copper	890000000
Antimony	1800000
Silver	550000
Gold	52000
Tellurium	32000
Bismuth	N/A
Indium	N/A

The overall market value of the metals targeted by ION4RAW, measured in terms of price X annual global production, is shown in Figure 11. It demonstrates a different perspective than considering supply in terms of weight alone. While copper's ubiquity provides it with the second-largest market value of target metals, the high value of precious metals, in particular gold and silver (widely traded as

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investment vehicles), means that their current market value is far greater than their relatively small material production might otherwise indicate.

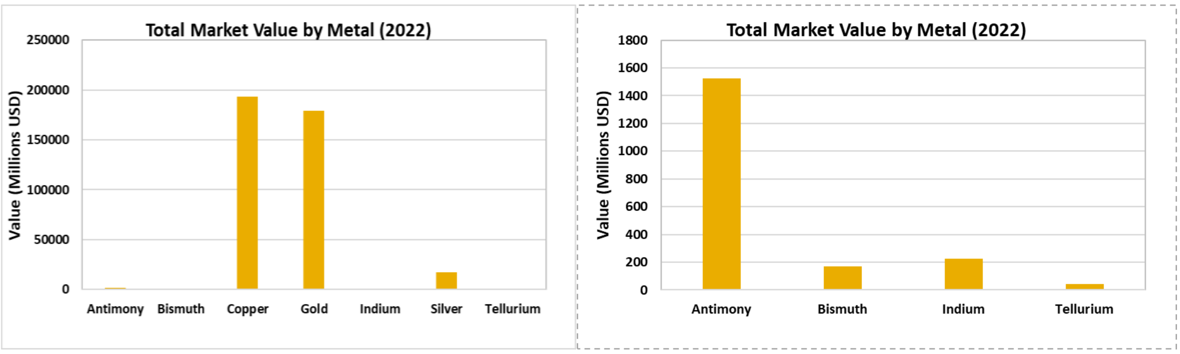

Figure 11. Total Market Value by Metal 2022 (USGS, 2023)

While copper and gold currently have market values of several orders of magnitude greater than other target metals, as has been developed in the global demand assessment, all metals targeted by ION4RAW are expected to see increased demand for use in rapidly emerging technologies. This increased demand is expected to significantly grow the total market for these minor metals. Even if supply does not keep pace with expected demand growth, it can be expected that the price of these metals would significantly increase, leading to an increase in their total market value.

2.2.3 Institutional Constraints on Target Metal Supply

Just as with the demand for metals, the supply of mineral products is complicated in practice and is contingent on much more than merely the rational economic decisions related to maximising revenue at a certain market price. Institutional constraints related to labour and environmental disruptions, public policy, and market structure also determine the supply of metals.

Numerous instances where **labour-related concerns** have disrupted target metal supply chains have occurred in recent years. For instance, the Escondida mine in Chile, which is the world's largest copper mine and responsible for roughly 5% of global output, was confronted with a 43-day strike in 2017 that sharply reduced its production during that period (Jamasmie, 2017).

Increasing the supply of metal commodities is also frequently complicated by **local opposition to mining**, typically on social or environmental grounds. This has, for instance, significantly impacted Europe's gold production and, in turn, the production of its companion metals. The example of Romania highlights the challenges faced in expanding European mining. The country witnessed perhaps the worst European environmental catastrophe since Chernobyl in 2000 when at the Baia Mare Gold mine, the dam containing cyanide-laced tailings burst and devasted the ecology and economy of the Somes river (Cunningham, 2005).

This experience of this disaster contributed in part to galvanising opposition against the proposed Rosia Montana Gold mining project in Romania. The Rosia Montana project would be located on Europe's largest gold deposits, at a location with deposits of numerous other CRMs. If undertaken, the project would become Europe's largest open-pit gold mine. However, local opposition to the planned relocation of nearby residents eventually sparked a national movement against the project on environmental grounds, and to this date, it has failed to receive parliamentary approval to begin extraction (Velicu, 2015).

One promising development in averting similar difficulties and ensuring that locals most impacted by mining developments reap the benefits has been the emergence of **community development**

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agreements signed between locals and mining companies (O'Faircheallaigh, 2013). The pursuit of agreements between locals and the company that eventually commercialises ION4RAW should be considered key to ensuring a socially just project while also mitigating the risk of potential disruptions in production.

Alongside responsible dialogue between private sector actors and locals, proper **government regulation** of the mining and metallurgical industry is key in maintaining a stable supply of raw materials for economic development while also balancing the need to avoid environmental and social externalities. Given the globalised nature of contemporary manufacturing supply chains, industrial and trade policies play a key role in structuring the distribution of metal supply. Countries may also place high taxes on mining rents or, in certain cases, cap mineral exports or nationalise production (Halland, Lokanc, & Nair, 2015). Uncertainty related to these policy mechanisms risks leading to metal price volatility, potentially discouraging private investment in mining and processing, and limiting global metal supply.

Moreover, Europe has among the world's most stringent environmental regulations for mining operations, which can limit its domestic metal extraction due to regulatory costs and barriers. One notable example came in 2019 when in response to a report by the IPBES regarding the impact of the extractive industry on biodiversity and widespread mobilization by local populations and environmental NGOs, the French government revoked the authorisation of the Montagne d'Or open pit gold mine in French Guyana (Monde & AFP, 2019). The example of the Montagne d'Or projects is the importance of stringent environmental review of mining projects to preserve the health of current and future environments and local populations.

Europe currently imports most of its supply of all the metals targeted by ION4RAW and is thus vulnerable to public policy shifts coming from exporting countries. The primary national producer of each target metal (at either extraction or processing), along with its share of the global supply, is listed in Table 7.

Table 7. Primary national producer of target metals (European Commission, 2020)

Raw Material	Stage	Main Global Supplier	Share
Antimony	E	China	74%
Bismuth	P	China	80%
Copper	E	Chile	30%
Gold	E	China	14%
Indium	P	China	48%
Silver	E	Mexico	21%
Tellurium	E	China	54%

*E = Extraction, P = Processing, CRM in orange, non-CRM in brown

As can be seen, **China** is the primary producer of five of the seven target metals. Its production of these materials is dominated by state-owned enterprises and has been used by the Chinese government as a strategic element in its push to develop downstream industries in emerging technologies such as wind and solar (Wiebke, Kostka, & Stegen, 2017). The willingness of the Chinese government to restrict the EU supply of these metals has been demonstrated in recent years, as it has implemented various export quotas and tariffs on several of the target metals.

Most recently, a dispute was filed at the WTO by the EU in 2016 regarding Chinese restrictions on eleven metals, including antimony, copper and indium, which ultimately led China to reverse course and drop their export restrictions (WTO, 2016). The recent EU-China comprehensive agreement on

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investment, agreed in principle in December 2020 (European Commission, 2020), may contribute to stabilising flows of investment and trade between the two parties and, in turn, stabilising the European supply of target metal imports.

The fact that Europe is currently a large net importer of all the metals targeted by ION4RAW is also reflected in the fact that none of the **world's largest firms** producing the target metals are based within the European Union. The list of the 30 largest mining firms producing at least one of the target metals can be seen in Table 8, ranked according to market cap at the beginning of 2022 (PwC, 2022). As indicated in Table 8, the only firm based within the European single market is Swiss mining giant Glencore.

Table 8. List of 30 largest mining firms producing at least one of the ION4RAW target metals

Company	Country	Commodity Focus
BHP Group Ltd.	Australia / UK	Diversified
Rio Tinto Ltd.	Australia / UK	Diversified
Vale S.A.	Brazil	Diversified
Glencore Plc	**Switzerland**	**Diversified**
Freeport-McMoRan Inc.	USA	Copper
Anglo American plc	UK / South Africa	Diversified
Newmont Corporation	USA	Gold
MMC Norilsk Nickel	Russia	Nickel
Zijin Mining Group Company Ltd.	China	Diversified
Grupo México, S.A.B. de C.V.	Mexico	Diversified
Barrick Gold Corporation	Canada	Gold
Saudi Arabian Mining Company (Ma'aden)	Saudi Arabia	Diversified
Public Joint Stock Company (Polyus)	Russia	Gold
Hindustan Zinc Ltd.	India	Zinc
Antofagasta plc	UK	Copper
China Molybdenum Co., Ltd.	China	Diversified
First Quantum Minerals Ltd.	Canada	Copper
Teck Resources Ltd.	Canada	Diversified
Newcrest Mining Ltd.	Australia	Gold
South32 Ltd.	Australia	Diversified
Agnico Eagle Mines Ltd.	Canada	Gold
Shandong Gold Mining Co., Ltd.	China	Gold
Impala Platinum Holdings Ltd.	South Africa	Platinum Group Metals
Kirkland Lake Gold Ltd.	Canada	Gold
Ivanhoe Mines Ltd.	Canada	Diversified
Gold Fields Ltd.	South Africa	Gold
Jiangxi Copper Company Ltd.	China	Copper
Fresnillo PLC	Mexico	Diversified
Sibanye Stillwater Ltd.	South Africa	Platinum Group Metals and gold
AngloGold Ashanti Ltd.	South Africa	Gold

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Europe's minor share of the global market for the non-ferrous metals targeted by the Project points to the final major determinant of metal supply, **market structure**. The global market for copper, gold and their companion metals is highly concentrated, with the largest global firms having significant power to determine global supply. For instance, the world's three largest copper-producing firms, **Codelco** (owned by the Chilean government and therefore not listed above) (Codelco, 2020), **BHP** (BHP, 2020), and **Glencore** (Taboada, 2020) produced roughly 25% of global copper in 2020.

The largest multinational metal producers also demonstrate a tendency within the market towards **vertical integration** in commodity value chains. Major metal producers typically do not specialise merely in mining but also own and operate their mineral processing, concentration, and refining plants. The market power of large multinational metal commodity-producing firms reflects the high barriers to entry that small businesses face when entering the sector. In particular, metal extraction and production typically entail very large fixed capital costs related to exploration and processing equipment, meaning that the necessary debt would need to be paid down over the course of decades (Halland, Lokanc, & Nair, 2015).

The concentrated market power of major firms may be particularly acute with respect to by-product metals (Nassar, Graedel, & Harper., 2015). Most by-product metals lack market liquidity since they are typically sold in direct contract negotiations between producers and industrial consumers rather than being traded on commodity exchanges such as the London Metal Exchange. The dynamic interactions between host metal and by-product metal supply, as well as the concentrated power of major mining firms, will be considered in section 4 of this report, where strategic proposals for bringing ION4RAW technology to the market will be explored in more depth.

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3 Market assessment of the ION4RAW target metals

Information on the ION4RAW target metals was largely sourced from the European Commission, a Study on the EU's list of Critical Raw Materials (2020), Factsheets on Non-critical Raw Materials and Critical Raw Materials, produced as part of the SCRREEN Project (European Commission, 2020).

3.1 Antimony

Antimony and ION4RAW

Antimony is a CRM (EI=4.77; SR=2.01, in 2020). In the ores analysed for the ION4RAW Project by BRGM, antimony was found in the Cobre las Cruces mine (386 mg/kg), Cononish Gold mine (2.8 mg/kg), El Valle Boinas mine (140 mg/kg), El Porvenir mine (129 mg/kg), Cerro Lindo Cu mine (25.6 mg/kg), and Cerro Lindo Zn mine (75.7 mg/kg) (BRGM, 2021).

Element description

Antimony (chemical symbol Sb) is a metalloid chemical element with the atomic number 51. It is rare in the earth's crust, with an abundance of merely 0.4 ppm. The most common ore mineral of antimony is stibnite (Sb_2S_3). Antimony is a co- or by-product of the production of gold, lead, copper, and zinc. Due to its poor thermal and electric conductivity as well as its hard and brittle mechanical properties, antimony is not typically used commercially as a metal on its own. Instead, antimony has its most frequent commercial applications as a compound, primarily in the form of antimony oxides and particularly diantimony trioxide (Sb_2O_3).

Processing

Figure 12 illustrates the antimony value chain, from its exploration to its recycling.

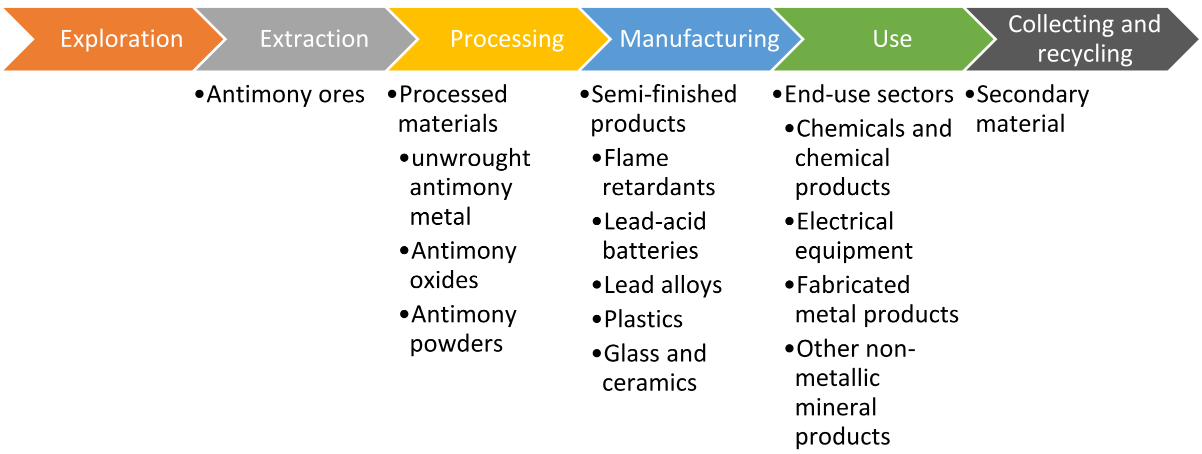

Figure 12. Simplified value chain for antimony for the EU (European Commission, 2020)

Global Market

The world mine production in 2021 represented 110,000 tonnes (as opposed to 160,000 tonnes in 2019) and was constrained as a result of mine shutdowns linked to the covid-19 pandemic and environmental audits in China. China accounted for 55% (60,000 tonnes) of global mine production, followed by Russia (25,000 tonnes), Tajikistan (13,000 tonnes), and Australia (4,000 tonnes.) There are big unexploited deposits in Myanmar (16% of known reserves) and Kyrgyzstan (12%). (USGS, 2022)

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Global consumption of antimony is assessed to have increased from 2016 to 2020, primarily in flame retardants, lead-acid batteries, and plastics. Asia will likely remain the leading area regarding consumption and accounted for about 60% of global consumption by 2021 (USGS, 2022).

Most of the conversion of antimony ores into antimony metal or ATO occurs in China (European Commission, 2020) despite the opening of a new antimony plant in Oman treating 40,000 tonnes of antimony-gold concentrates into 20,000 tonnes of antimony metal and antimony trioxide. China has dominated the global import pattern of antimony ores since 2002 by importing 74.7% of the antimony ores exported globally from 2002 to 2019. In 2019, the main exporters in volume were Russia (30,000 tonnes), Tajikistan, Myanmar, and Australia. (Wang, et al., 2021)

The antimony market size was reported at USD 1.77 billion in 2018. The antimony market is expected to have a compound annual growth rate of 6.7% for the forecast period of 2022-2029, reaching USD 3,698.23 million by 2029. (Data bridge market research, 2022)

The application of antimony in the chemical industry is projected to drive the antimony market (Marketwatch Press Release, 2019). The majority of antimony is traded on annual contracts, and only small amounts are sold on the open market.

Antimony can be substituted. Compounds of chromium, tin, titanium, zinc and zirconium can substitute for antimony in the manufacture of pigments and glass. However, in its main application (i.e. as a flame retardant), antimony is much harder to substitute. In addition, in other applications, such as, for instance, the production of plastics, its substitution would be associated with a price & performance penalty.

EU Supply trends

Antimony is traded in various forms, such as ores and concentrates, antimony trioxide (ATO), unwrought antimony metal and powders, and scrap. The EU is a net importer of antimony ores and concentrates, supplied predominantly from Turkey and Bolivia. Import from Turkey increased from approximately 700 tonnes in 2010 to 1334 tonnes in 2021. The import from Bolivia has an average of 350 tonnes in the past 20 years. (Eurostat, 2022)

The major suppliers of antimony oxides for the EU are China and South Korea, representing more than 95 percent. The U.S., U.K. and Bolivia have been supplying minor quantities, and their share has been declining in recent years.

With a capacity of more than 10,000 tonnes of ATO per year, SICA (France) is the first European manufacturer (SICA, 2021).

The European Union has also been exporting insignificant amounts of antimony products, with an average of 600 tonnes per year over the last two decades. In 2021, the export volume was 464 tonnes.

Known EU Deposits

In Europe, WP2 By-products Potential Evaluation of ION4RAW has identified antimony resources in the following countries: Austria, Bulgaria, Bosnia and Herzegovina, Switzerland, Germany, Spain, Finland, France, Great Britain, Georgia, Greece, Hungary, Ireland, Italy, and Romania and Poland.

The location of the known antimony deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 13 below. The mines within close range of an antimony deposit are also listed as candidates for adopting ION4RAW in Table 9.

Targets for Mining

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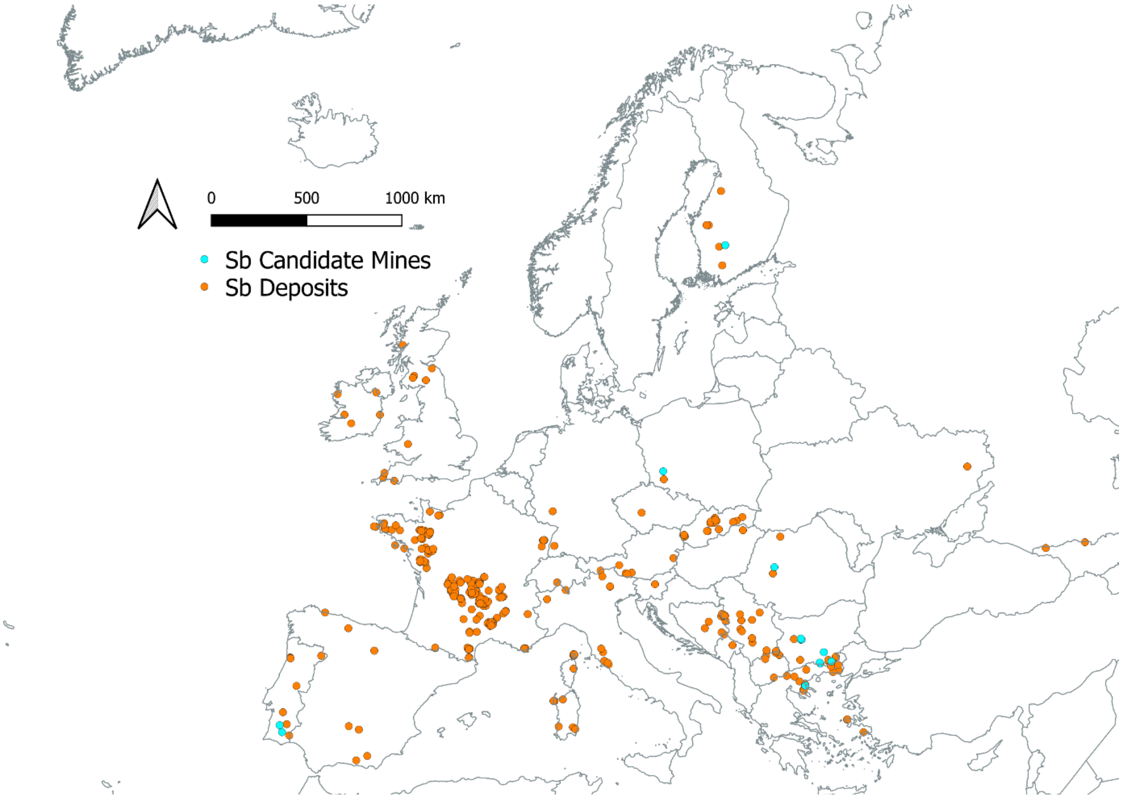

Figure 13. Antimony potential target mines close to deposits

Table 9 highlights potential mines that could be interested in using the ION4RAW process in order to recover antimony.

Table 9. List of potential antimony mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Greece	Kassandra Mine	Hellas Gold S.A.	Gold
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Chelopech	Dundee Precious Metals Inc.	Copper, Gold
Bulgaria	Mine at Pirdop	Aurubis	Copper
Bulgaria	Ada Tepe	Dundee Precious Metals Inc.	Gold
Portugal	Aljustrel	I'M SGPS SA	Copper
Bulgaria	Chala	Gorubso-Kardzhali AD	Gold
Finland	Orivesi	Dragon Mining Limited	Gold
Greece	Stratoni	Eldorado Gold Corporation	Silver
Poland	Polkowice- Sieroszowice Mine	KGHM	Copper, Silver
Portugal	Neves Corvo Mine near Castro Verde	Lundin Mining Corp. (LMC)	Copper, Zinc
Romania	Rosia Poieni Mine	Cuprumin	Copper
Bulgaria	Mine at Erma Reka	Minstroy Holdings	Lead-zinc
Bulgaria	Mine at Kurdjali*	Velocity Minerals	Gold

*Likely operating

3.2 Bismuth

Bismuth and ION4RAW

Bismuth is a CRM (EI=4.01; SR=2.22, in 2020). In the ores analysed for the ION4RAW Project by BRGM, bismuth was found in the Cobre las Cruces mine (152 mg/kg), Cononish Gold mine (2.1 mg/kg), El valle Boinas mine (44.9 mg/kg), El Porvenir mine (358 mg/kg), Cerro Lindo Cu mine (5.9 mg/kg), Cerro Lindo Zn mine (75.5 mg/kg) (BRGM, 2021).

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Element description

Bismuth (chemical symbol Bi and atomic number 83) is a very brittle metal with a pinkish metallic lustre. In the Earth's crust, bismuth is about twice as abundant as gold. The most important ores of bismuth are bismuthinite (sulfide), bismutite (carbonate) and bismite (oxide) (Hammond, 2004). Native bismuth is known in Australia, Bolivia, and China.

The two main sources for the recovery of bismuth metal are known to be lead and tungsten extraction and processing, with 50 to 60% coming from lead processing. Minor recovery of bismuth can also come from the metallurgy of tin and copper, for instance, in Japan, although in most cases, it is seen as a penalising impurity in those treatments (Blazy, 2013) (Krenev, 2015).

Processing

Figure 14 highlights the simplified value chain for bismuth.

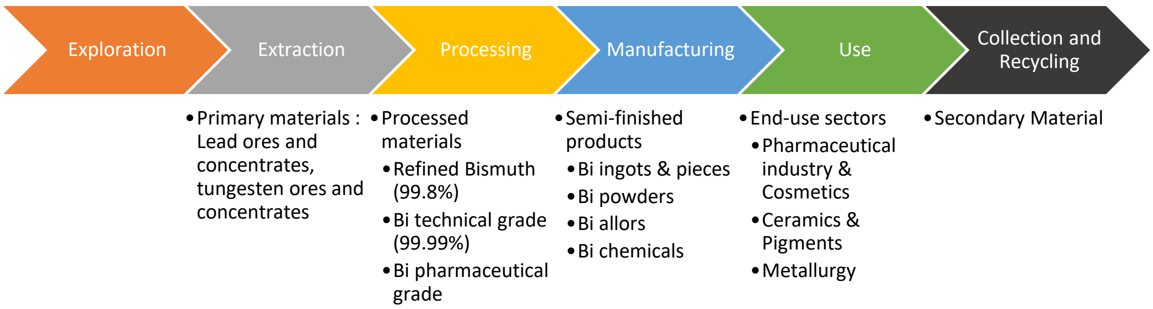

Figure 14. Simplified value chain for Bismuth (European Commission, 2020)

After extraction, refining is needed to obtain bismuth metal of a purity of at least 99.8%. With the current technology, the thermal route is preferred. During this process, caustic soda and potassium nitrate are added to the molten bismuth to remove impurities (As, Sb, Se, Te, Sn). The addition of Zn metal can be necessary when impurities include copper, silver and gold (Blazy, 2013). Final treatment with soda ash can bring purity to 99.99% Bi (technical grade). Other processes exist depending on the nature of the impurities and the required quality of final products. Electrolytic refining is preferred to obtain higher purity, up to 99.999% (pharmaceutical grade).

Bismuth can be commercialised in the form of high-purity ingots, pieces, pellets, or even powdered oxide.

Global Market

Global production was estimated at 19,000 tonnes in 2021 (USGS 2022). The top 5 producers were China (16,000 tonnes), Laos (1,000 tonnes), Korea (1,000 tonnes), Japan (600 tonnes), and Kazakhstan (240 tonnes). (USGS, 2022)

The perceived criticality of bismuth is due to its market concentration and the recognition that it has many valuable end-uses, with a high proportion of dissipative products that are not recoverable. The supply bottlenecks are primarily due to the concentration of production to a few countries and, to an extent, the industrial inertia that has led to bismuth being disregarded as a valuable by-product.

Global demand for bismuth is estimated to grow at 5% by year, averaging over 2021-2030. The rising application of bismuth in the automotive industry to protect rust coatings, brake lining, etc., is expected to boost the market (Market Research Future, 2021). There may also be growth in

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applications where there is a requirement for very low-temperature solders, where bismuth is competitive.

Another emerging market could come from the substantial interest in developing new classes of semiconductors, thermoelectric materials and topological insulators. It could lead to the development of emerging **semiconductor compounds and alloys** that contain bismuth (BIWS, 2018). Indeed, bismuth may also help resolve one of the problems in miniaturising semiconductor devices, the contact resistance between a metal electrode and a monolayer semiconductor material.

The decarbonated energy transition also has the potential to disrupt the market and increase demand for bismuth. Bismuth has been found very effective in converting light sources into energy, making it a **"photovoltaic" material**. Unlike most photovoltaics, however, bismuth also has unique electronic properties as it offers a wider band gap allowing it to absorb more invisible light (Brandt, et al., 2015).

EU Supply trends

Bismuth supply is strongly reliant on Asian production; notably, the skarn deposits Núi Pháo in Vietnam and Shizhuyuan in China (Deady, Moon, & Moore, 2022). As a by-product, the bismuth supply chain is firstly dependent on the primary production of **lead and tungsten**.

At the world level, the bismuth supply chain is, in large part, relying on the Chinese supply of primary refined materials (purity of 99.8% Bi), still containing a lot of impurities. Those materials are massively exported to Europe, North America and Southeast Asia for further refining.

The 5N Plus facility in Germany accounts for 94% of all bismuth imports into the European Union, or 1488 tonnes in 2019. In 2018 the market share of imports from China dropped by almost 30% to 41%, while EU-27 imports remained approximately the same at 32%. The remainder was covered by a new trade flow of imports from Laos (Deady, Moon, & Moore, 2022).

In Europe, BGS Mineral Statistics mentions mine production in Bulgaria of 3 tonnes in 2013. Bismuth is produced in Bulgaria as a lead-bismuth alloy (7% Bi content) by the Bulgarian smelter KCM 2000 Group (KCM 2000 Group, 2019). EU Production of a lead-bismuth alloy (6-12% Bi content) is also cited in Germany and produced by Aurubis (Aurubis, 2019) & Boliden in Sweden.

Known EU Deposits

During the Minerals4EU (2019) project, resources of bismuth were reported only in Bulgaria in the category "No statistical data available but resources known or believed to exist". However, WP2 has identified bismuth resources in the following countries: Austria, Bulgaria, Germany, Spain, Finland, France, Great Britain, Northern Macedonia, Norway, Romania, Poland, Sweden, and Serbia.

The location of the known bismuth deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 15 below. The mines within close range of a bismuth deposit are also listed as candidates for adopting ION4RAW in Table 10.

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Targets for Mining

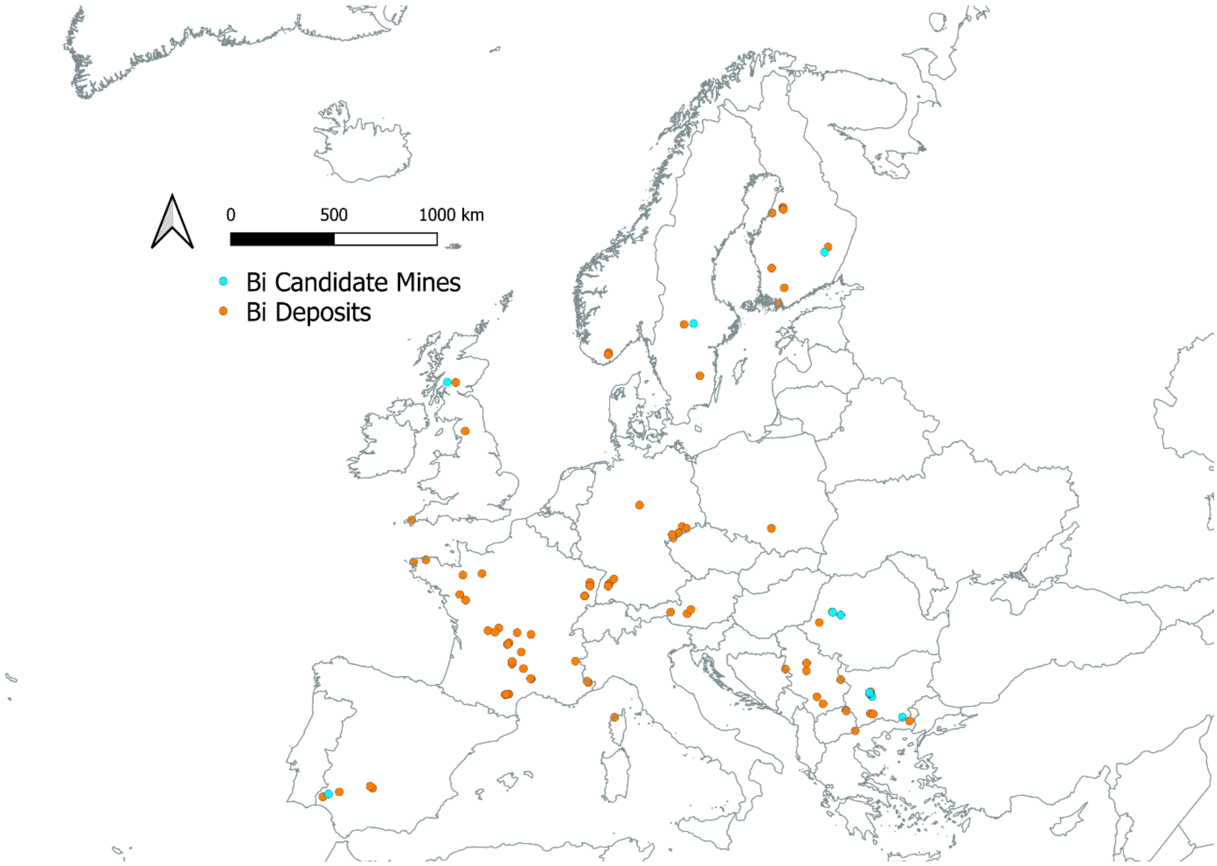

Figure 15. Bismuth Potential Target Mines close to deposits

Table 10 highlights potential mines that could be interested in using the ION4RAW process to recover bismuth.

Table 10. List of potential mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Bulgaria	Mine at Panagurishte	Asarel-Medet AD.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Chelopech	Chelopech Mining Ltd	Copper, Gold
Bulgaria	Mine at Pirdop	Aurubis	Copper
Romania	Rosia Poieni Mine	Cuprumin	Copper
Bulgaria	Ada Tepe	Dundee Precious Metals Inc.	Gold
Romania	Baita Plai	Vast Resources PLC	Copper
United Kingdom	Cononish	Scotgold Resources Limited	Gold
Sweden	Lovisa	Lovisagruvan AB	Lead
Spain	MATSA	Government of Abu Dhabi; Trafigura Beheer B.V.	Copper
Finland	Outokumpu Mining Camp	FinnCobalt	Cobalt, Nickel

Strategic Considerations for ION4RAW

- Follow exploration projects in copper mines in Bulgaria, Slovakia and Portugal.
- EU companies to target: 5N Plus, which controls the majority of the bismuth market and specialty and which subsidiary in Belgium is among the largest world importers of Bi (5N Plus, 2015) & BASF, which is one of Europe's largest producers of bismuth vanadate ($BiVO_4$), a key pigment for use in coatings and paints.

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- Belgium bismuth metal production is supplied by various EU producers mainly, i.e. Umicore in Belgium, Aurubis Cu plant in Germany, Boliden in Sweden and for some years from the Nui Phao mine in Vietnam (BGR 2019).
- Refining is needed to obtain Bi-metal of a purity of at least 99.8%. Companies that refine Bi might be interested in the ION4RAW technology.

3.3 Indium

Indium and ION4RAW

Indium is a CRM (EI=3.25; SR=1.79, in 2020). In the ores analysed for the ION4RAW Project by BRGM, indium was found in the Cobre las Cruces mine (2.8 mg/kg), Cononish Gold mine (0.5 mg/kg), El valle Boinas mine (2.5 mg/kg), El Porvenir mine (23 mg/kg), Cerro Lindo Cu mine (3.3 mg/kg), Cerro Lindo Zn mine (18 mg/kg) (BRGM, 2021).

Element description

Indium (chemical symbol In and atomic number 49) is a very soft, ductile and malleable silvery metal with a hardness of 1.2 on the Mohs scale. It has a density of 7.31 g/cm^3 (similar to tin's), a low melting point of 156.6°C, a high boiling point of 2072°C, and becomes superconducting at 3.37 K (-269,78°C). The most important commercial source of indium is the zinc mineral sphalerite. Approximately 95% of the refined primary Indium produced in the world comes from zinc ores processing (Lokanc, 2015).

Processing

Figure 16 illustrates the indium value chain, from its exploration to its recycling.

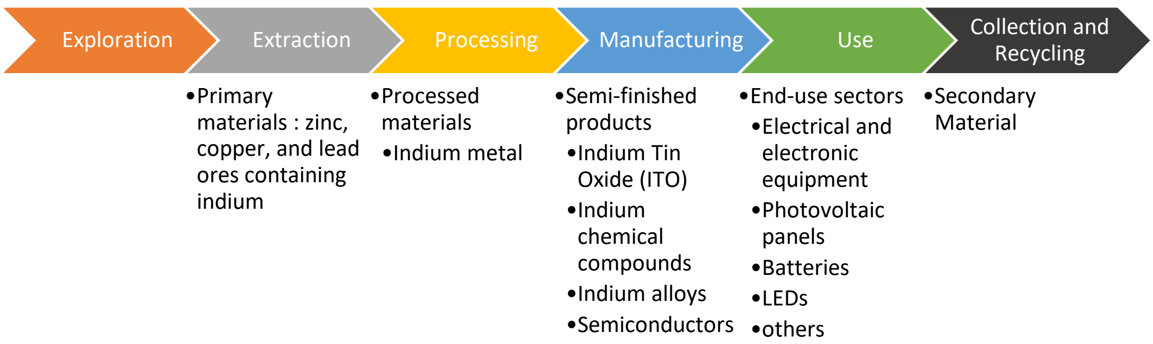

Figure 16. Simplified value chain for Indium (European Commission, 2020)

Global market

The global production of indium was 920 tonnes, with China and South Korea accounting for the majority of the production at around 530 tonnes and 200 tonnes, respectively. (USGS, 2022)

Indium had a worldwide market value of USD 420 million in 2019 and is expected to grow at a CAGR of approximately 4.2% over the next five years, reaching USD 540 million by 2024. (Marketwatch, 2019)

Indium resources and reserves are typically derived from zinc and copper resources. Finland, Greece, Portugal, Romania, Bulgaria, Spain, and Sweden, along with Ireland and Poland, extract zinc in the EU, which can potentially produce indium as a by-product, except for Poland and Ireland. Peru, China, Australia, and Canada are other countries outside the EU that also extract indium.

The main ITO producers are Samsung Corning Precision Materials Korea Co. Ltd. and Heesung metal Ltd. in the Republic of Korea and JX Nippon Mining & metals Corp., and Mitsui metal mining Co. Ltd.

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in Japan (USGS, 2016). All flat panel displays (FPDs) manufacturing takes place in Japan, South Korea and China.

Indium's application in PV cells and batteries makes it a significant element for achieving low-carbon energy solutions in the EU economy, aligning with the objectives of a climate-neutral economy.

The demand for indium will be mainly driven by thermal interface materials, LED, and alloys from 2022 onwards. Secondary refined indium production is mostly from recycling new scrap instead of end-of-life recovery. Indium is commonly recovered from Indium Tin Oxide (ITO) scrap, especially in Japan and South Korea. The amount of secondary indium recovered from scrap exceeds primary indium production, but exact data is not available.

EU Supply trends

The EU imports most of its indium from China, Taiwan, the United States, and the United Kingdom, and the most well-known EU producer of virgin indium is Auby, Nyrstar, in France. Vital Materials (Germany) also produces indium metal, chemicals and alloys from secondary feeds.

The main demand drivers for indium in the future are expected to be thermal interface materials, alloys, and LED. Secondary indium production, which comes from the recycling of manufacturing waste, is estimated to exceed primary indium production.

Known EU Deposits

Approximately 95% of the refined indium produced in the world comes from the processing of **zinc ores** (Lokanc, 2015).

In Europe, most of the indium mineralisation is located in Variscan units and, to a small extent, in Proterozoic (Sweden), Caledonian and Alpine formations. The Portuguese Neves-Corvo VMS-type Cu-Zn-Sn deposit contains the largest known indium resource in Europe, estimated at 3480 tonnes. The Neves-Corvo mine produces zinc and tin concentrates that probably, also contain significant amounts of indium. Since indium is not recovered in all zinc and tin refineries, it is not clear how much indium is produced from the Portuguese ores. Resources of indium have been identified by WP2 in Austria, Bulgaria, Czech Republic, Germany, Spain, France, Great Britain, Hungary, Northern Macedonia, Italy, Portugal, Sweden, and Serbia.

The location of the known indium deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 17 below. The mines within close range of an indium deposit are also listed as candidates for adopting ION4RAW Table 11 below.

Targets for Mining

Indium is found as a trace element in some zinc, copper, lead and tin minerals but is mostly recovered from the **zinc-sulphide mineral sphalerite**. The concentration of indium in volcanic and sediment-hosted base-metal sulphide deposits, which are generally characterised by high metal abundance, is in the range of 20–200 ppm. Other types of deposits containing significant and recoverable amounts of indium include polymetallic vein-type deposits, vein-stockwork deposits of tin and tungsten and epithermal deposits (Schwarz-Schampera, 2014).

Figure 17 highlights the deposits and close indium mines that could benefit from the ION4RAW technology.

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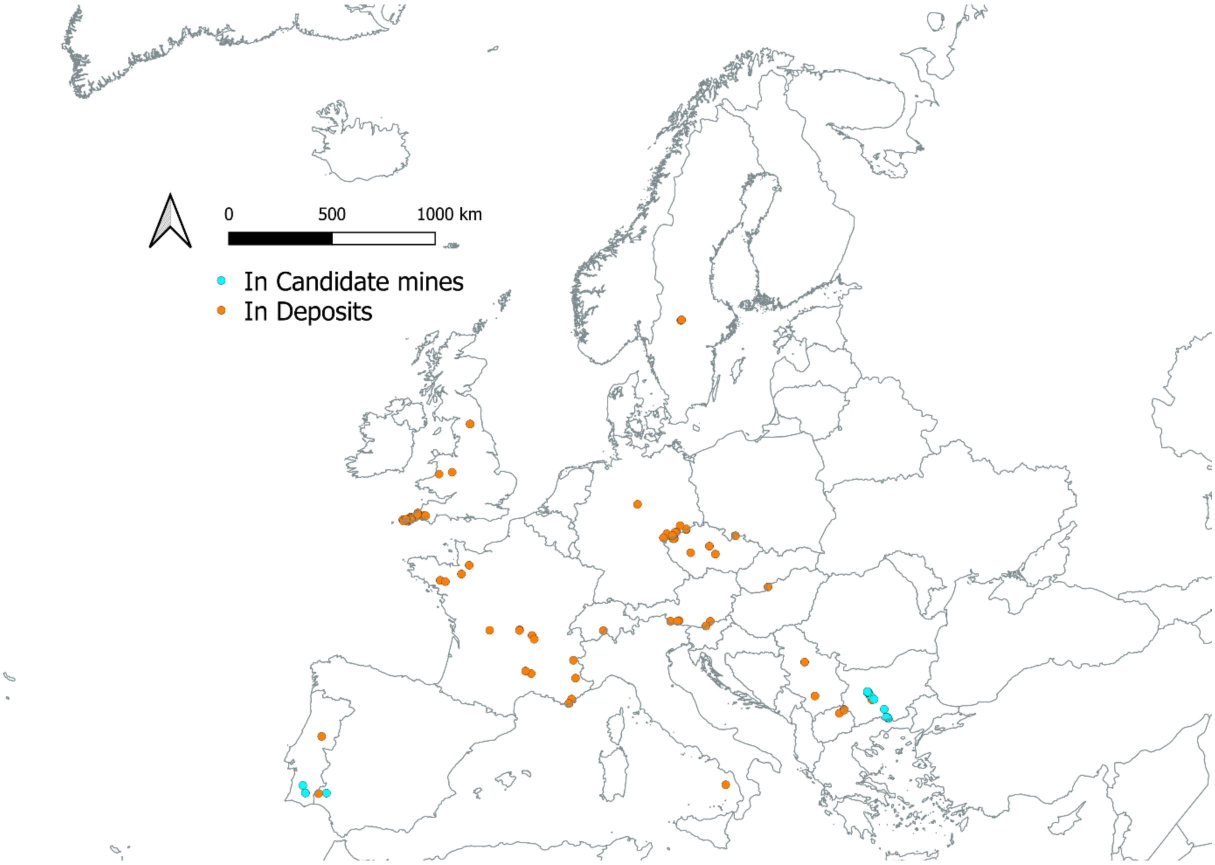

Figure 17. Indium Potential Target Mines and nearby deposits

Table 11 below highlights active mines near indium deposits that could be interested in using the ION4RAW process in order to recover indium.

Table 11. List of potential indium mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Bulgaria	Mine at Panagurishte	Asarel-Medet AD.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Chelopech	Dundee Precious Metals Inc.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Pirdop	Aurubis	Copper
Portugal	Neves Corvo Mine near Castro Verde	Lundin Mining Corp. (LMC)	Copper
Bulgaria	Mine at Erma Reka	Minstroy Holdings	Lead-zinc
Portugal	Aljustrel	I'M SGPS SA	Copper
Spain	MATSA	Government of Abu Dhabi; Trafigura Beheer B.V.	Copper
Bulgaria	Varba-Batantsi	Gorubso-Madan JSC	Zinc
Bulgaria	Mine at Kurdjali*	Velocity Minerals	Gold
Bulgaria	Mine at Laki*	Velocity Minerals	Gold
Bulgaria	Mine at Rudozem*	Rudmetal JSC	Lead-zinc

*Likely Operating

Strategic Considerations for ION4RAW

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- Targeting European market users and countries refining indium: Belgium and France refined Indium from imported concentrates, residues and slags.
    - In France, Nyrstar commissioned a new virgin indium plant at Auby in 2012, which produces indium metal.
    - In Belgium, Umicore produced refined Indium at its Hoboken plant from dust and residues generated by its lead-copper processing plant.
    - In Germany, Saxony Minerals and Exploration AG is working at the Pöhla deposit in Saxony, Germany, with the aim of starting tungsten, tin, indium and fluorite production.
- Despite efforts, recycling of Indium from post-consumer scrap is currently negligible. Very little old scrap (1%) is recycled worldwide because of minor Indium concentrations in final products, a lack of appropriate technology, or low economic incentives compared to recycling costs (Ylä-Mella, 2016).

3.4 Tellurium

Tellurium and ION4RAW

Tellurium is not considered a CRM by the EU. In the ores analysed for the ION4RAW Project by BRGM, tellurium was found in the Cobre las Cruces mine (<2.5 mg/kg), Cononish Gold mine (18.4 mg/kg), El Valle Boinas mine (3.7 mg/kg), El Porvenir mine (60.5 mg/kg), Cerro Lindo Cu mine (<2.5 mg/kg), Cerro Lindo Zn mine (12.5 mg/kg) (BRGM, 2021).

Element description

Tellurium (chemical symbol Te) is a chemical element identified with the atomic number 52. It is considered semi-metal and has both metallic and non-metallic properties. Tellurium is very rare; its share in the earth's crust is about 0.01 ppm. It can be found in its native form, but usually, it occurs in telluride minerals – tellurium compounds with lead and silver (most common), gold, selenium, or platinum. Native tellurium, however, extremely rare, appears as a soft, silvery-white material with a metallic shine.

Processing

The overwhelming majority of tellurium is produced from anode slimes collected from copper refining. The remainder, around 10%, is derived from lead refining skimmings but also from the smelting of bismuth, copper, and lead-zinc ore. (USGS, 2022). The most common method used is through an electrolytic process which is a cost-effective technique applied to high-grade copper ores; tellurium is collected as an impurity of the copper processing.

Figure 18 below illustrates the tellurium value chain, from its exploration to its recycling.

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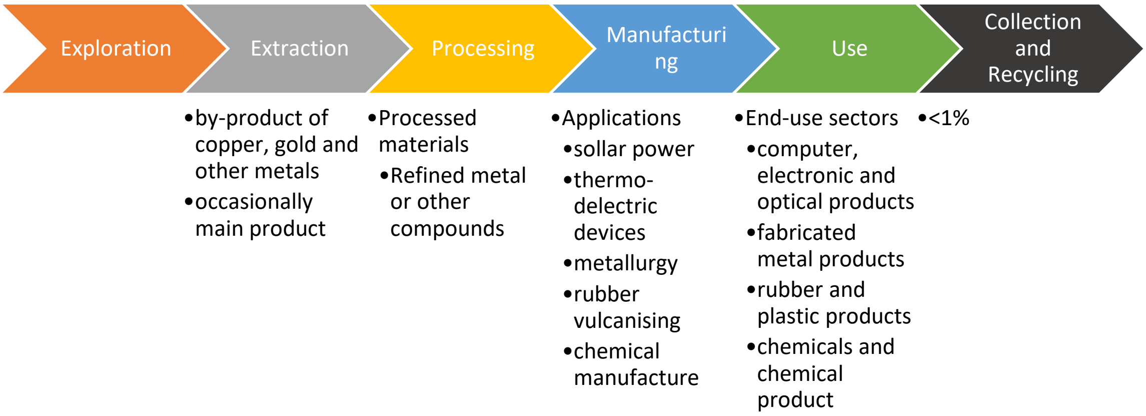

Figure 18. Simplified value chain for Tellurium in the EU (European Commission, 2020)

Global market

Mining data being difficult to obtain most flows record the refined production of tellurium. The United States geological survey reports China with 340 tonnes in 2021. Among the main producing countries are China (54%), the United States (14%), and Japan (10%) (WMD, 2019). Secondary sources for tellurium are of low importance, as its recycling rate is below 1% (UNEP, 2011).

The market for tellurium is not transparent as it is a small market with confidential agreements between producers and consumers. China is the leading producer of refined tellurium, obtained from copper anode slimes and smelting processes. Other significant producers include Japan, Russia, and Sweden. (USGS, 2022)

Tellurium is sold in various forms, such as powder or granules, ingots, or pieces, with a purity of 99.5% or higher. The demand for tellurium is primarily driven by its use in thin-film cadmium telluride solar panels and thermoelectric applications. Major global producers include Umicore, Boliden, Grupo Mexico, Norilsk Nickel, Rio Tinto, 5N Plus, and II-VI Incorporated. First Solar is the largest producer of Cd-Te solar panels but doesn't disclose the quantities of tellurium they consume.

The tellurium market was projected to grow at a rate of 3% annually from 2018 to 2022, mainly due to its use in Cd-Te thin film solar panels and the investigation of new applications.

First Solar is expected to produce 16GW of Cd-Te solar panels annually by 2024. This increase in production could result in the company's demand for tellurium exceeding the global supply by up to 70% in 2020. (S&P Global, 2021) First Solar is seen as a more responsible alternative as they do not use polysilicon. Polysilicon manufacturers in China's Xinjiang region could be linked with the suppression of Uyghur and Muslim minorities, including forced labour. (S&P Global, 2021)

To enhance and streamline the tellurium market, copper producers need to recognise its financial viability. Typically, higher demand leads to higher prices that would be coupled with increased capital investments. However, to achieve this, many observers believe that tellurium prices need to rise significantly to attract more investment. (S&P Global, 2021)

EU Supply trends

In the EU, Sweden has large reserves in the Kankberg mine operated by Boliden and produced around 40 tonnes per year from 2012 to 2016 (European Commission, 2020). Bulgaria also produced refined tellurium with around 5 tonnes per year (European Commission, 2020).

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Depending on the year, the EU is a net exporter or net importer of tellurium. The EU had an average apparent consumption of 27 t per year in the period 2012-2016. In 2017 and 2018, imports amounted to 216 and 777 tonnes, whereas exported tellurium amounts remained constant at 478 and 417 tonnes (Blengini, Latunussa, & Eynard, 2020).

Known EU Deposits

As previously mentioned, in the EU, Sweden has large reserves in the Kankberg mine operated by Boliden and in Bulgaria. WP2 of ION4RAW has also identified tellurium resources in Bulgaria, Finland, France, Great Britain, Italy, Poland, Romania, and Serbia.

The location of the known tellurium deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 19 below. The mines within close range of a tellurium deposit are also listed as candidates for adopting ION4RAW in Table 12.

Targets for Mining

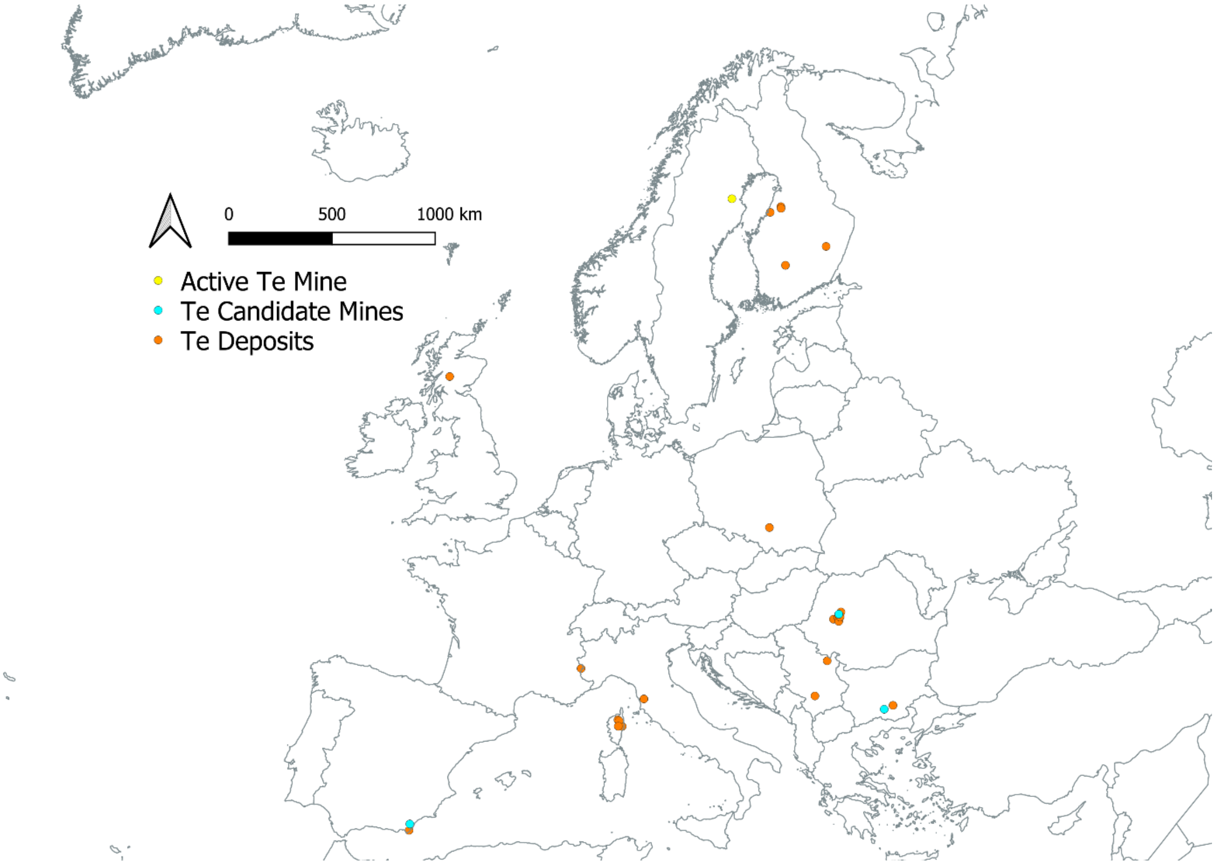

Figure 19. Tellurium potential target mines close to deposits

Table 12 below highlights potential mines that could be interested in using the ION4RAW process in order to recover tellurium.

Table 12. List of potential tellurium mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Sweden	Mine at Kankberg	Boliden Mineral AB	Gold, Tellurium
Romania	Baita Plai	Vast Resources PLC	Copper
Bulgaria	Chala	Gorubso-Kardzhali AD	Gold
United Kingdom	Cononish	Scotgold Resources Limited	Gold
Finland	Kaapelinkulma	Dragon Mining Limited	Gold

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Country	Mine	Company	Commodity
Finland	Orivesi	Dragon Mining Limited	Gold
Finland	Outokumpu Mining Camp	FinnCobalt	Cobalt, Nickel
Romania	Rosia Poieni Mine	Cuprumin	Copper
Spain	Cerro Colorado open pit mine	Atalaya Mining	Copper
Bulgaria	Mine at Laki*	Velocity Minerals	Gold

*Likely operating

Strategic Considerations

- Boliden, a large Swedish mining company, could be considered as a potential client for the uptake of the ION4RAW technology.
- Beyond the EU, the main consumers of the EU's tellurium exports are China (46%), Morocco (18%), and Thailand (16%).

3.5 Copper

Copper and ION4RAW

Copper is not considered a CRM for the EU; however, its use will be crucial to the global energy transition as the world could consume between 60% and 90% of copper resources by 2050 (Les Echos, 2022). The ores analysed for the ION4RAW Project are sulfidic ores, where copper is a carrier metal. In the samples analysed by BRGM, copper was found in the Cobre las Cruces mine (36,913 mg/kg), Cononish Gold mine (836 mg/kg), El Valle Boinas mine (3,808 mg/kg), El Porvenir mine (2,756 mg/kg), Cerro Lindo Cu mine (5,465 mg/kg), Cerro Lindo Zn mine (27,030 mg/kg) (BRGM, 2021).

Element description

Copper (chemical symbol Cu; from Latin "cuprum") is a ductile, reddish metal used since the early days of human history. It is an important trace element for many living organisms, including humans (Lossin, 2001). There are over 150 identified copper minerals, but only around ten of them are of economic importance. About half of the world's copper production is mined from chalcopyrite ($CuFeS_2$) (BGS, 2007). Copper does not react with water but slowly reacts with atmospheric oxygen. This oxidation forms a thin protective layer of brown-black copper oxide that prevents the bulk of the copper from being oxidised. In the absence of air, copper is also resistant to many acids, such as hydrochloric acid, sulphuric acid or acetic acid (Römpp , 2006).

Processing

Figure 20 below illustrates the copper value chain, from its exploration to its recycling.

Mined ores generally contain 0.5 to 3% copper. The first phase in processing the ore is concentration, which increases the copper content to 25 to 35%. This is carried out at the mine site, involving crushing and grinding, followed by physical processing and separation stages. The conversion into pure copper is done using two techniques: pyrometallurgical processes (including smelting and electrolytic refining) and hydrometallurgical processes (including leaching, solvent extraction and electro-winning).

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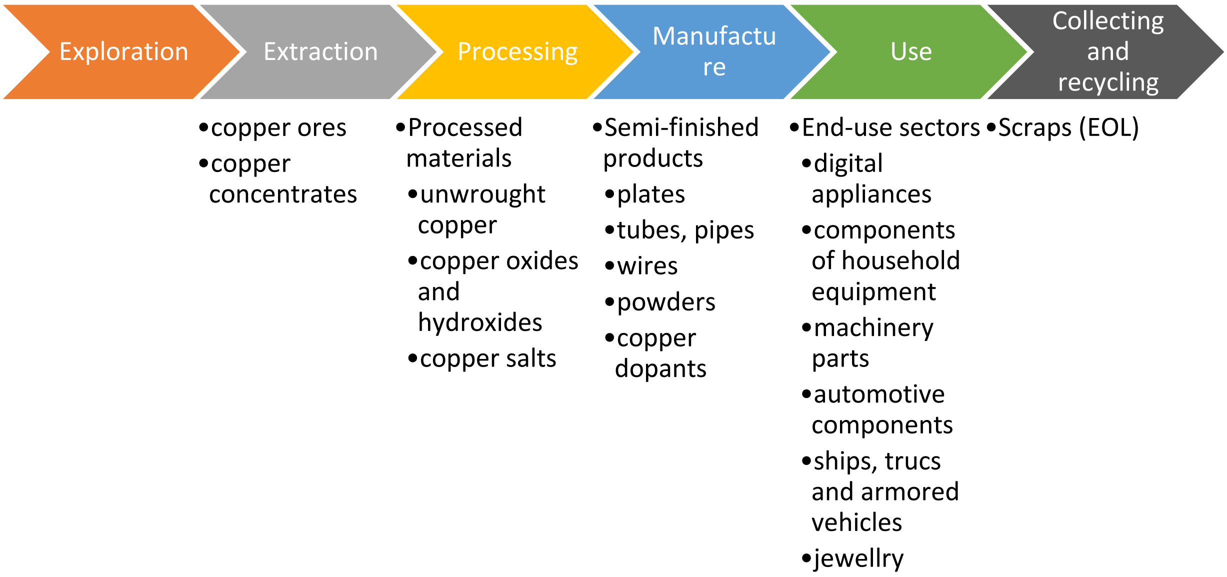

Figure 20. Simplified value chain for copper for the EU (European Commission, 2020)

Global Market

Global mine production in 2021 was about 21,000 Ktonnes. Chile was a significant player (5600 ktonnes) before China (1800ktonnes), the Democratic Republique of Congo (1800 Ktonnes), Peru (2200ktonnes), the US (1200Ktonnes), Australia (900Ktonnes). Other countries were important such as Russia (820Ktonnes), Zambia (820 Ktonnes), Mexico (720 Ktonnes), and Indonesia (810 Ktonnes). (USGS 2022)

Most reserves are in Chile (about 23% of the world's reserves), while other significant reserves are in Australia, Peru, Russia, Mexico, and the US.

Copper trading takes place in the London Metal Exchange (LME), the Commodity Exchange Division of the New York Mercantile Exchange (COMEX/NYMEX) and the Shanghai Futures Exchange (SHFE). Recently, contracts of smaller lot sizes were introduced at the exchanges (ICSG, 2019a)

A few major players dominate a significant portion of the market. The top 5 biggest copper miners are Codelco, Freeport McMoRan, Glencore, BHP and Southern Copper. The copper market size is expected to grow by a Compound Annual Growth Rate of 3.26% between 2021 and 2026, with the fastest growth happening in Asia-Pacific. Increasing demand from the construction, electrical and electronic industries will boost the market's growth (Technavio, 2022).

It is expected for copper demand to grow in the coming decades due to the increased demand for electric motors and vehicles (SGU, 2019).

EU Supply trends

Copper trends can be assessed at the mine stage and processing stage, and most commonly, copper is traded in the form of concentrates.

Mining activity in the EU mainly takes place in Poland, Spain, Bulgaria, Sweden, Portugal, and Finland. In addition, small amounts are mined in Romania, Cyprus and Slovakia.

The average EU imports of copper ores and concentrates for the period 2012-2016 amounted to 766 ktonnes, coming principally from Chile (27%), Peru (19%) and Brazil (14%). Within the EU, major international importers of ores and concentrates are Germany, Bulgaria and Finland (ICSG, 2019a).

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The biggest share of the refined copper supply was sourced from within the EU, from Germany (22%), Poland (18%), Spain (13%), and Belgium (13%), which made up two-thirds of the average total sourcing for the period 2012- 2016. By far, the largest non-EU supplier was Russia (67%), followed by Kazakhstan, the United Kingdom, Serbia and South Africa (each 1%). The world's main producers of refined copper, China, Chile and Japan, seem to direct their refined copper to other destinations outside the EU or use the commodity themselves.

Known EU Deposits

Mining activity in the EU mainly takes place in Poland, Spain, Bulgaria, Sweden, Portugal, and Finland. In addition, small amounts are mined in Romania, Cyprus, and Slovakia.

Europe has significant copper deposits in Poland, with resources of about 34 Mtonnes of copper (USGS, 2013)and resource data for some countries in Europe are available on the Minerals4EU (2019) website. WP2 of this project has identified copper deposits in the following countries: Albania, Armenia, Austria, Bulgaria, Belgium, Bosnia and Herzegovina, Czech Republic, Cyprus, Germany, Spain, Finland, France, Great Britain, Greece, Hungary, Ireland, Italy, Northern Macedonia, Norway, Poland, Portugal, Romania, Slovakia, Sweden, and Serbia.

Targets for Mining

There are many copper mines in the EU. For the purpose of ION4RAW, mines with demonstrated or suspected presence of other target by-product metals should be prioritised. The location of the known copper deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 21 below. The active copper mines (or mines within close range of a copper deposit) are also listed as candidates for adopting ION4RAW in Table 13.

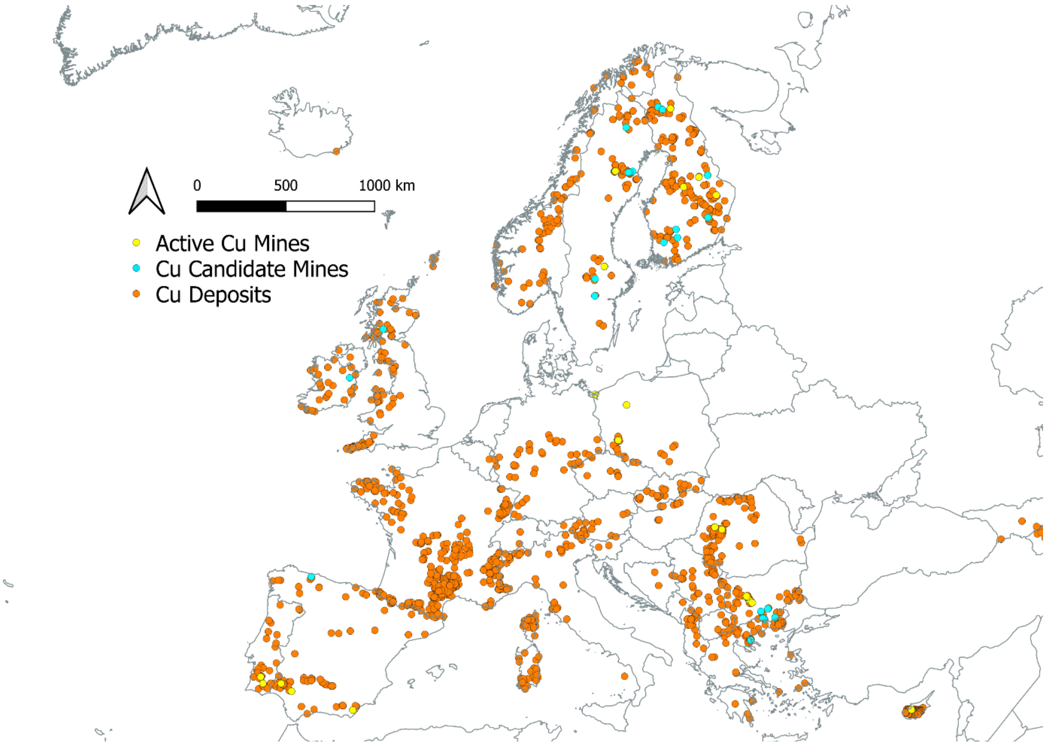

Figure 21. copper potential target mines close to deposits

Table 13 highlights potential mines (copper, cobalt, gold, nickel, zinc, platinum, silver) that could be interested in using the ION4RAW process in order to recover copper.

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Table 13. List of potential copper mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Portugal	Aljustrel	I'M SGPS SA	Copper
Bulgaria	Mine at Panagurishte	Asarel-Medet AD.	Copper
Spain	MATSA	Government of Abu Dhabi; Trafigura Beheer B.V.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Cyprus	Skouriotissa	Hellenic Copper Mines Ltd	Copper
Spain	Las Cruces	First Quantum Minerals Limited	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Pirdop	Aurubis	Copper
Romania	Rosia Poieni Mine	Cuprumin	Copper
Spain	Cerro Colorado open pit mine	Atalaya Mining	Copper
Romania	Baita Plai	Vast Resources PLC	Copper
Finland	Kylylahti	Boliden AB	Copper, Cobalt, Gold, Nickel, Zinc
Finland	Kevitsa	Boliden AB	Copper, Cobalt, Gold, Platinum
Bulgaria	Mine at Chelopech	Chelopech Mining Ltd	Copper, Gold
Sweden	Mine at Garpenberg	Boliden AB	Copper, Gold, Lead, Silver, Zinc
Sweden	Mine at Kristineberg	Boliden Mineral AB	Copper, Gold, Lead, Silver, Zinc
Finland	Mine at Pyhasalmi	First Quantum Minerals	Copper, Gold, Pyrite, Zinc
Sweden	Mine at Aitik	Boliden Mineral AB	Copper, Gold, Silver
Sweden	Mine at Renstrom	Boliden Mineral AB	Copper, Lead, Gold, Silver, Zinc
Sweden	Zinkgruvan Mine	Lundin Mining Corp. (LMC)	Copper, Lead, Silver, Zinc
Finland	Sotkamon Kaivos	Terrafame Oy	Copper, Nickel, Zinc
Poland	Rudna Mine	KGHM	Copper, Silver
Poland	Polkowice-Sieroszowice Mine	KGHM	Copper, Silver
Poland	Lubin Mine	KGHM	Copper, Silver
Portugal	Neves Corvo Mine near Castro Verde	Lundin Mining Corp. (LMC)	Copper, Zinc
Finland	Outokumpu Mining Camp	FinnCobalt	Cobalt, Nickel
United Kingdom	Cononish	Scotgold Resources Limited	Gold
Finland	Orivesi	Dragon Mining Limited	Gold
Bulgaria	Chala	Gorubso-Kardzhali AD	Gold
Bulgaria	Ada Tepe	Dundee Precious Metals Inc.	Gold
Finland	Jokisivu	Dragon Mining Limited	Gold
Finland	Kaapelinkulma	Dragon Mining Limited	Gold
Bulgaria	Mine at Kurdjali	Gorubso Co.	Gold
Bulgaria	Mine at Laki	Gorubso Co.	Gold
Finland	Pahtavaara Mine	Rupert Resources	Gold
Greece	Kassandra Mine	Hellas Gold S.A.	Gold
Spain	El Valle and Carles mines	Orvana	Gold
Sweden	Bjorkdal Mine	Mandalay Resources	Gold

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Country	Mine	Company	Commodity
Finland	Kittilä mine	Agnico Eagle	Gold
Sweden	Mine at Kankberg	Boliden Mineral AB	Gold, Tellurium
Sweden	Lovisa	Lovisagruvan AB	Lead
Bulgaria	Mine at Erma Reka	Minstroy Holdings	Lead-zinc
Bulgaria	Mine at Rudozem	Rudmetal JSC	Lead-zinc
Greece	Stratoni	Eldorado Gold Corporation	Silver
Finland	Silver Mine	Sotkamo Silver Aktiebolag	Silver
Ireland	Tara Mine	Boliden Mineral AB	Silver, Lead-zinc
Bulgaria	Varba-Batantsi	Gorubso-Madan JSC	Zinc

Strategic Considerations for ION4RAW

- European mine production is dominated by the production in **Poland, which accounts for over half of the copper mining in Europe** (WMD, 2019).
- The conversion into pure copper is done using two techniques: In targeting the candidate mines, it would be worth considering the suitability of either pyrometallurgical processes (including smelting and electrolytic refining) and hydrometallurgical processes (including leaching, solvent extraction and electro-winning) at the target mines with the ION4RAW process.

3.6 Silver

Silver and ION4RAW

Silver is not considered a CRM for the EU. Silver is a by-product in sulfidic ores, and in the ores analysed for the ION4RAW Project by BRGM, silver was in the Cobre las Cruces mine (27.0 mg/kg), Cononish Gold mine (38.7 mg/kg), El Valle Boinas mine (18.3 mg/kg), El Porvenir mine (144 mg/kg), Cerro Lindo Cu mine (47.9 mg/kg), Cerro Lindo Zn mine (115 mg/kg) (BRGM, 2021).

Element description

Silver (chemical symbol Ag) is a chemical element with atomic number 47. Silver is one of the eight precious or noble metals which are resistant to corrosion. This metal is soft, very malleable and ductile and has the highest electrical and thermal conductivity of all metals (Lenntech, 2016). The presence of Silver in the earth's crust is somewhat rare, with 53 parts per million upper crustal abundance (Rudnick, 2003).

Silver is almost always monovalent in its compounds, but an oxide, a fluoride, and a sulphide of divalent silver are known. It is not a chemically active metal but reacts with nitric acid (forming the nitrate) and hot concentrated sulphuric acid. It does not oxidise in air but reacts with the hydrogen sulphide present in the air, forming silver sulphide (tarnish). This is why silver objects need regular cleaning. Silver is stable in water.

The value chain of silver is explained in Figure 22.

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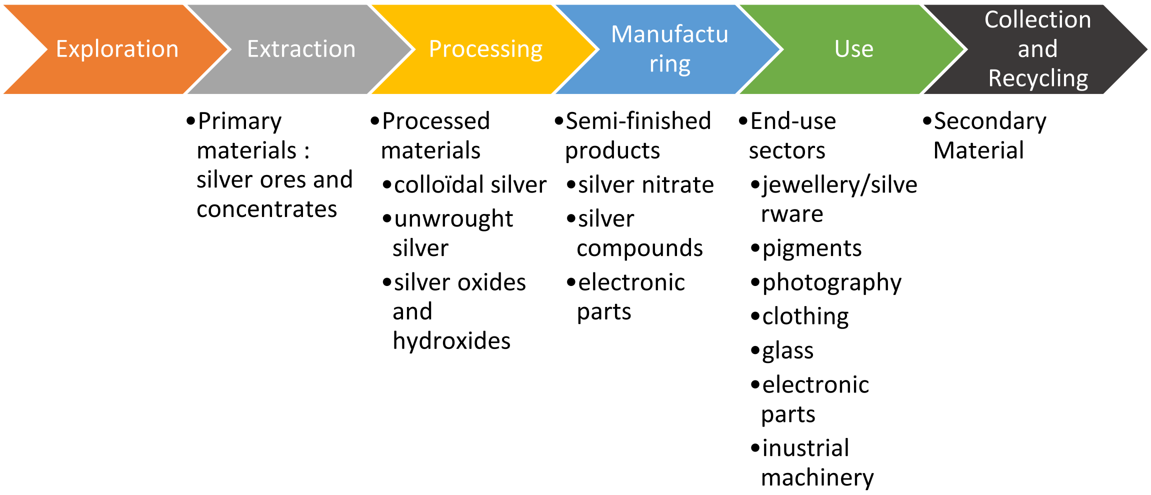

Figure 22. Simplified value chain for Silver (European Commission, 2020)

Global Market

The average global production of silver ore was 24,000 tonnes in 2021 ((USGS, 2022). Only about 30% of the annual supply comes from primary silver mines, while over a third is produced at lead/zinc operations and 20% from copper mines (Mining Intelligence, 2019). Mexico is the world's leading silver ore producer (5,600 tonnes), followed by China (3,400 tonnes), Peru (3,000 tonnes), then Chile (1,600 tonnes) and Russia (1,300 tonnes). (USGS, 2022)

Six of the top 20 producers are primary silver miners. The primary players in silver production include Industrias Penoles (Mexico), Fresnillo (Mexico), Polymetal International (Russia), Pan American Silver Corp (Canada), Wheaton Precious Metals (Canada), Coeur Mining (North & South America), and Buenaventura Mining (Peru).

Silver reserves are estimated to be around 530,000 tonnes worldwide, with major reserves found in Peru (120,000 tonnes), Australia (90,000 tonnes), and Poland (67,000 tonnes). Silver ore production increased in 2021 from 2020 in Argentina, India, Mexico, and Peru after shutdowns due to the COVID-19 pandemic. (USGS, 2022)

The estimated domestic uses for silver were a physical investment (26%), electrical and electronics (21%), coins and medals (11%), jewelry and silverware (4%), and other (38%). Other applications for silver include use in antimicrobial bandages, clothing, pharmaceuticals, and plastics, batteries, bearings, brazing and soldering, catalytic converters in automobiles, electroplating, inks, mirrors, photography, photovoltaic solar cells, water purification, and wood treatment.

The diversity in production is also demonstrated in the global imports and exports of silver. The order of magnitude of the market value of the annual silver imports and exports is estimated at USD 900 million and USD 1.42 billion, respectively (UN Comtrade, 2019).

Silver demand is expected to increase in the future due to the expected growth of electric vehicles (EVs) and continued investment in solar photovoltaic energy. Additionally, the use of inductively coupled power transfer technology to wirelessly charge vehicles using silver-plated induction coils and the use of silver in the generation of nuclear energy may significantly contribute to the low-carbon economy that the EU is pursuing for 2050.

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EU Supply trends

Silver nowadays is primarily obtained as a by-product **from lead-zinc mines, copper mines, and gold mines**. Most recent silver discoveries have been associated with gold occurrences; however, copper and lead-zinc occurrences that contain by-product silver will continue to account for a significant share of reserves and resources in the future.

Known EU Deposits

The EU mine production of silver is concentrated in Poland and Sweden, that account for 5% and 2% of the global production, respectively. WP2 of ION4RAW has identified silver resources in the following countries: Albania, Armenia, Austria, Azerbaijan, Belgium, Bulgaria, Bosnia and Herzegovina, Czech Republic, Cyprus, Switzerland, Germany, Spain, Finland, France, Great Britain, Greece, Hungary, Ireland, Italy, Northern Macedonia, Norway, Poland, Portugal, Romania, Slovakia, Sweden, Ukraine, and Serbia.

Targets for Mining

The location of the known silver deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 23 below. The active silver mines or mines within close range of a silver deposit are also listed as candidates for adopting ION4RAW in Table 14.

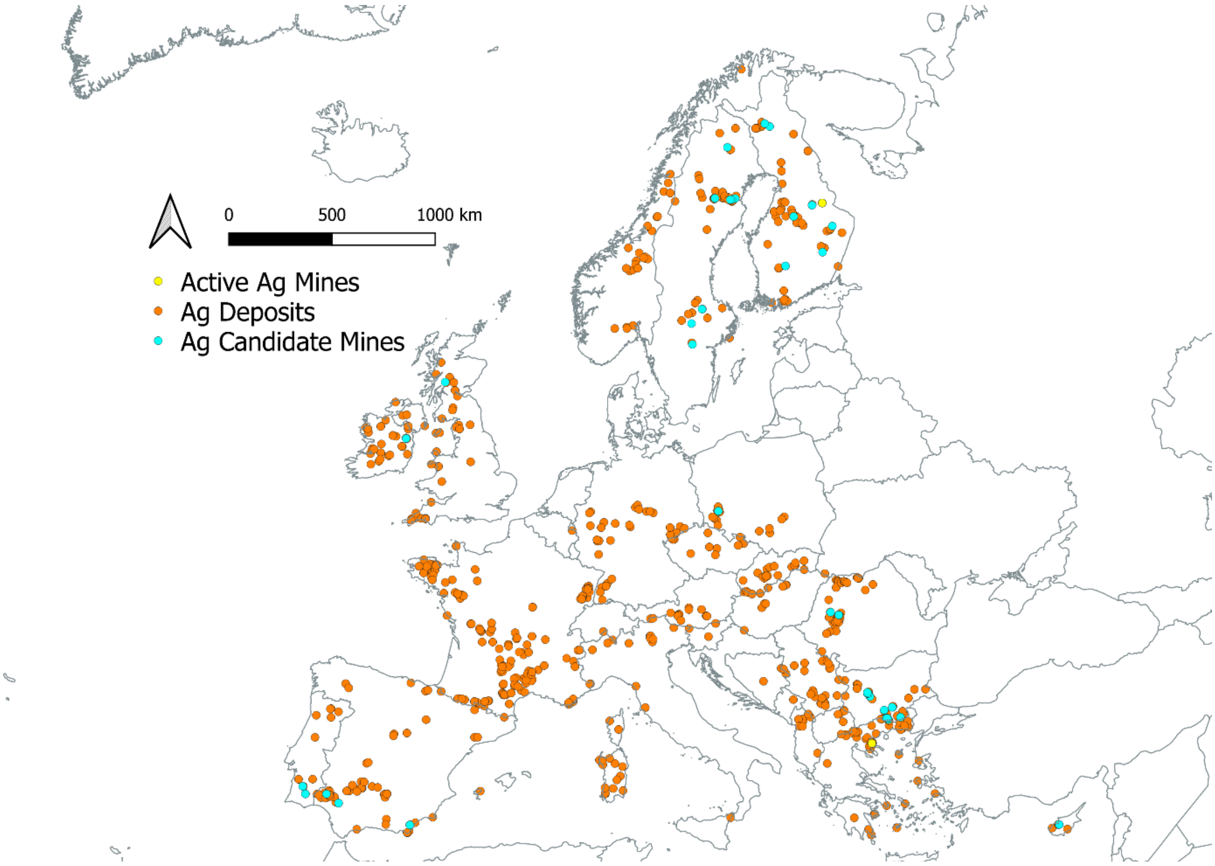

Figure 23. Silver potential target mines close to deposits

Table 14 highlights potential mines (silver, zinc, lead, copper, gold, lead, pyrite, gold) that could be interested in using the ION4RAW process to recover silver.

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Table 14. List of potential silver mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Greece	Stratoni	Eldorado Gold Corporation	Silver
Finland	Silver Mine	Sotkamo Silver Aktiebolag	Silver
Sweden	Zinkgruvan Mine	Lundin Mining Corp. (LMC)	Zinc, Lead, Copper, Silver
Sweden	Mine at Aitik	Boliden Mineral AB	Copper, Gold, Silver
Sweden	Mine at Kristineberg	Boliden Mineral AB	Zinc, Copper, Lead, Gold, Silver
Sweden	Mine at Renstrom	Boliden Mineral AB	Zinc, Copper, Lead, Gold, Silver
Poland	Polkowice-Sieroszowice Mine	KGHM	Copper, Silver
Sweden	Mine at Garpenberg	Boliden Mineral AB	Zinc, Silver, Copper, Gold, Lead
Ireland	Tara Mine	Boliden Mineral AB	Silver, Lead-zinc
Greece	Kassandra Mine	Hellas Gold S.A.	Gold
Sweden	Bjorkdal Mine	Mandalay Resources	Gold
Bulgaria	Mine at Panagurishte	Asarel-Medet AD.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Chelopech	Dundee Precious Metals Inc.	Gold, Copper
Bulgaria	Mine at Pirdop	Aurubis	Copper
Finland	Mine at Pyhasalmi	First Quantum Minerals	Copper; Zinc; Gold; Pyrite
Finland	Pahtavaara Mine	Rupert Resources	Gold
Portugal	Neves Corvo Mine near Castro Verde	Lundin Mining Corp. (LMC)	Copper, Zinc
Romania	Rosia Poieni Mine	Cuprumin	Copper
Spain	Alfredo underground mine	Atlantic Copper S.A. / Freeport McMoRan Copper & Gold Inc.	Copper
Spain	Cerro Colorado open pit mine	Atalaya Mining	Copper
Sweden	Mine at Kankberg	Boliden Mineral AB	Gold, Tellurium
Bulgaria	Mine at Erma Reka	Minstroy Holdings	Lead-zinc
Bulgaria	Mine at Kurdjali	Velocity Minerals	Gold
Bulgaria	Mine at Laki	Velocity Minerals	Gold
Bulgaria	Mine at Rudozem	Rudmetal JSC	Lead-zinc
Bulgaria	Ada Tepe	Dundee Precious Metals Inc.	Gold
Portugal	Aljustrel	I'M SGPS SA	Copper
Romania	Baita Plai	Vast Resources PLC	Copper
Bulgaria	Chala	Gorubso-Kardzhali AD	Gold
United Kingdom	Cononish	Scotgold Resources Limited	Gold
Finland	Kittilä mine	Agnico Eagle	Gold
Finland	Kylylahti	Boliden AB	Copper, Cobalt, Gold, Nickel, Zinc
Spain	Las Cruces	First Quantum Minerals Limited	Copper
Sweden	Lovisa	Lovisagruvan AB	Lead
Spain	MATSA	Government of Abu Dhabi; Trafigura Beheer B.V.	Copper
Finland	Orivesi	Dragon Mining Limited	Gold
Finland	Outokumpu Mining Camp	FinnCobalt	Cobalt, Nickel
Cyprus	Skouriotissa	Hellenic Copper Mines Ltd	Copper
Finland	Sotkamon Kaivos	Terrafame Oy	Copper, Nickel, Zinc
Bulgaria	Varba-Batantsi	Gorubso-Madan JSC	Zinc

Strategic Considerations

- Consider targeting lead-zinc, copper and gold mines since Silver is a by-product.
- The EU mine production of silver is concentrated in Poland and Sweden, that account for 5% and 2% of the global production, respectively.

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3.7 Gold

Gold and ION4RAW

Gold is not considered a CRM for the EU. Gold is a by-product in sulfidic ores, and in the ores analysed for the ION4RAW Project by BRGM, gold was in the Cobre las Cruces mine (0.37 mg/kg), Cononish Gold mine (8.32 mg/kg), El Valle Boinas mine (2.54 mg/kg), El Porvenir mine (0.96 mg/kg), Cerro Lindo Cu mine (0.11 mg/kg), Cerro Lindo Zn mine (0.36 mg/kg) (BRGM, 2021).

Element description

Gold (chemical symbol Au; atomic number 79; atomic weight: 196.967; melting point: 1,064.18°C; boiling point: 2,856°C; density: 19.32 g/cm^3) is a dense, soft, malleable and ductile metal with a bright yellow colour and lustre. Gold, like silver and platinum-group metals, is a noble and precious metal. The term 'noble' refers to gold's ability to resist corrosion and oxidation in moist air. It has high thermal and electrical conductivity. It is rare in the Earth's crust, with an estimated abundance of 0.004 ppm (Lide, 2008). It is found in veins and alluvial deposits chiefly as the native metal, although it commonly occurs in a solid solution series with silver (as electrum) and alloyed with copper and palladium. Less commonly, it occurs in minerals as gold compounds, often with tellurium.

Figure 24 highlights the value chain for gold.

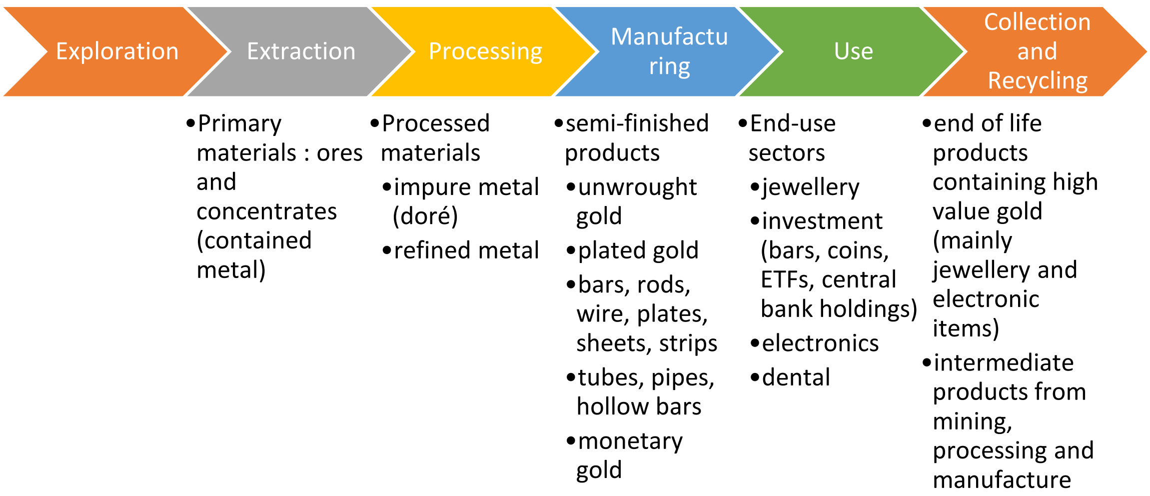

Figure 24.Value chain for gold

Global Market

The global gold mining market was valued at USD 197.58 billion in 2021 and saw significant volatility in 2020 due to the COVID-19 pandemic and other factors. Despite the instability in economies, gold is seen as consistently in high demand, making jewellery a valuable asset that can be easily liquidated when necessary, driving the market growth.

There is no single country that dominates the global gold market. Although China is a top producer of refined gold, its production is comparable to other countries. The top 5 producers in 2021 were China (365 tonnes), Australia (330 tonnes), Russia (300 tonnes), the USA (180 tonnes), and Canada (170 tonnes), for the global production of 3000 tonnes. (USGS, 2022) The leading market players and top 5 gold-producing companies are Newmont, Barrick Gold, Navoi Mining & Metallurgical, PJSC Polyus, and AngloGold Ashanti.

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The largest gold reserves are found in Australia, accounting for approximately 20% of the global total, with the remaining reserves spread across various countries. (USGS, 2022)

In 2021, China and India were the top importers, followed by Switzerland, the UAE, South Africa, and Guinea.

Gold's luster, colour, and resistance to tarnishing give it a "precious" character, making it a highly sought-after material for jewellery, its primary use. Furthermore, gold is used as a currency standard in coins and bars, a safe haven for preserving wealth, decoration, and plating on a range of electrical and electronic equipment. Additionally, gold-198, a radioisotope with a half-life of 2.69 days, is used in certain cancer treatments in medicine and dentistry.

Gold trading operates on a global scale, with key trading centres being the London OTC market, the US futures market, and the Shanghai Gold Exchange. These markets account for over 90% of global trading and are connected through arbitrage activities, but there are still differences in regulations, taxes, and bar standards between countries that prevent a single integrated market from existing.

Gold is mostly traded as bullion with a fineness ranging from 995 to 998, and it can also be traded in various forms, such as unwrought gold, plated gold, powder, granules, bars, and more.

The market value of the annual gold production is estimated at USD 7 trillion.

Gold and its alloys are traded in a wide variety of forms, including unwrought gold, plated gold, powder, granules, bars, rods, wire, plate strips, sheets, foils, tubes and pipes, which brings complexity to the market.

EU Supply trends

Gold supplies are derived from primary sources (mines), both within and outside the EU, and from secondary sources (refineries), both within and outside the EU.

From outside the EU, imports of precious metals, ores and concentrates were dominated in the period 2012-2016 by South Africa, with close to 74 % of the total by value.

Gold is **mined in several EU member states** (primarily in Finland, Sweden, Bulgaria, Spain and Turkey), but the corresponding production levels are relatively small on a global scale (0.8% in total). Mined Gold is further **refined in processing** installations located in these countries or in other European countries, such as **Poland**.

Europe has important gold refining and fabrication industries based on supply from both primary and secondary materials derived from sources within and outside the EU. China is the world's largest producer (14%), followed by Australia (8%), Russia (8%) and the United States (7%). In the EU, Finland is the biggest producer averaging 8.6 tonnes per year (0.3% worldwide) over 2012-2016. Bulgaria and Sweden produce 7.2 and 6.4 tonnes per year, respectively, and the rest of Europe contributes with another 4.8 tonnes per year (WMD, 2019)

On average, for the period 2012-2016, the EU consumed about 300 tonnes per year of gold to produce jewellery and for technology and dentistry uses (World Gold Council 2019d).

Known EU Deposits

- **Various gold mines exist in the EU countries**, in particular in Sweden (8 Boliden mines, Blaiken mine, Svartliden mine and Faboliden mine), Finland (Pahtavaara mine, Kittila mine, Orivesi

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mine), Spain (2 Rio Narcea mines), Greenland (Nalunaq mine), Ireland (Omagh mine) and Portugal, with large mining projects and important gold exploration projects (TGM, 2019).

- In the Balkans, Bulgaria operates the Chelopech mine, the Kardzhali mine has been licensed, and the Krumovgrand mine is expected to get its license.
- In Romania, the gold mine of Rosia Montana is expected to get its license, while in Serbia, it has been announced that three state mines have been conceded to a major gold mining company for further exploration. The same happened recently in Kosovo (TGM, 2019).
- In Greece, Hellas Gold has been given a mining license quite recently (September 2019), and the company is beginning operations.
- In Turkey, the Turkish Gold Miners Association showed ten active gold mines in 2014. The gold mines of Cayeli, Mastra, Kisladag and Efemcukuru are operating, while two more mines are under development. There are currently approximately 70 active gold research and exploration projects in Turkey. Eldorado Gold, Thracean Gold Mining's parent company, developed and operates the Kisladag and Efemcukuru gold mines in Turkey.
- WP2 has identified additional gold deposits in the following countries: Albania, Armenia, Austria, Azerbaijan, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Spain, Finland, France, Great Britain, Georgia, Greece, Hungary, Ireland, Italy, Northern Macedonia, Norway, Pakistan, Poland, Portugal, Romania, and Slovakia.

Targets for Mining

The location of the known gold deposits, as well as active mines that are within 50km of these deposits, are shown in Figure 25 below. The active gold mines or mines within close range of a gold deposit are also listed as candidates for adopting ION4RAW in Table 15.

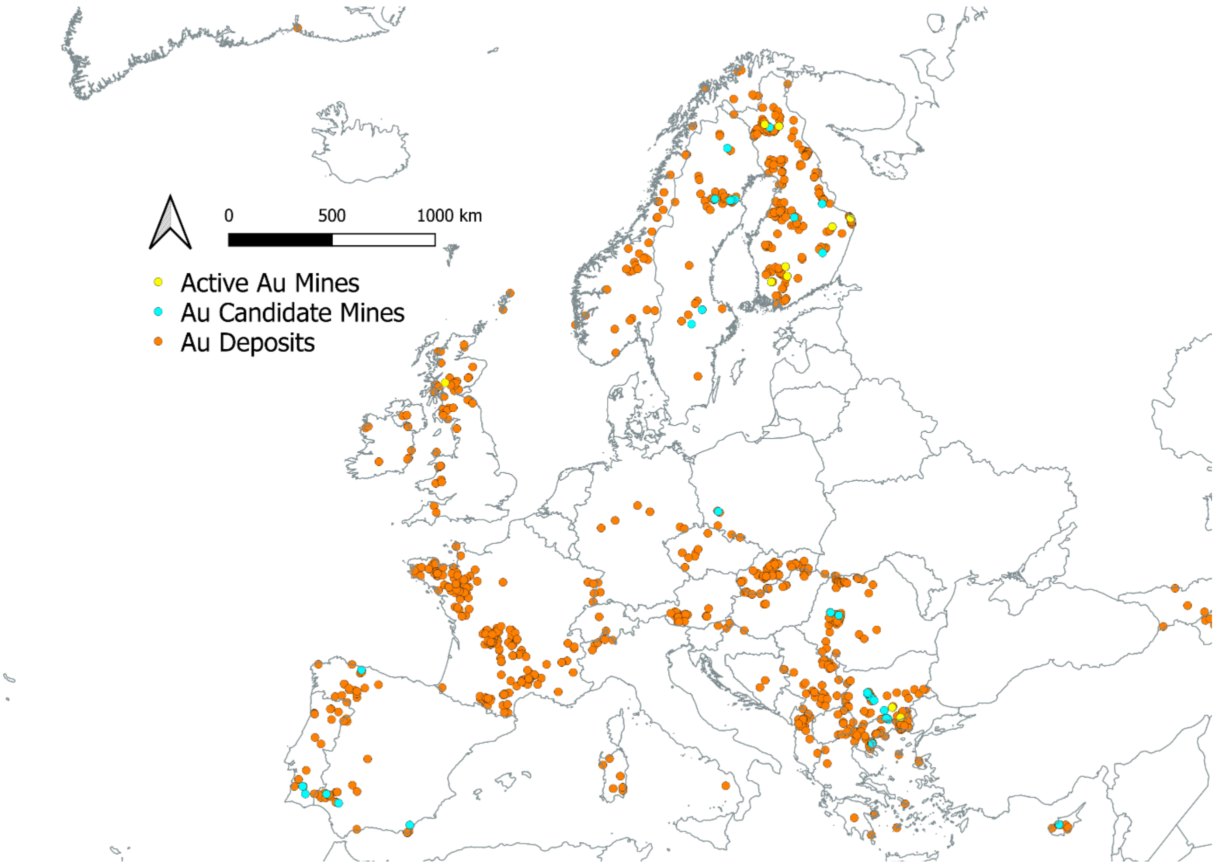

Figure 25. gold potential target mines close to deposits

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Table 15 highlights potential mines (copper, cobalt, gold, nickel, zinc, platinum, silver, tellurium) that could be interested in using the ION4RAW process in order to recover gold.

Table 15. List of potential gold mines that could implement the ION4RAW technology

Country	Mine	Company	Commodity
Finland	Pahtavaara Mine	Rupert Resources	Gold
Greece	Kassandra Mine	Hellas Gold S.A.	Gold
Spain	El Valle and Carles mines	Orvana	Gold
Sweden	Bjorkdal Mine	Mandalay Resources	Gold
Sweden	Mine at Kankberg	Boliden Mineral AB	Gold, Tellurium
Bulgaria	Mine at Kurdjali	Gorubso Co.	Gold
Bulgaria	Mine at Laki	Gorubso Co.	Gold
Bulgaria	Ada Tepe	Dundee Precious Metals Inc.	Gold
Bulgaria	Chala	Gorubso-Kardzhali AD	Gold
United Kingdom	Cononish	Scotgold Resources Limited	Gold
Finland	Jokisivu	Dragon Mining Limited	Gold
Finland	Kaapelinkulma	Dragon Mining Limited	Gold
Finland	Kittilä mine	Agnico Eagle	Gold
Finland	Orivesi	Dragon Mining Limited	Gold
Finland	Pamaplo	Endomines Oy	Gold
Sweden	Mine at Aitik	Boliden Mineral AB	Copper, Gold, Silver
Sweden	Mine at Kristineberg	Boliden Mineral AB	Zinc, Copper, Lead, Gold, Silver
Sweden	Mine at Renstrom	Boliden Mineral AB	Zinc, Copper, Lead, Gold, Silver
Bulgaria	Mine at Chelopech	Chelopech Mining Ltd	Gold, Copper
Finland	Mine at Pyhasalmi	First Quantum Minerals	Copper; Zinc; Gold; Pyrite
Sweden	Mine at Garpenberg	Boliden AB	Zinc, Silver, Copper, Gold, Lead
Sweden	Mine at Kristineberg	Boliden Mineral AB	Zinc, Copper, Lead, Gold, Silver
Finland	Kevitsa	Boliden AB	Cobalt, Copper, Gold, Platinum
Finland	Kylylahti	Boliden AB	Copper, Cobalt, Gold, Nickel, Zinc
Bulgaria	Mine at Panagurishte	Asarel-Medet AD.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Srednogorie	Elatzite-Med Ltd.	Copper
Bulgaria	Mine at Pirdop	Aurubis	Copper
Poland	Polkowice- Sieroszowice Mine	KGHM	Copper, Silver
Portugal	Neves Corvo Mine near Castro Verde	Lundin Mining Corp. (LMC)	Copper; Zinc
Romania	Rosia Poieni Mine	Cuprumin	Copper
Spain	Cerro Colorado open pit mine	Atalaya Mining	Copper
Bulgaria	Mine at Erma Reka	Minstroy Holdings	Lead-zinc
Bulgaria	Mine at Rudozem	Rudmetal JSC	Lead-zinc
Portugal	Aljustrel	I'M SGPS SA	Copper
Romania	Baita Plai	Vast Resources PLC	Copper
Spain	Las Cruces	First Quantum Minerals Limited	Copper
Sweden	Lovisa	Lovisagruvan AB	Lead
Spain	MATSA	Government of Abu Dhabi; Trafigura Beheer B.V.	Copper
Finland	Outokumpu Mining Camp	FinnCobalt	Cobalt, Nickel
Finland	Silver Mine	Sotkamo Silver Aktiebolag	Silver
Cyprus	Skouriotissa	Hellenic Copper Mines Ltd	Copper
Greece	Stratoni	Eldorado Gold Corporation	Silver
Bulgaria	Varba-Batantsi	Gorubso-Madan JSC	Zinc

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Strategic Considerations

The production of gold is highly energy-intensive, and the processing of the ore involves toxic substances and chemical components. However, no environmental restriction on placing it on the market and using gold is known. Among existing mines, it is probably more strategic to prioritise sulfidic ores (Cu) containing Au, given the presence of other ION4RAW target metals.

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4 Bringing ION4RAW to market to expand the supply of target by-product metals

After considering the global market for all target metals and offering an overview of each individual target metal, this chapter of the report seeks to begin charting a path to market for the ION4RAW technology. In keeping with the Raw Material Initiative's ambition of increasing the European supply of target metals, the decision was taken to focus first on bringing ION4RAW to market within the European single market.

This chapter explores what a **commercial application** of ION4RAW could look like in practice based on feedback from the industrial experts interviewed within the task. Their guidance, along with strategic discussions between partners, led to the development of three separate scenarios for commercialising ION4RAW. These are each outlined briefly, along with a series of strategic considerations that commercial partners will need to take into consideration if they seek to adapt their process to the needs of potential customers. The results of the mapping exercise to identify potential European mines that may be interested in deploying ION4RAW is also presented in this chapter.

4.1 Strategic Path to Market

4.1.1 The value of by-products

One notable change in the value proposition of ION4RAW between the outset of the project and the time of this deliverable writing is the assumed capacity of the process to recover both main and by-product metals. To maximise the recovery of critical raw materials (particularly antimony and bismuth), the decision was taken by the consortium to select a DES and optimised leaching conditions that enabled high recovery rates of by-products with the low recovery of primary metals (particularly copper and gold). This technical decision has major implications for the commercial value of ION4RAW.

Most value contained within the deposits studied within the ION4RAW project is represented by Ag, Ag, Cu, Pb, and Zn. This is typical of mines on sulphide deposits around the world and leads to a first conclusion regarding the market demand for ION4RAW technology. **The ION4RAW process will need to work to avoid reducing the recovery of main metals.**

A second conclusion emerges as well by considering the limited value of the by-products within the project's ores, which is that it will be challenging to justify major capital and operating costs for mining clients based solely on the revenue produced by selling by-products. Demand for the technology will be more robust if the process is able to cover its expenses by **transforming a mine's costs into additional revenue streams.**

These two key conclusions about the market for ION4RAW led to the development of the three exploitation scenarios below. Each of these scenarios has several open-ended technical and economic unknowns at this stage in the project, which will be analysed further in the technical roadmap done by T7.3 and the economic analysis in T7.4. However, if feasible, they would all need to be capable of the following:

1. Operating as a complement to a conventional mineral processing route capable of recovering main metals
2. And recovering by-products while reducing operating costs and environmental impact

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The next subsection will present three approaches to using ION4RAW results that could be capable of meeting these two key criteria.

4.1.2 Three technical exploitation scenarios capable of creating value

Scenario 1: ION4RAW as a first step before standard processing routes

The first possible scenario involves ION4RAW being deployed as a treatment process to remove by-products before standard refining processes for Cu, Au or Pb-Zn. A high-level flowsheet depicting this scenario is presented in Figure 26 below.

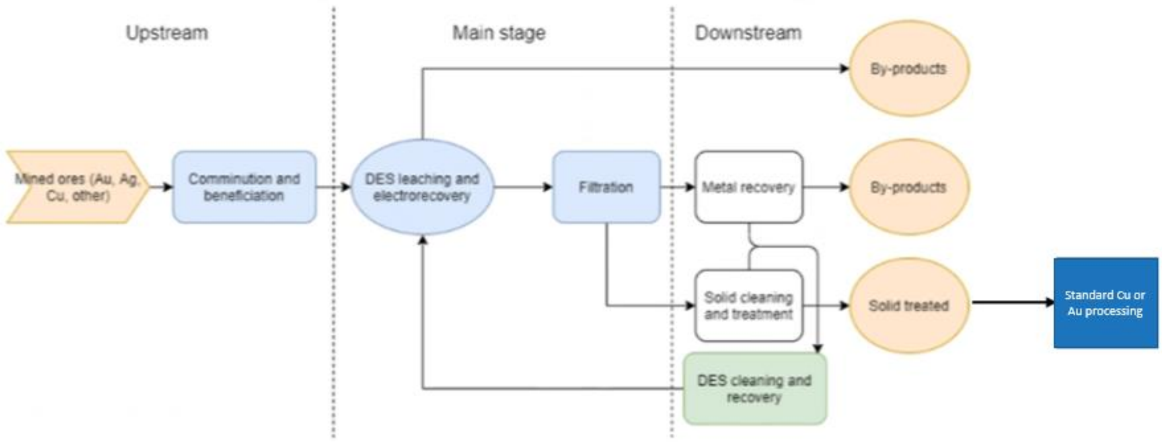

Figure 26. Technical exploitation scenario 1 standard processing imagined process flow

Scenario 1 is the most closely in line with the original design of the ION4RAW process. The key distinction is that rather than valorising treated solids for use in construction, they would be sent further downstream for conventional processing routes. An overview of the key benefits, barriers, and remaining technical unknowns to be addressed by the project in WP6 and WP7 is presented in Table 16 below.

Table 16. Strategic assessment of scenario 1

Competitive advantage
The main competitive advantage provided by this scenario would be the **removal of refining penalties** associated with several of the by-products targeted by ION4RAW. Interviews with mining experts indicated that antimony, bismuth and tellurium, for instance, are currently considered by the industry as "**impurities**" within copper and gold concentrates due to the difficulty in separating them from main metals during refining. Mining companies that are not vertically integrated with refineries, therefore, typically face a penalty in the value of their concentrate if it is shipped to a refiner with elevated concentrations of these by-products. Mining companies that also own their refineries likewise face higher costs of refining main metals if their mines produce concentrates with large amounts of by-products. If this scenario were to be adopted in a modular manner (as an add-on to existing processing circuits), it would allow these materials that currently represent a cost for the miner to become a **source of revenue.**
Barriers to adapting the current process
At its current stage of research, the ION4RAW project currently faces two key barriers to making this scenario a commercial reality.

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- The DES leachate selected for optimisation is currently **leaching significant quantities of main metals from the concentrate** (ex. around 30% of Cu). If this metal is not fully recovered in a pure form alongside the by-products, the process risks destroying value for miners by significantly reducing the output of their main revenue stream(s).
- The ION4RAW process has yet to **demonstrate a capacity to recover pure by-product metals**, meaning the process outputs will have no commercial application unless they undergo additional refining steps.

Key technical questions

Beyond consistently working towards improving the rate of recovery and purity of the target metals of ION4RAW, the process continues to have several unanswered technical performance questions that will determine its eventual suitability for being brought to market according to this scenario.

- How suitable are the treated solids from the ION4RAW process for conventional refining? For ION4RAW to be deployed in this scenario, it should not interfere with standard (pyro and hydro) refining processes that recover main metals. Effective implementation will require miners and refiners to collaborate on ensuring this.
- Can the ION4RAW process be commercialised as a “turnkey solution” for mining clients, where specific DES and process parameters are tailored to unique orebody compositions to maximise the recovery of by-products of interest to that miner?
- Will impurities build up over time in the processing circuit if the DES is cycled multiple times?
- How will the effluent DES and any solid waste that is not suitable for refining be disposed of?

This scenario, therefore, has a clear market potential but will require additional work to become a reality. Two other scenarios could also be considered to deploy ION4RAW in the market; these scenarios work on waste streams rather than trying to integrate the technology into a primary processing route. They are presented below.

Scenario 2: ION4RAW as a tailings treatment technology

The second scenario envisions commercialising ION4RAW as a mining waste treatment technology. This would entail treating flotation tailings to recover by-product metals that would otherwise be disposed of as waste. A high-level flowsheet representing this scenario is presented in Figure 27 below.

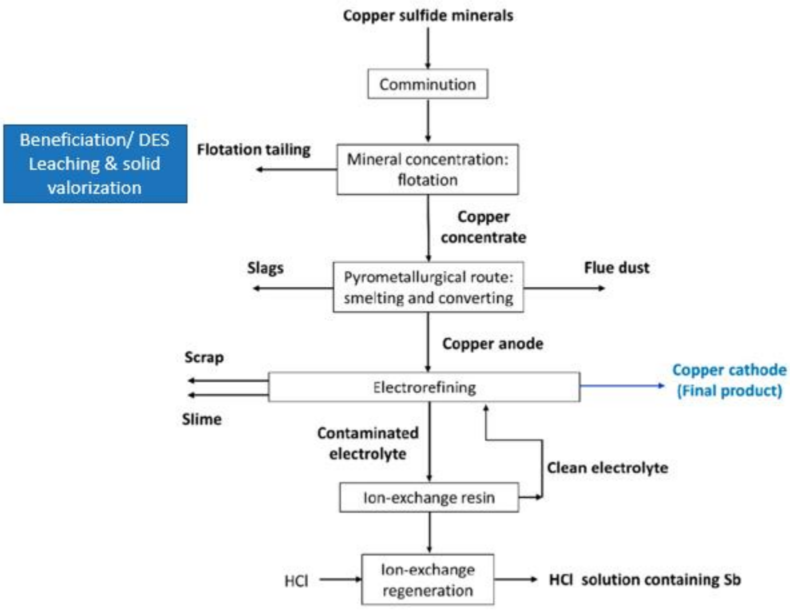

Figure 27. Scenario 2 treatment of tailings flowsheet based on (Barros & al., 2022)

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The ION4RAW project has produced some research data that is relevant to Scenario 2. The DES was tested on blended concentrate samples that mixed flotation concentrate with tailings. The material composition data of ore samples used by the project also allows for the composition of tailings to be inferred within the project. A strategic overview of the benefits, barriers, and unknowns of commercialising ION4RAW according to this scenario is presented in Table 17 below.

Table 17. Strategic assessment of Scenario 2

Competitive advantage
The main competitive advantage provided by this scenario would be the **generation of added value** in the form of by-products and perhaps additional main metals **from a waste product.** To be commercially viable, this would need to be deployed in a manner that **reduces the environmental and economic costs of tailings disposal.** This scenario would not necessarily have to operate at a profit so long as it is able to reduce the very significant costs associated with tailings disposal. Therefore, the valorisation of bulk material is a core element of this scenario, as it would enable mining companies to avoid the major costs of building and managing tailings dams or other tailings disposal systems. If ION4RAW can demonstrate an ability to safely remove and/or immobilise toxic elements within tailings to improve their environmentally sustainable disposal, this could be an added selling point for this scenario.
Barriers to adapting the current process
The primary barrier to adapting this scenario is that tailings have quite low concentrations of target metals that render the ION4RAW process ineffective at leaching significant amounts of them. To become viable, **an additional beneficiation stage** would be needed **to concentrate the tailings sufficiently before DES leaching.**
Key technical questions
There are three major technical questions related to this scenario: • Can the DES effectively leach viable quantities of target metals from flotation tailings? And if not, what solutions are available to enhance the concentration of target elements within the tailings? • What do the results from WP3 about solid treatment demonstrate about the most viable strategy to valorise the bulk material contained within the tailings after leaching? Could this strategy be deployed at scale in an environmentally and ecologically sustainable manner? • Can DES leaching offer any improvements in the environmental performance of tailings disposal, particularly in relation to the disposal of hazardous elements and heavy metals?

Treating tailings using the ION4RAW process could offer certain benefits but remains challenging due to the material composition of the feedstock. Scenario 3 will also be analysed below as an approach to treating different metallurgical wastes using ION4RAW results.

Scenario 3: ION4RAW as a refining residue processing technology

The third scenario envisions using the results from ION4RAW to process waste products produced by the refining industry. This scenario is the least mature of the three and remains highly open-ended based on the choice of feedstock and the need to tailor the parameters of DES leaching according to its material composition. A high-level overview of the feedstocks produced by conventional copper processing is presented in Figure 28 below.

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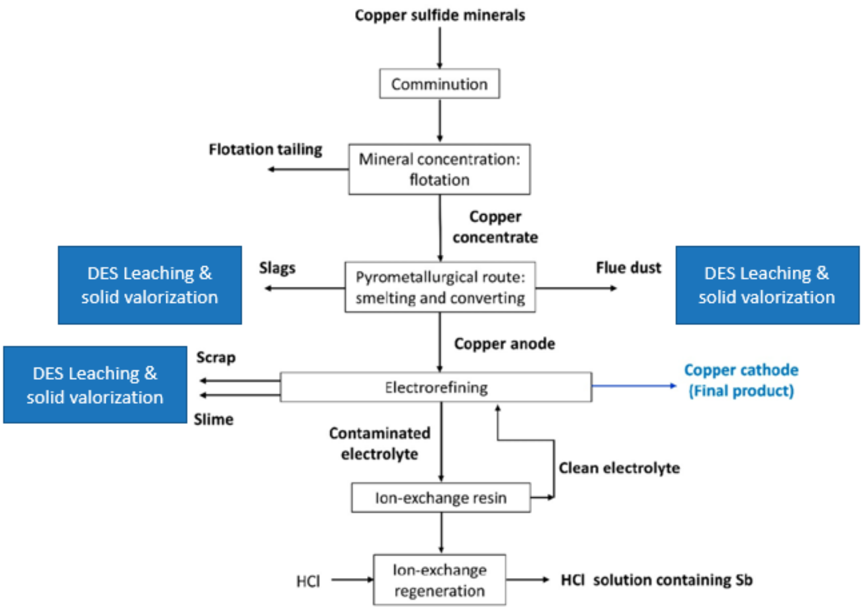

Figure 28. Scenario 3 treatment of refining residues flowsheet based on (Barros & al., 2022)

While this scenario remains undeveloped at this stage in the project, it has significant potential to position ION4RAW as a more economically viable, environmentally sustainable processing technology for the refining industry. Most of the target by-products recovered in ION4RAW are already recovered from refining side streams; for instance, global tellurium supply is dependent on copper anode slimes from electro-refineries.

If by-product metals were fully recovered from copper refineries around the world, this has the potential to significantly increase the global supply of ION4RAW's target metals, boosting tellurium by an estimated ~777 tonnes/year., antimony by ~1,497 tonnes/year., and bismuth by 1,632 tonnes/year. (Mcnulty, Jowitt, & Belousav, 2022). A strategic overview of this scenario is presented in Table 18 below.

Table 18. A strategic overview of scenario 3

Competitive advantage
As with scenario 2, the main competitive advantage provided by this scenario would be the generation of added value in the form of by-products and perhaps **additional main metals from a waste product.** However, the client in this scenario is **metal refineries** rather than miners. To be commercially viable, this would need to demonstrate cost reductions compared to standard recovery procedures that refiners use to produce by-products. Lowering the energy consumption, carbon emissions (and, in turn, costs related to ETS), and cost of chemicals are all viable paths for ION4RAW to bring refining costs down.
Barriers to adapting the current process
The primary barrier to adapting this scenario is that ION4RAW has been tailored for use on flotation concentrates rather than feedstocks produced as side streams from refining. The rate of dissolution of target metals within the DES will likely vary depending on the material characteristics of the chosen feedstock.

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Within the remainder of the current ION4RAW project, it will not be possible to assess the performance of the technology in refining waste streams; however, it may be possible to consult existing academic literature and propose pathways for further research.
Key technical questions
There are several major technical questions related to this scenario: • Based on material composition, which refining waste stream from sulphide mineral concentrates (e.g., Cu, Au, Pb-Zn) is best suited both technically and economically for becoming a feedstock for DES leaching? • How variable is the composition of this feedstock, and how well-suited is it for leaching (possible recovery rates)? • How easily can ION4RAW fit into existing processing routes at metal refineries? • What strategies are available to valorise the bulk material remaining after leaching?

4.1.3 Key factors that will determine industry demand for ION4RAW results

The additional interviews feeding into this second market analysis report provided key insights that allowed for the three exploitation scenarios to emerge. Interviews with industry experts also helped provide a clearer understanding of the existing demand in the mining and metallurgy sector for ION4RAW technology. At this stage in research, there are too many unknowns about the performance of ION4RAW to make definitive statements regarding commercial interest. However, several factors could make ION4RAW or similar iono-metallurgical processing routes increasingly appealing to the mining industry.

Key drivers of demand according to industry feedback

- There is a strong industry demand for an **alternative to cyanidation** to recover gold. Though the DES chosen for upscaling in ION4RAW has low recovery rates of gold, research should continue to explore the possibility of selectively leaching gold using DES. This would dramatically reduce costs for mining companies related to environmental regulations they face in relation to cyanide use, which is entirely banned in certain jurisdictions and has a very low social acceptance.
- Companies seek a **tailored processing solution** that will selectively leach the by-products that are the most highly concentrated within their specific orebody. As research on DES performance continues to advance, it may be possible to **envision commercialising an array of DES leaching options**, with specific parameters chosen based on the mineralogy of a given deposit where ION4RAW would be deployed. The capacity to process numerous metals through an integrated circuit will become increasingly valuable in the coming decades as mines are increasingly confronted with complex ore bodies. This is because as demand for base metals such as copper continues to increase and high-grade reserves are exhausted, the mines of the future will be lower grade, deeper, and larger footprint operations (Valenta, Kemp, Owen, Corder, & Lèbre, 2019).
- The ION4RAW process will be most viable if deployed with **minimal alterations to standard mineral processing equipment**. This will help reduce the capital costs of deploying the process at scale. If successful, flotation reagents could be slightly adapted to maximise concentrations of by-product recovery during beneficiation. Standard hydrometallurgical equipment could likely be used, as well as conventional equipment for electrodeposition.
- Mining companies will need to be certain that the ION4RAW process faces **no regulatory barriers** and is compliant with the environmental regulations in its jurisdiction. Treatment of effluent will be particularly important to document with respect to safety.
- The cost of **carbon emissions** under the European Emissions Trading Scheme will continue rising in coming years, making pyrometallurgical processing continuously more costly.

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Moreover, the European Commission's Carbon Border Adjustment Mechanism (CBAM) will also make carbon-intensive imports more costly. This is driving increased interest among European miners and refiners in alternative processing technologies.

- If ION4RAW can demonstrate an ability to produce low-carbon footprint metals, this could open the opportunity for metal producers to sell their products for a slight premium as **"eco" branded**. For instance, Swedish miner Boliden recently became the world's first company to launch a "low carbon copper" product with greenhouse gas certifications (Boliden, 2023).

Roadmap of next actions needed to reach the market

The information presented in this analysis will be built upon by WP7 in coordination between the technical roadmap task 7.3, the economic analysis T7.4, the regulatory analysis T7.5 and the exploitation plan. Together they will consider the three technical exploitation scenarios to decide which appears the most viable to pursue for future activities with ION4RAW results.

Several post-project activities should also be considered to maximise the chances of ION4RAW reaching the market.

The essential post-project activity to enable commercial deployment of ION4RAW is **demonstrating the technology as effective at a large scale via a pilot located at an active mine**. The mining industry is a highly risk-averse industry that is not particularly amenable to rapid innovations. Mines require massive CAPEX and have particularly long lead times. This leads miners to favour well-established processing technologies over innovations. Therefore, securing an early adopter of the ION4RAW process will be the first major hurdle, which, once cleared, will demonstrate to the industry that this technology has a proven track record and can be deployed with low risk.

One approach that could prove effective to secure investments in upgrading processing equipment for ION4RAW is to **directly involve downstream industrial clients** of by-product metals. The by-products targeted by ION4RAW have much smaller, more illiquid, markets than conventional metals traded openly on financial markets. Therefore, downstream industrial consumers of these materials have an interest in securing supply by investing all the way up the value chain at the mine. For instance, the solar panel manufacturing company First Solar is a major global consumer of tellurium that could be interested in investing in recovering an additional supply of the metal with an offtake agreement in place.

Interviews indicated that given the importance of engineering consulting firms in designing and building processing equipment in the mining industry, **a consulting firm would be best placed to commercialise the technology**. Ideally, this company would have experience working with miners during exploration and could commercialise the technology as part of feasibility studies with a miner looking to expand their footprint or upgrade their operation. This approach was detailed in the intermediate exploitation plan D7.12. Future work in WP7 will continue to facilitate discussions between research and commercial partners to help enable this pathway to market.

4.2 List of Candidate Mines for Commercialisation

An overview of all the identified copper, gold, silver, lead and zinc mines in Europe located within 50 km of a known deposit of target metals are presented in Figure 29 and Table 19. Due to available data,

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only mines located within continental Europe are considered, and future work could be done to account for active mines in overseas territories.

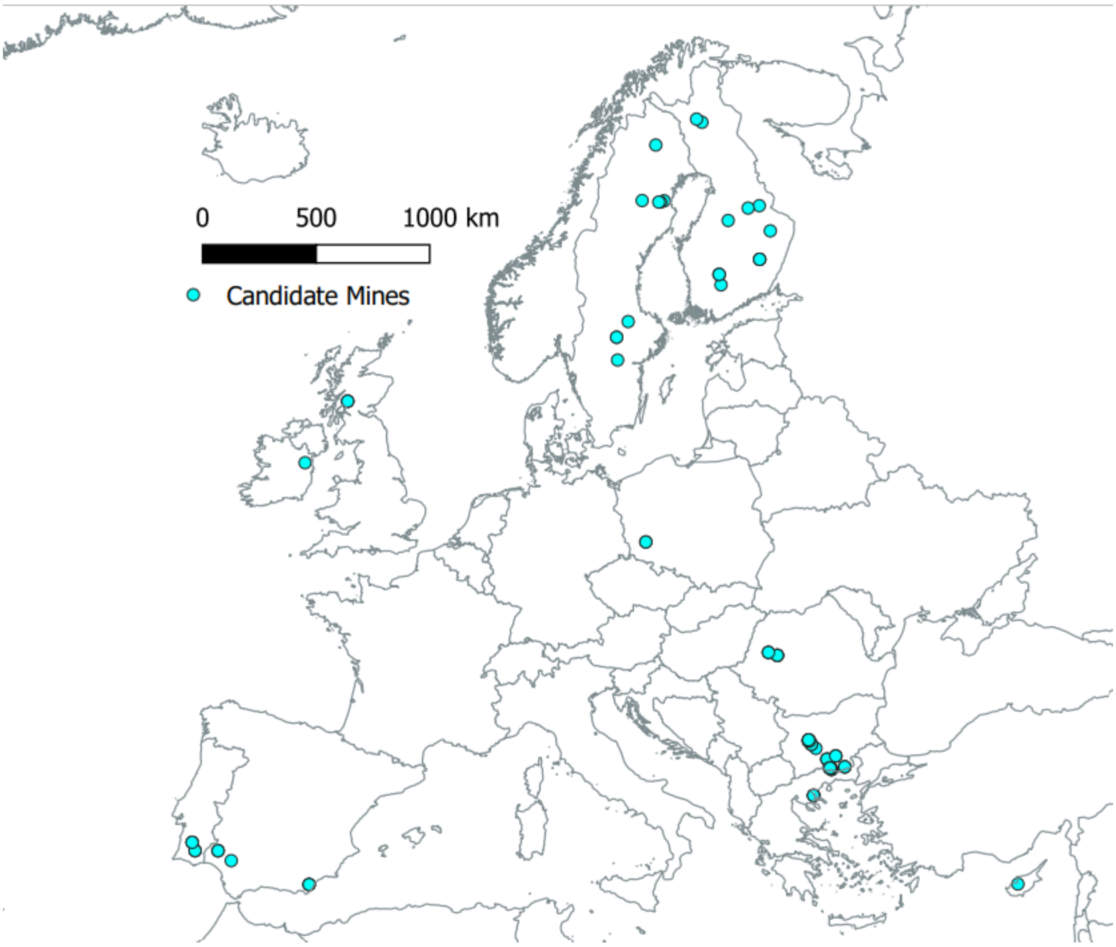

Figure 29. All candidate mines to adopt ION4RAW process

Table 19 lists all the mines identified within 50km of at least one target metal for the project. The main commodity actively being mines at the mine currently is listed, as well as the operating company and the owner of the mine.

Table 19. All Candidate Mines for Commercialisation

Country	Commodity	Mine name	Operating Company	Main Investor	Target Byproducts
Bulgaria	Copper	Mine at Srednogorie	Elatzite-Med Ltd.		Ag, Bi, In, Sb
Bulgaria	Copper, Gold	Mine at Chelopech	Chelopech Mining Ltd	Dundee Precious Metals Inc.	Ag, Bi, In, Sb
Bulgaria	Copper	Mine at Pirdop	Aurubis		Ag, Bi, In, Sb

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Country	Commodity	Mine name	Operating Company	Main Investor	Target Byproducts
Romania	Copper	Rosia Poieni Mine	Cuprumin	100% Public	Ag, Bi, Sb, Te
Bulgaria	Copper	Mine at Panagurishte	Asarel-Medet AD.		Ag, Bi, In
Spain	Copper	MATSA	Government of Abu Dhabi (Venturer) 50%; Trafigura Beheer B.V. (Venturer) 50%	NA	Ag, Bi, In
Bulgaria	Gold	Ada Tepe	Dundee Precious Metals Inc. (Owner) 100%	NA	Ag, Bi, Sb
United Kingdom	Gold	Cononish	Scotgold Resources Limited (Owner) 100%	Crown Estate Commissioners (Northern Ireland) (Royalty) 4%	Ag, Bi, Te
Romania	Copper	Baita Plai	Vast Resources PLC (Owner) 100%	NA	Ag, Bi, Te
Finland	Cobalt, Nickel	Outokumpu Mining Camp	FinnCobalt		Ag, Bi, Te
Bulgaria	Lead-zinc	Mine at Erma Reka	Minstroy Holdings		Ag, In, Sb
Bulgaria	Gold	Mine at Kurdjali	Gorubso Co.	Velocity Minerals	Ag, In, Sb
Portugal	Copper	Aljustrel	I'M SGPS SA (Owner) 100%	Wheaton Precious Metals Corp. (Streaming)	Ag, In, Sb
Portugal	Copper, Zinc	Neves Corvo Mine near Castro Verde	Lundin Mining Corp. (LMC)		Ag, In, Sb
Bulgaria	Gold	Mine at Laki	Gorubso Co.	Velocity Minerals	Ag, In, Te
Bulgaria	Gold	Chala	Gorubso-Kardzhali AD (Owner) 100%	NA	Ag, Sb, Te

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Country	Commodity	Mine name	Operating Company	Main Investor	Target Byproducts
Finland	Gold	Orivesi	Dragon Mining Limited (Owner) 100%	NA	Ag, Sb, Te
Sweden	Lead	Lovisa	Lovisagruvan AB (Owner) 100%		Ag, Bi
Bulgaria	Lead-zinc	Mine at Rudozem	Rudmetal JSC		Ag, In
Bulgaria	Zinc	Varba-Batantsi	Gorubso-Madan JSC (Owner) 100%		Ag, In
Poland	Copper, Silver	Polkowice-Sieroszowice Mine	KGHM		Ag, Sb
Greece	Silver	Stratoni	Eldorado Gold Corporation (Owner) 100%	Wheaton Precious Metals Corp. (Streaming)	Ag, Sb
Greece	Gold	Kassandra Mine	Hellas Gold S.A.	Eldorado	Ag, Sb
Spain	Copper	Cerro Colorado open pit mine	Atalaya Mining		Ag, Te
Finland	Copper, Gold, Pyrite, Zinc	Mine at Pyhasalmi	First Quantum Minerals		Ag
Finland	Gold	Pahtavaara Mine	Rupert Resources		Ag
Finland	Silver	Silver Mine	Sotkamo Silver Aktiebolag (Owner) 100%	UPM-Kymmene Oyj (Royalty)	Ag
Sweden	Copper, Gold, Silver	Mine at Aitik	Boliden Mineral AB		Ag
Cyprus	Copper	Skouriotissa	Hellenic Copper Mines Ltd (Owner) 100%		Ag
Finland	Copper, Cobalt, Gold, Nickel, Zinc	Kylylahti	Boliden AB (publ) (Owner) 100%		Ag
Sweden	Copper, Gold, Lead, Silver, Zinc	Mine at Garpenberg	Boliden AB		Ag

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Country	Commodity	Mine name	Operating Company	Main Investor	Target Byproducts
Sweden	Gold	Bjorkdal Mine	Mandalay Resources		Ag
Sweden	Gold, Tellurium	Mine at Kankberg	Boliden Mineral AB		Ag
Sweden	Copper, Gold, Lead, Silver, Zinc	Mine at Kristineberg	Boliden Mineral AB		Ag
Finland	Gold	Kittilä mine	Agnico Eagle		Ag
Sweden	Copper, Lead, Gold, Silver, Zinc	Mine at Renstrom	Boliden Mineral AB		Ag
Finland	Copper, Nickel, Zinc	Sotkamon Kaivos	Terrafame Oy		Ag
Ireland	Silver, Lead-zinc	Tara Mine	Boliden Mineral AB		Ag
Spain	Copper	Las Cruces	First Quantum Minerals Limited (Owner) 100%	Royal Gold, Inc. (NSR)	Ag
Sweden	Copper, Lead, Silver, Zinc	Zinkgruvan Mine	Lundin Mining Corp. (LMC)	Lundin Mining Corp 100%	Ag
Bulgaria	Copper	Mine at Srednogorie	Elatzite-Med Ltd.		In
Finland	Gold	Kaapelinkulma	Dragon Mining Limited (Owner) 100%		Te

Given the numerous mines in Europe that could potentially deploy ION4RAW, several **strategic criteria** are proposed below for gauging the potential value for European mining firms to implement the Project results at an industrial scale.

- **Emphasise mines with a high number of target metals in nearby deposits**

ION4RAW should enter the market as a solution for operations working to extract and process complex ores. In the current metal market, the presence of by-product metals that are not valorised in a mine's ore poses costs to the operation due to additional treatment to remove impurities during processing and refining.

As shown in Table 19 numerous mines have been identified in geologies near multiple known by-product metal deposits. This is particularly the case of **several mines located in Bulgaria**, as well as the **Rosia Poieni mine in Romania**.

- **Prioritise CRM production potential**

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Purely economic calculations when bringing ION4RAW to market may lead the technology to be directed toward the recovery of high-priced precious metals. While economic viability will be key to bringing the technology to market, given the public financing of the Project, there is also an ambition to fulfill the policy ambitions of the European Commission by increasing Europe's supply of critical metals.

- **Commercialise at larger European mines to maximise recovery**

To fulfill the Project's overall objective of decreasing the supply risk of CRMs, the ambition of bringing the processing technology to market is to maximise Europe's domestic production of by-product metals.

Two factors will be key to consider here in estimating the potential of a mine to increase by-product output: the mine's **rate of production of its carrier metal** and the **grade of by-product metals** present within the extracted ore.

- **ESG: Prioritise sustainable environmental, social and governance conditions**

Another significant factor that Project partners should consider when bringing their technology to market is the ESG performance of the mine that will be adopting it at scale. The historical performance with respect to environmental, social and governance criteria, as well as the local acceptance of mining development, may be considered in the final assessment of which mines are best suited for adopting the ION4RAW process at scale. Engaging with local communities to monitor the social and environmental impact of ION4RAW can help improve its sustainability when deployed.

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5 CONCLUSION

This report has sought to provide an overview of the market for ION4RAW's innovative mineral processing technology. To accomplish this, the **major drivers of demand for the 5 by-product metals and two main metals targeted by ION4RAW** were first considered, as were the factors that influence the **supply** of these metals. Each of the target metals was then analysed more closely in Section 3 of the report.

Alongside the overview of the market conditions for each metal, the report has also worked to chart a path to market for ION4RAW by exploring **three potential technical pathways to exploiting the technology commercially** and by listing the **active mines in Europe that are best suited to adopting a novel technology for recovering by-product metals**. Thus, the active mines within 50 km of a known deposit of each by-product metal were located and listed in Section 3 as well. Finally, Section 4 of this report elaborated on several criteria that should be accounted for in working to commercialise ION4RAW and in selecting candidate mines for the technology.

This final market analysis report (D7.3) comes slightly over one year after this intermediate report (D7.2). The second report has built upon the work done for this report while also refining the analysis of how the Project results should be strategically commercialised. In particular, as the technical work in the Project has advanced, the number of target metals has been narrowed to five, with their two main metals (Cu and Au) also being explored in this report.

In the interim period between both reports, the largest war in continental Europe since 1945 has also broken out. This has further exposed the vulnerability of Europe to geopolitical concentration in critical raw materials and the interdependency between energy and metal markets.

This final market analysis report thus has demonstrated that ION4RAW has significant market potential. There is **strong present, and future demand for the metals targeted by the Project**, and the EU is confronted with supply instability for many of the metals as well. However, there is still significant technical and economic work needed to allow the ION4RAW results to reach their full market potential.

This will be carried on through the final portion of the project, as well as by partners taking up the most promising results post-project. While many factors will ultimately determine the success of the technology at penetrating the market, there is certainly a **strong need for ambitious efforts to improve the recovery of by-product metals** within Europe to provide the material foundation for a sustainable future.

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6 Bibliography

Airbus. (2018). *Airbus Global Market Forecast*. Retrieved from https://www.airbus.com/aircraft/market/global-market-forecast.html

Alves-Dias. (2018). *Cobalt: demand-supply balances in the transition to electric mobility.*

Argusmedia. (2019). *News – China to auction Fanya Ga, Ge, Se, Te stocks*. Retrieved from https://www.argusmedia.com/en/news/1994012-china-to-auction-fanyaga-ge-se-te-stocks

Aurubis. (2019). Retrieved from: https://www.aurubis.com/products/minormetals/lead-bismuth-alloy

Barros, K. S., & al., e. (2022). Chemical composition data of the main stages of copper production from sulfide minerals in Chile: a review to assist circular economy studies. *Minerals*, 250.

Bartlett. (2013). *Technical report on the copper-silver production operations of KGHM Polska Miedź S.A. in the Legnica-Glogów copper belt area of southwestern Poland.* Micon International Ltd.

BGS. (2007). *Commodity Profile Copper*. Retrieved from https://www2.bgs.ac.uk/downloads/directDownload.cfmid=1410&noexcl=true&t=Copper%20

BGS. (2018). *World Mineral Production 2012-2016*. Retrieved from https://www2.bgs.ac.uk/mineralsuk/statistics/home.html

BHP. (2020, February). *Copper.* Retrieved from BHP.com: https://www.bhp.com/our-businesses/our-commodities/copper/

Bio Intelligence Service. (2015). *Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials - Final Report.*

BIWS. (2018). *International Workshop on Bismuth-Containing Semiconductors*. Retrieved from http://www.cgi.kit.ac.jp/iwbs2018.html.

Blazy. (2013). Métallurgie extractive du bismuth. *Editions Techniques de l'Ingénieur, doc. M 2316*, p. 15.

Blengini, G. A., Latunussa, C. E., & Eynard, U. (2020). *Study on the EU's list of Critical Raw Materials.*

Bobba, S. (2020). *Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study.* Luxembourg: European Commission.

Boliden. (2023, February 13). *Launching metals with low climate impact*. Retrieved from Boliden.com: https://www.boliden.com/operations/products/low-carbon-copper

Brandt, R. E., Kurchin, R. C., Hoye, R. L., Poindexter, J. R., Wilson, M. W., & Sulekar, S. (2015). Investigation of Bismuth Triiodide (BiI3) for Photovoltaic Applications. *The Journal of Physical Chemistry*.

BRGM. (2021, January). ION4RAW ore analyses. *WP2 By-products potential evaluation*. ION4RAW ECCP.

CDA. (2016). *Copper Development Association inc. Applications – Machined products*. Retrieved from https://www.copper.org/applications/rodbar/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Chandler, D. (2021). Advance may enable "2D" transistors for tinier microchip components. *MITNews*.

Cleantech. (2018). *Investing News*. Retrieved from https://investingnews.com/innspired/tellurium-market-renewable-energy/

Codelco. (2020). *Información financiera y operacional.* Retrieved from codelco.com: https://www.codelco.com/prontus_codelco/site/edic/base/port/inversiones.html

Copley, M. (2021). First Solar's growth plans hinge on opaque market for tellurium. *S&P Market Intelligence*.

CRM Alliance. (2022). *Antimony.* Retrieved from CRM Alliance: https://www.crmalliance.eu/antimony

Cunningham, S. A. (2005). Incident, accident, catastrophe: cyanide on the Danube. *Disasters*, 99-128.

Data bridge market research. (2022). *Market Analysis and Insights: Global Antimony Market.* Retrieved from https://www.databridgemarketresearch.com/reports/global-antimony-market

Data, W. M. (2019). *Iron and Ferro Alloy Metals, non Ferrous Metals, Precious Metals, Industrial Minerals, Mineral Fuels, Austrian Federal Ministry of Sustainability and Tourism*. Retrieved from http://www.en.bmwfw.gv.at/Energy/WorldMiningData/Seiten/default.aspx.

Deady, E., Moon, C., & Moore, K. (2022). Bismuth: Economic geology and value chains. *Ore Geologic reviews*.

DERA. (2017). *Chart des Monats, Oktober 2017. Preisparität zwischen Platin und Palladium*. Retrieved from https://www.deutscherohstoffagentur.de/DERA/DE/Publikationen/Chart_des_Monats/cdm_node.html

DERA. (2018). *Chart des Monats, Juni 2018. Neue DERA Rohstoffrisikobewertung – Kobalt*. Retrieved from https://www.deutsche-rohstoffagentur.de/DERA/DE/Publikationen/Chart_des_Monats/cdm_node.html

DERA. (2019). *Volatilitätsmonitor*. Retrieved from https://www.deutsche-rohstoffagentur.de/DERA/DE/Rohstoffinformationen/Rohstoffpreise/Volatilitaetsmonitor/volatilitaetsmonitor_node.html

DERA. (n.d.). *Volatilitätsmonitor*. Retrieved from https://www.deutsche-rohstoffagentur.de/DERA/DE/Rohstoffinformationen/Rohstoffpreise/Volatilitaetsmonitor/volatilitaetsmonitor_node.html

DKI. (2016). *Deutsches Kupferinstitut/copperalliance Anwendungen für Kupfer und Kupferegierungen*. Retrieved from https://www.kupferinstitut.de/anwendungen/

ECI. (2016). *European Copper Institute: Curious about copper*. Retrieved from https://copperalliance.eu/docs/default-source/resources/curious-about-cu.pdf?sfvrsn=2

ECI. (n.d.). *European Copper Institute: Curious about copper*. Retrieved from https://copperalliance.eu/docs/default-source/resources/curious-about-cu.pdf?sfvrsn=2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Eurometaux. (2022, September 14). *EU emergency energy intervention: More urgency needed to save at-risk metals producers.* Retrieved from eurometaux.eu: https://eurometaux.eu/media/saeo2z2x/20220914-eurometaux-press-release-eu-energy-crisis-support-package.pdf

European Commission. (2008). *Policy and strategy for raw materials*. Retrieved from The raw materials initiative: https://ec.europa.eu/growth/sectors/raw-materials/policy-strategy_en

European Commission. (2010). *Report of the Ad-hoc Working Group on defining critical raw materials.* DG Enterprise and Industry.

European Commission. (2015). *Trade for all: Towards a more responsible trade and investment policy.* Luxembourg: European Union.

European Commission. (2020, 03 10). *A New Industrial Strategy for Europe.* Retrieved from eur-lex.europa.eu: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0102

European Commission. (2020). *Study on the EU's list of Critical Raw Material: Factsheets on Non-critical Raw Materials.* Brussels.

European Commission. (2020). *Study on the EU's list of Critical Raw Materials, Factsheets on Critical Raw Materials.* Brussels: Publications Office of the European Union.

European Commission. (2020, December 30). *trade.ec.europa*. Retrieved from EU and China reach agreement in principle on investment: https://trade.ec.europa.eu/doclib/press/index.cfm?id=2233

Eurostat. (2019). *International Trade Easy Comext Database.* Retrieved from http://epp.eurostat.ec.europa.eu/newxtweb/

Eurostat. (2022). *Comext database.* Retrieved from http://epp.eurostat.ec.europa.eu/newxtweb/

Fastmarkets. (2019). *Effects of US-China trade war on bismuth mart.* Retrieved from American Metal Market: https://www.amm.com/Article/3900776/Trade/Effects-of-US-China-trade-war-onbismuth-mart.html

Fraunhofer ISI. (2016). *Rohstoffe für Zukunftstechnologien*. Retrieved from DERA-Rohstoffinformationen: https://www.deutscherohstoffagentur.de/DERA/DE/Downloads/Studie_Zukunftstechnologien2016.pdf?__blob=publicationFile&v=5

FreeportMcMoRan. (2014). Retrieved from https://www.fcx.com/sites/fcx/files/documents/fast_facts/ClimaxMoly_Brochure_2014.pdf

GFMS. (2011). *The future of silver industrial demand. GFMS at Thomson Reuters. Commissioned by the Silver Institute*. Retrieved from http://www.silverinstitute.org/%20site/wpcontent/uploads/2011/07/futuresilverindustrialdemand.pdf

Gregoir, L., & Acker, K. V. (2022). *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge.* Leuven: Eurométaux.

Hagelüken. (2019). *Die Märkte der Katalysatormetalle Platin, Palladium und Rhodium* . Retrieved from Metall - Fachzeitschrift für Metallurgie: https://www.gdmb.de/en/gdmb-verlag-gmbh/for-readers/metall/contents/2019/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Halland, H., Lokanc, M., & Nair, A. (2015). *The extractive industries sector: essentials for economits, public finance professionals, and policy makers.* The World Bank.

Hammond, C. (2004). *The Elements, in Handbook of Chemistry and Physics.*

Henckens. (2018). Molybdenum resources: Their depletion and safeguarding for future generations. *Resources, Conservation and Recycling*, 61-69.

I2A. (2021). *Antimony*. Retrieved from https://www.antimony.com/membership/member-list/

ICSG. (2019). *International Copper Study Group. The World Copper Factbook 2019*. Retrieved from https://www.icsg.org/index.php/111-icsg-releases-latest-copper-market-forecast-2019-2020

Jamasmie, C. (2017, April 21). *Strike at Escondida hurt Rio Tinto copper output.* Retrieved from mining.com: https://www.mining.com/strike-at-escondida-hurt-rio-tinto-copper-output/

Johnson Matthey. (2019). *PGM market report*. Retrieved from http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Jolly, J. (2020, January 5). *Cutting battery industry's reliance on cobalt will be an uphill task.* Retrieved from the Guardian: https://www.theguardian.com/environment/2020/jan/05/cutting-cobalt-challenge-battery-industry-electric-cars-congo

K.Mallaley, & Morris, D. (1989). Analysis of the Betterton-Kroll process: the removal of bismuth from lead bullion. *Science Direct*.

KCM 2000 Group. (2019). Retrieved from https://www.kcm2000.bg/products?page=pb

Krenev, V. A. (2015). Processes for the recovery of bismuth from ores and concentrates. *Theoretical Foundations of Chemical Engineering , 49*(4), 540-544. doi:10.1134/S0040579515040132

Lauri. (2018). *SCRREEN D3.1. Identification and quantification of primary CRM resources.*

Lauri, L. (2018). *Identification and quantification of primary CRM resources in Europe.* SCRREEN project D3.1.

Lenntech. (2016). *Silver*. Retrieved from https://www.lenntech.com/periodic/elements/

Les Echos. (2022). « En trois décennies, nous allons consommer 60 % des ressources de cuivre connues ». *Les Echos*.

Lide. (2008). *CRC Handbook of Chemistry and Physics.* Boca Raton, Florida: Taylor & Francis Group.

Lokanc. (2015). *The availability of Indium: The Present, Medium Term, and Long Term*. Retrieved from National Renewable Energy Laboratory (NREL): http://wwwnrelgov/docs/fy16osti/62409pdf

Lossin. (2001). Copper. In *Ullmann's Encyclopedia of Industrial Chemistry.*

Market Research Future. (2021). *Bismuth Market Research Report.*

Marketwatch. (2019). *Press Release: Indium market size share 2019 – global industry*. Retrieved from https://www.marketwatch.com/press-release/indiummarket-size-share-2019-global-industry-analysis-trends-industry-demand-growthopportunities-and-forecast-2024-2019-10-18

Marketwatch Press Release. (2019). Retrieved from : https://www.marketwatch.com/pressrelease/the-antimony-market-size-is-estimated-to-be-

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

usd-177-billion-in-2018-and-isprojected-to-reach-usd-237-billion-by-2023-at-a-cagr-of-60-between-2018-and-2023-

Mcnulty, B., Jowitt, S., & Belousav, I. (2022). THE IMPORTANCE OF GEOLOGY IN ASSESSING BY- AND COPRODUCT METAL SUPPLY POTENTIAL; A CASE STUDY OF ANTIMONY, BISMUTH, SELENIUM, AND TELLURIUM WITHIN THE COPPER PRODUCTION STREAM. *Economic Geology*, 1367-1385.

Melcher. (2013). Germanium. In *Critical Metals Handbook.* Gus Gunn. doi:doi:10.1002/9781118755341.ch8

Mikolajczak. (2009). *Availability of Indium and Gallium*. Retrieved from Indium Corporation of America: wwwcommodityintelligencecom/images/2010/jan/11%20jan/availability_of_indium_and_

Minerals4EU. (2019). Retrieved from European Minerals Yearbook: http://minerals4eu.brgm-rec.fr/m4eu-yearbook/theme_selection.html

Mining Intelligence. (2019). *Mining Intelligence Research*. Retrieved from https://www.miningintelligence.com/

MMTA. (2016). *Minor Metals Trade Association* . Retrieved from https://mmta.co.uk/metals/te/

Monde, L., & AFP. (2019, May 6). Montagne d'or en Guyane et lutte contre le gaspillage… Macron promet des mesures pour la biodiversité. *Le Monde*.

Monnet, A. (2018). *Report on major trends affecting future demand for critical raw materials.* Paris: LGI.

Mordor Intelligence. (2022). *ANTIMONY MARKET - GROWTH, TRENDS, COVID-19 IMPACT, AND FORECASTS (2023 - 2028).* Retrieved from Mordor Intelligence: https://www.mordorintelligence.com/industry-reports/antimony-market

Nassar, N. T., Graedel, T. E., & Harper., E. M. (2015). By-product metals are technologically essential but have problematic supply. *Science Advances*, 1-10.

Ndlovu. (2015). Anglo American Platinum: Precious Metals Supply. *Presentation given at EC International Conference, Exchange of good practices on metal by-products recovery.*

OEC. (2019). *Observatory of Economic Complexity*. Retrieved from https://oec.world/en/profile/hs92/280490/

OECD. (2018, October). *Global Material Resources Outlook to 2060*. Retrieved from http://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf

OECD. (2019). *Global Material Resources Outlook to 2060 Economic Drivers and Environmental Consequences.* OECD Publishing.

O'Faircheallaigh, C. (2013). Community development agreements in the mining industry: an emerging global phenomenon. *Community Development*, 222-238.

Polish Geological Institute. (2017). Retrieved from https://www.emodnet.eu/en/reports

PwC. (2022, June 10). *Mine 2022: A critical transition.* Retrieved from pwc.com: https://www.pwc.com/gx/en/industries/energy-utilities-resources/publications/mine.html

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

Reuters. (2019). *Cobalt's price crash bottoming out, stocks to hinder quick rally*. Retrieved from https://www.reuters.com/article/us-cobalt-prices-electric/cobalts-price-crash-bottoming-out-stocks-to-hinder-quick-rally-idUSKCN1Q11EP

Römpp . (2006). *Kupfer*. Retrieved from https://roempp.thieme.de/lexicon/RD-11-02420

Roskill. (2015). *Global Industry Markets and outlook*. Retrieved from https://roskill.com/market-report/rhenium/

Rudnick. (2003). Composition of the Continental Crust. In *Treatise on Geochemistry* (p. 659). Elsevier.

S&P Global. (2021). First Solar's growth plans hinge on opaque market for tellurium. *S&P global*.

S&P Global Market Intelligence . (2019). *Metals & Mining properties, Market Intelligence Platform*. Retrieved from https://www.spglobal.com/marketintelligence/en/campaigns/metals-mining

Schwarz-Schampera. (2014). Indium. In *Critical Metals Handbook* (pp. 204-229). John Wiley & Sons.

SGU. (2019). Swedish Geological Service: Information on Copper demand by electric vehilces.

SICA. (2021). *Antimony*. Retrieved from https://www.sica-chauny.com/en/products/antimony

Silverprice. (2019). *History of Silver price*. Retrieved from https://silverprice.org/silver-price-history.html

Śmieszek. (2017). Metallurgy of non-ferrous metals in Poland. *Journal of Chemical Technology and Metallurgy*, 221-234.

Survey, U. G. (2020). *Mineral commodity summaries 2020.* Retrieved from USGS.gov: https://doi.org/10.3133/mcs2020.

T.E., G., Gus, G., & Luis Tercero, E. (2014). *Critical Metals Handbook.* John Wiley & Sons.

Taboada, J. L. (2020, February 3). *Glencore 2020 coal, copper production met guidance.* Retrieved from marketwatch: https://www.marketwatch.com/story/glencore-2020-coal-copper-production-met-guidance-2021-02-03-24855857

Tercero. (2018). *Critical Raw Material substitution profiles.* SCRREEN project D5.1.

TGM. (2019). *Thracean Gold Mining S.A. - Gold mines in the EU*. Retrieved from https://www.tgm.gr/project-information/gold-mines-in-the-eu/?lang=en

The Guardian. (2019). Retrieved from https://www.theguardian.com/environment/2019/mar/12/resource-extraction-carbon-emissions-biodiversity-loss

The World Bank. (2020). *Annual GDP growth - European Union*. Retrieved from https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=EU

Umicore. (2019, September). Consultation after Critical Raw Materials Validation Workshop. Brussels.

UN Comtrade. (2019). *United Nations Comtrade Database*. Retrieved from https://comtrade.un.org/data/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

UNEP. (2011). *Recycling rates of metals*. Retrieved from http://www.unep.org/resourcepanel/portals/24102/pdfs/metals_recycling_rates_110412-1.pdf

USDS. (2018). *Selenium and Tellurium, 2016 Minerals Yearbook*. Retrieved from https://www.usgs.gov/centers/nmic/selenium-and-tellurium-statistics-and-information

USGS. (2013). *2013 Minerals Yearbook - Poland*. Retrieved from https://minerals.usgs.gov/minerals/pubs/country/2013/myb3-2013-pl.pdf

USGS. (2016). *Selenium and Tellurium, 2016 Minerals Yearbook*. Retrieved from https://www.usgs.gov/centers/nmic/selenium-and-tellurium-statistics-and-information

USGS. (2016). *Mineral Commodity Summaries: Germanium*. Retrieved from https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineralpubs/germanium/mcs-2016-germa.pdf

USGS. (2016). *Mineral Commodity Summary.* Retrieved from https://minerals.usgs.gov/minerals/pubs/commodity/antimony/

USGS. (2017). *Mineral Commodity Summaries .* U.S. Geological Survey.

USGS. (2017). *Mineral Yearbook - Data release: Germanium*. Retrieved from https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fspublic/atoms/files/myb1-2017-germa-adv.xlsx

USGS. (2019). *Mineral Commodity Summaries 2019*. Retrieved from https://www.usgs.gov/centers/nmic/mineral-commodity-summaries

USGS. (2019). *Tin - Mineral Commodity Summaries*.

USGS. (2022). *Mineral Commodities Summary.* Retrieved from https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf

USGS. (2023). *MINERAL COMMODITY SUMMARIES 2023.* Reston, Virginia.

Valenta, R., Kemp, D., Owen, J., Corder, G., & Lèbre, E. (2019). Re-thinking complex orebodies: Consequences for the future world. *Journal of Cleaner Production*, 216-226.

Velicu, I. (2015). Demonizing the sensible and the 'revolution of our generation'in Rosia Montana. *Globalizations*, 846-858.

Wang, C., Zhong, W., Wang, A., Sun, X., Li, T., & Wang, X. (2021). *Mapping the evolution of international antimony ores trade pattern based on complex network.* Retrieved from Science direct: https://www.sciencedirect.com/science/article/abs/pii/S030142072100430X?via%3Dihub

Wiebke, R., Kostka, G., & Stegen, K. S. (2017). China's supply of critical raw materials: Risks for Europe's solar and. *Energy policy*, 692-699.

Willner, J., & Fornalczyk, A. (2021). Studies on the Content of Selected Technology Critical Elements in Electronic Waste. *Materials*.

WMD. (2019). *World Mining Data*. Retrieved from http://www.en.bmwfw.gv.at/Energy/WorldMiningData/Seiten/default.aspx

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815748. The content of this report does not reflect the official opinion of the European Union. Responsibility for the information and views expressed lies entirely with the author(s).

WTO. (2016). *DS 509: China — Duties and other Measures concerning the Exportation of Certain Raw Materials*. Retrieved from WTO.org: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds509_e.htm

Ylä-Mella, J. (2016). Drivers and Constraints of Critical Materials Recycling: The Case of Indium Resources. *Resources, 5*, 34. doi:doi:103390/resources5040034

7 Annex – Interviewed Experts

Table 20. List of Interviewed Experts

Company	Business Activity	Position of Interviewee
Scotgold	Gold Miner	In house consultant
Wardell-Armstrong	Mining consulting firm	Metallurgist
Boliden	Multi-metal miner	Mineral processing manager
First Quantum Minerals (Cobre las cruces)	Copper miner	Senior Innovation Specialist
Orvana (Orovalle)	Gold miner	Director of exploration and technical services
Cumbrex	Mining consulting firm	Senior Consultant Geologist

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