

# TOWARDS A STRONG AND SUSTAINABLE EUROPEAN REFRACTORY METALS SUPPLY-CHAIN

MSP-REFRAM Final Report



*MSP-REFRAM is a Coordination and Support Action funded by the Horizon 2020 programme under the pillar Societal Challenge 5. After 18 months of work carried out between January 2016 and June 2017, PROMETIA and its members are proud to present the conclusions of their analyses of the refractory metal value chain.*

*This document highlights the main results of the project based on literature surveys, expert group discussions and data analyses. It presents the state-of-the-art as well as innovation pathways in the refractory metal value chains that could help boost the production of these metals in Europe and increase Europe's independence regarding their supply.*

*We hope that this document will serve as a basis for innovative R&D projects, and in the medium term to new pilots and future industrial developments.*

*Do not hesitate to use this information in your future research projects!*

Christophe Poinssot  
President of PROMETIA

Stéphane Bourg  
PROMETIA Chairman and MSP-REFRAM Coordinator



MSP-REFRAM has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 688993.

# CONTENTS

<b>PROLOGUE</b>	4
<b>EXECUTIVE SUMMARY FOR POLICY MAKERS</b>	6
<b>1 INTRODUCTION</b>	8
1.1 MSP-REFRAM as a key point in boosting Europe's role in the refractory metals scene	10
1.2 Niobium and Tungsten: two critical raw materials among refractory metals	11
<b>2 CURRENT WORLDWIDE PRODUCTION AND RESERVES: WHERE IS EUROPE?</b>	12
2.1 European scene: supply and demand	15
2.2 Balance between supply and demand	18
<b>3 REFRACTORY METALS MINING IN EUROPE: UNEXPLOITED AND MISSING RESOURCES</b>	20
<b>4 SECONDARY SOURCES AND URBAN MINING: RECYCLING AS A WAY TOWARDS SUSTAINABLE SUPPLY</b>	24
4.1 Secondary sources	24
4.2 Urban mining	25
<b>5 SUBSTITUTION: A TRICKY APPROACH?</b>	28
5.1 Potential substitutes for refractory metals	28
5.2 Refractory metals as substitutes	34
<b>6 EUROPEAN VALUE CHAIN FOR REFRACTORY METALS</b>	35
6.1 A closer look to refractory metals main applications	35
6.2 Refractory metals value chain	37
<b>7 ENVIRONMENTAL AND SOCIAL ASPECTS</b>	43
<b>8 GOING TO THE FUTURE</b>	46
8.1 Future uses	46
8.2 Supply and demand estimations	46
8.3 Research trends	49
8.4 Redesigning the value chains	51
<b>9 CONCLUSIONS AND POLICY RECOMMENDATIONS</b>	56
9.1 Policy recommendations and actions needed	56
<b>ANNEXES</b>	59
<b>REFERENCES</b>	60
<b>TECHNICAL ANNEX A: MAIN PROCESSING TECHNOLOGIES</b>	64
<b>TECHNICAL ANNEX B: REFRACTORY METALS MAIN SUBSTITUTES</b>	74
<b>ANNEX C: MAIN EUROPEAN STAKEHOLDERS IN REFRACTORY METALS VALUE CHAINS</b>	76

# PROLOGUE

Molybdenum, Niobium, Rhenium, Tantalum, Tungsten. The name of a group of five metals, the refractory metals, which have one particular thing in common: their melting point is above 2 000° C, above all the other known metals. The melting point of Tungsten, the highest of all metals, is 3 422° C.

This report is about refractory metals, related issues and solutions to address them. None of these metals are very abundant in nature: Molybdenum and Tungsten are about ten times rarer than lead and about fifty times rarer than copper. The rarest metal of this group, Rhenium, is much rarer than gold, albeit it costs only a fraction of gold.

While many persons may never have heard of some of these metals, one may wonder why they matter. The point is that they play an essential role in the economy and in our daily lives, providing us with some unique services. Examples of their key uses are:

- **Molybdenum:** it is used to produce highly corrosion resistant steel and stainless steel, used for instance in seawater for deep-sea oil exploration and production, or the construction of oil and gas refineries. Without Molybdenum, the world oil and gas production capacity would be much reduced. It also is a key ingredient for lightweighting cars, buildings and bridges and for the construction of pipelines, thanks to its use in making high-strength low-alloy steel (HSLA) containing tiny amounts of Molybdenum (<0.5%).
- **Niobium:** after Molybdenum, it is the other key ingredient of HSLA steel. The addition of tiny amounts of Molybdenum and/or Niobium, needed to produce HSLA steel, make it possible to reduce the weight of the parts made from HSLA steel by up to 40% when compared to the use of conventional carbon steel. This means large resources and energy savings.
- **Rhenium:** the rarest of the metals provides us cheap and increasingly energy efficient air travel. Why? This is explained just below.
- **Tantalum:** our smartphones and tablets would not exist without tantalum as this is the metal that made it possible to miniaturise the size of capacitors, a key electric component of their motherboards. But a large part of Tantalum production comes from the conflict torn Great Lakes region of Africa where, despite the efforts undertaken to certify Conflict-free Tantalum supply chains, it remains difficult to monitor on the ground how this metal is actually produced.
- **Tungsten:** it is in the drilling bits of our household drills as well as in the teeth of the dozer buckets, as well as in many other applications that cut and grind through rock or concrete, thanks to the extreme hardness and resistance to wear and tear of tungsten carbide.

All these metals can be mixed, in variable proportions, with aluminium, boron copper, cobalt, chromium, nickel and ruthenium to form a superalloy, a nickel basis alloy with extreme resistance to heat, wear and fatigue. This is the family of alloys used to make the disks and blades of jet engine turbines, allowing very high fuel combustion temperatures, which in turn provides for enhanced fuel efficiency and lower emissions of modern jet engines.

These examples show the importance of refractory metals to modern technologies, to resources efficiency and to our daily lives. However, the European Union produces only some of them (Rhenium and Tungsten) and none of the others, being dependent on imports mainly from Brazil (Niobium), Chile (Molybdenum and Rhenium) and China (Molybdenum, Tantalum, Tungsten).

This report concludes the MSP-REFRAM project, providing its findings, conclusions and recommendations. It addresses a series of issues of importance both to the competitiveness of the European Union economy and to its sustainable development goals, where resources efficiency plays a major role. Issues that are of importance not only to scientists and engineers but to every citizen and to sustainable development goals. MSP-REFRAM was a multi-stakeholder platform involving 21 partners from industry, academia and research institutes, supported by an equally diverse Advisory Board, and operated over 19 months (from January 2016 to July 2017) to identify, from a European Union perspective, the issues and possible solutions, such as recycling or substitution of these metals.

This project was co-funded by the European Union under the Horizon 2020 Research and Innovation Programme.

Welcome to the realm of refractory metals.

**Dr. Patrice Christmann**  
*Independent Researcher & Consultant*  
*Member of the Advisory Board*

# EXECUTIVE SUMMARY FOR POLICY-MAKERS

Different pathways have been identified through MSP-REFRAM to improve the performance of the EU refractory metals supply and to address the challenges that have arisen in the European refractory metals arena. The pathways identified concern technical performance and policy recommendations. In general, investing more in new extracting technologies and subventions for recycling will be needed as well as more transparency in the actions being undertaken in Europe, such as recycling rates, for example. More research in metal extraction from secondary resources and recycling methods will be required as will further studies and pilot plant demonstrations for promising technologies that have been developed at the laboratory level.

## TUNGSTEN

- Recycling Tungsten Carbide is very effective, as most scrap materials are richer in Tungsten than ores. Demand for Tungsten products is increasing, and companies can lower their raw material costs and make bigger profits by recycling Tungsten scraps. Moreover, the importance of the environmental aspect must be acknowledged, although unrelated to dependence issues. Recycling of Tungsten Carbide may be performed by direct methods rather than indirect ones, i.e. transforming Tungsten scrap into powder of the same composition by chemical or physical means, or a combination of both. Recycling will be effective with good product collection programs and new Tungsten recycling facilities. New recycling technologies will also be needed.
- Investing in the development of new mines.
- A thorough knowledge of the EU refractory metals arena and value chain is also in order, i.e., a detailed study of the arrangements and agreements between different companies. By doing so, one would observe that Asian funds sometimes take large shareholdings in mining companies whose resources are essentially outside of China. One example is the Drakeland project, which hosts the RCF Capital fund. When the participations are not capital-intensive, they constitute purchasing the raw materials in the form of off-take contracts, as is the case with the Barruecopardo project in Spain, in which the Noble group, which is Singaporean, buys production in advance.

## NIOBIUM

- In 2020, 12 million tons of waste in electrical and electronic equipment is expected to be produced. Furthermore, the end-of-life vehicle projection for the year 2019 is 9 million. The recycling of Niobium from these applications could meet at least part of the EU Niobium demand for the foreseeable future, but more investing in extraction facilities and methodology is needed.
- The extraction of Niobium from high-strength, low-alloy steels (HSLA) could be a promising source of Niobium, as this is the main application of Niobium. More research is needed in this field.
- Investment in research for the recovery of Nb and Ta from Tungsten carbide sludge ([Nb] = 5.6% and [Ta] = 7.2%).

## TANTALUM

- Capacitors and electronic parts are considered to be new resources, allowing 40% Ta recycling in the EU. To increase recycling, central waste collection centres and waste-channeling streams will be needed. The recycling

rate (currently between 10% and 30%) could be improved to prevent product scarcity. The recycling industry could focus not only on old scraps (cemented carbides and alloys) but also on end-of-life products with high Tantalum grades (electrolytic capacitors: 36.7%, wave filters: 33%, and semiconductors: 28.6 %).

- New deposits could also be exploited. Resources are present in Europe (see the mapping done in the MSP-REFRAM), including, for example, Treguennec in Brittany (France) with a potential of 1600 tons of Tantalum.
- Old tin tailings containing Tantalum (or Niobium) could be exploited for Tantalum extraction, using improved technologies (they represented only 10% of the world Tantalum production in 2012).
- Investment in new innovative processing and innovative extractive metallurgy for secondary resources and recycling; if a 20% recycling rate were achieved, about 60 tons of Ta recycled every year.
- Penalties for companies importing from conflict-affected regions or countries with poor labour conditions.

There is currently no real supply risk in the EU arena in terms of technological needs, but the situation could change with stricter regulations concerning supply from conflict-affected regions or countries with poor labour conditions, or because of increased environmental concerns. More transparency could be promoted among EU processors to assess actual production more accurately and better estimate the EU's needs and weaknesses.

## MOLYBDENUM

- Potential innovations on recovery from secondary resources (mill scale, dust, slag, etc.) are needed. For example, smelting reduction Mo-containing mill scale in EAF ~ 5 wt.% mill scale can be charged into EAF with no operation problem.
- Establishing more efficient sorting and recovery systems (improving Molybdenum recovery to > 50 %).
- Using generated residual materials as by-products as well as wastes.

## RHENIUM

- Establishing a database for Rhenium-containing product inventories, sales, product information of components, expected wastes.
- Promoting sorting logistics and collection efficiency of Rhenium-containing end-of-life products, and establishing a stable supply source.
- Promoting pre-processing efficiency by using innovative and scale-up technologies.
- Scale-up market access and engage large companies, suppliers and specialized groups in Re recycling.
- Encouraging manufacturers to improve product design, taking easy disassembly, reuse and recycling into account.
- Development of Rhenium recovery method for materials of diameter >30 mm, which are not currently processed.
- Innovative technologies for conversion of commercially prepared Rhenium compounds (mainly ammonium perrhenate) to more technologically advanced and processed functional compounds, materials or components.
- Promote the recycling of super-alloys (83.3% of the Re production).

# 1 INTRODUCTION

Refractory metals (Tungsten or W, Tantalum or Ta, Rhenium or Re, Molybdenum or Mo, and Niobium or Nb) are highly strategic metals for society as they are present in different kinds of industrial processes and common everyday products and technologies. Today, with the exception of Rhenium, these metals are mainly imported from China (W, Mo, Ta), Brazil (Nb and Ta), Chile (Mo et Re) but also from the USA and Canada, among others. European primary production is only a small percentage of the global production of these metals, with only Rhenium being produced in significant amounts in the EU (Poland accounted for 15% of total world production in 2013), with Tungsten being produced in Austria, Spain and Portugal and total EU production representing about 2.7% of the world production). Moreover, even though Tantalum is mainly mined in Africa, China remains the world’s leading Tantalum processing country. The impact of trade restrictions put in place by China is therefore highly visible to the consumer. In 2009, the EU argued that the barriers created by China to restrict exports of its raw materials would cost EU companies at least EUR 20 billion on a yearly basis [1]. Nonetheless, refractory metal resources do indeed exist in Europe, although very limited amounts are obtained from primary resources (ores) and the main resources for these metals are likely to be secondary resources (industrial waste, urban mines). Recycling of refractory metals from super-alloys has already been implemented to some degree, but much remains to be done in this area.

In this light, it would be possible to improve the supply value chain in the coming years if an industry that abides by European regulations and standards can be developed through better use of secondary or tertiary resources that can be found in these wastes, optimising the use of external resources as energy and water and at the same time reducing waste toxicity levels.

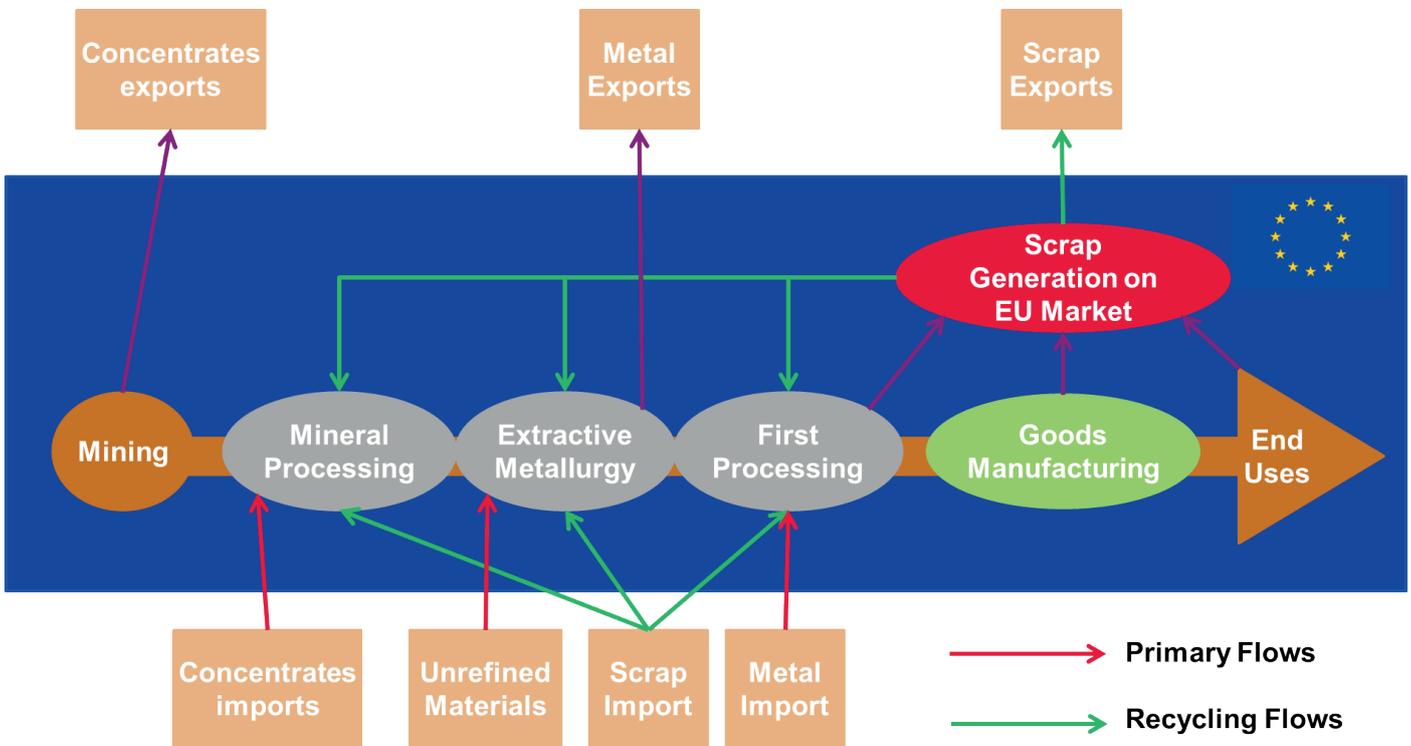


Figure 1. A schematic view of the value chain of metal; redrawn from [2]

# WHAT ARE REFRACTORY METALS?

*Refractory metals (Tungsten, Tantalum, Rhenium, Molybdenum and Niobium) can be mostly characterised by certain common physical properties: a high melting point (above 2000 °C), high density, special electrical properties, and inertness, especially as regards their ability to improve, even with small additions, the physical performance of steel and other metals.*

## **Tungsten (W)**

Tungsten is a greyish-white lustrous metal, which is a solid at room temperature. It has the highest melting point and lowest vapour pressure of all metals, and at temperatures over 1650°C has the highest tensile strength. It has excellent corrosion resistance and is attacked only slightly by most mineral acids [3]. Tungsten has been listed as one of the critical raw materials in Europe, both in terms of its high economic importance and its supply risk.



## **Niobium (Nb)**

Niobium is a soft greyish-silvery metal that resembles fresh-cut steel. It neither tarnishes nor oxidises in air at room temperature because of a thin coating of Niobium oxide. It does readily oxidise at high temperatures (above 200°C), particularly with oxygen and halogens. Niobium is not attacked by cold acids but is very reactive with several hot acids such as hydrochloric, sulphuric, nitric, and phosphoric acids. It is ductile and malleable [4]. Niobium has also been listed one of critical raw materials in Europe due to its high economic importance and its supply risk.



## **Tantalum (Ta)**

Tantalum (Ta) is a dense, tough and ductile element with very high melting point of 3017°C. It is also highly corrosion-resistant to most acids below 150°C and in most cases chemically inert. It has good thermal and electrical conducting properties, and it is easy to machine [5]. Ta was in the critical raw materials list of 2010 and was removed in 2014.



## **Molybdenum (Mo)**

Molybdenum is a shiny silvery metal moderately dense and moderately hard with sixth highest melting point of all elements: 2623°C. Of all engineering materials it has the lowest thermal expansion coefficient, and fairly high thermal conductivity [6].



## **Rhenium (Re)**

Rhenium is a metal with the second highest melting point, third highest Young's modulus, fourth highest density and high hardness, tensile strength and creep-rupture strength over a temperature range up to 2000°C. It exhibits corrosion resistance in seawater and hydrochloric and sulfuric acids, and inertness to most combustion gases, oxygen being an exception [7].



## 1.1 MSP-REFRAM AS A KEY POINT IN BOOSTING EUROPE'S ROLE IN THE REFRACTORY METALS SCENE

In 2014, European and international stakeholders (from research and industry) in the fields of extractive metallurgy and ore processing gathered to form a new association named PROMETIA. Thanks to the wide network of the PROMETIA Members, a multidisciplinary team of experts have been able to formulate the core of the MSP-REFRAM project, a EU-funded initiative, in order to provide the expertise required to cover the entire refractory metals value chain; the project includes public entities and civil society representatives, so as to foment a multi-stakeholder dialogue on a topic with such important societal, economic, geopolitical and environmental implications.

MSP-REFRAM's main contribution to improve the refractory metals supply chain is the identification of:

- Primary and secondary resources of refractory metal available for Europe
- New technologies that could be developed for refractory metals production, with a focus on secondary resources
- New markets and business models
- Regulations and standards that need to be changed or established to facilitate the emergence of new markets.

The strategic vision of MSP-REFRAM is therefore aimed at:

- Establishing a network covering the whole value chain for the most strategic refractory metals.
- Identifying tracks for innovation, breakthroughs, substitution options, new resources, addressing both technology and the market.
- Designing new value chains, taking into account new markets and opportunities, leading to waste reduction, water and energy savings and other benefits.
- Analysing their potential development in abidance with current policies, regulations and standards; identifying the related gaps and limitations; and proposing product development schemes, with the aim of lifting barriers and ultimately boosting the creation of new markets in Europe, thereby creating new jobs and wealth.
- Sharing the results widely and efficiently. To support systemic change, the knowledge generated in the project will be made widely available to stakeholders and to the public through dissemination actions including two-way communications, publications, and a web-based decision support system.

The main goal of the project is to facilitate strategic knowledge-based decisions by policy-makers and industrialists. Thus, by fostering the collaboration of a wide panel of experts in the MSP-REFRAM Committees (along the value chains and among stakeholders, public authorities and civil society organisations), MSP-REFRAM has coordinated a global reflection on the refractory metal value chain by:

- Establishing state-of-the-art refractory metals value chains including mining, processing and recycling applications.
- Analysing the innovation potential all along these value chains, including, technology, market and society/policy issues. Substitution opportunities will be proposed as well.
- Proposing new value chains including environmental regulations and standards evolutions needed as well as policy and society related issues and taking into account the new circular economy in sustainable development.

This will support the definition of global objectives and strategies, and creates the potential for the export of eco-innovative solutions and for tapping into new markets, in accordance with the strategic implementation plan of the EIP on Raw Materials.

## 1.2 NIOBIUM AND TUNGSTEN: TWO CRITICAL RAW MATERIALS AMONG REFRACTORY METALS

Of all the refractory metals considered in MSP-REFRAM, two of them (Niobium and Tungsten) are listed as Critical Raw Materials by the European Commission as they combine high economic importance to the EU with a high risk concerning their supply.

The European Union has recently declared Niobium as a critical metal material due to its singular characteristics, growing significance for EU manufacturers and the EU economy and high risk of supply shortage. The decision by the European Commission to include Niobium on the EU's critical raw materials list is based on the fact that:

- There is no production in the EU. More than 92% of Niobium is produced in Brazil, and 7% in Canada
- The estimated recycled share of total consumption is 20%. Although substitution of Niobium is possible, it may involve higher costs and/or a loss in performance

In the case of Tungsten, it will be difficult to satisfy the growing economic demand for it in the future. This has been evidenced by its inclusion on the European Union's (EU) raw material supply criticality list due to its high economic importance, wide range of applications, lack of viable substitutes as well as the EU's dependence on imports and trade concerns arising from China's dominant market position [13] with 85% estimated world mine production. The reasons why the European Commission decided to include Tungsten on the list of critical raw materials at the EU level are:

- Raw material supply (APT, oxide) is dominated by China which also has the largest reserves of Tungsten ore worldwide, which means high risks of quantitative and price disruption.
- Growing risks of «predatory» behaviour on the part of China in the Tungsten scrap market.
- Substitution possibilities limited by the cost of alternative materials/technologies, reduced performance, and fewer environmental friendly alternatives.
- Worldwide loss of know-how if the EU Tungsten value chain should fall apart as it is the leader in the development of many Tungsten products for automotive, aerospace, medical and lighting applications. The disappearance of the EU Tungsten industry would result in full dependence of several key industries on imports from abroad.

## 2 CURRENT WORLDWIDE PRODUCTION AND RESERVES: WHERE DOES EUROPE STAND?

China is the main refractory metals producer, as it is the leading producer of Tungsten (with 80% of world production in 2015) and Molybdenum (38% of world production in 2015). Brazil is leading the world production of Niobium (89% of world production in 2015), Rwanda is leading Tantalum production (50% of total world production in 2015) and lastly Chile is leading Rhenium production (50% of total world production in 2015). Moreover, in the cases of Niobium, Rhenium, Molybdenum and Tungsten, the most abundant reserves coincide with the biggest producers, so it seems that for the next 50 years, if the level of production remains constant, these countries will continue leading the world in production of refractory metals.

The future of Tantalum is uncertain due to the current conflicts in Africa. For the moment, it appears that, only considering the calculated estimations based on data from the 2016 USGS summaries, there will not be problems concerning worldwide production of refractory metals, as the reserves are high enough to allow for their extraction and therefore their supply for many years.

### TUNGSTEN

World Tungsten production in 2015 reached 87,000 tons [8], a 200-ton increase over 2014's 86,800 tons. China was the main producer as, of the total world production of 87,000 tons, it produced 71,000 tons, or 81.6% of the world total. The other minor producers, and their estimated reserves are listed in Table 1.

Country	Mine production (2015)	% of total production	Reserves (tons)	Reserves/Year production*
China	71,000	81	1,900,000	27
Vietnam	5,000	5,8	100,000	20
Russia	2,500	3	250,000	100
Others	2,100	2,4	67,000	319
Canada	1,700	2	290,000	171
Bolivia	1,200	1,4	-	-
Rwanda	1,000	1	-	-
Austria	870	1	10,000	11
Spain	730	1	32,000	44
Portugal	630	1	4,200	7
United Kingdom	600	1	51,000	85
<b>Total</b>	<b>87,330</b>		<b>3,307,200</b>	<b>783</b>

**Table 1. Mine production and reserves for Tungsten**

\*Estimated value based on 2015 production data. This value gives an idea of how many years a country could produce the same quantity with the known reserves. The value is approximate.

## NIOBIUM

In case of Niobium the situation is much easier. Brazil is the leading producer, followed by Canada. Main Niobium reserves coincide with production sites, as they are identified in Brazil (4,100,000 tons) and Canada (200,000 tons).

Country	Mine production (2015)	% of total production	Reserves	Reserves/Year production*
Canada	8,519	11	200,000	23,5
Brazil	68,576	89	4,100,000	60
<b>Total</b>	<b>77,095</b>		<b>4,300,000</b>	<b>83,5</b>

**Table 2. Mine production and reserves for Niobium**

\*Estimated value based on 2015 production data. This value gives an idea of how many years a country could produce the same quantity with the known reserves. The value is approximate

## TANTALUM

Rwanda provided almost 50% of the 2014 world production of concentrate. Other countries, such as Congo and Brazil, played a lower but still significant role (16.56% and 12.58%, respectively). Australia and China also contributed with low percentages to total production. The available figures concerning worldwide Tantalum production are 67,000 tons in Australia and 36,000 in Brazil (>100,000 tons). There is no information available for China, Congo, and Rwanda reserves.

Country	Mine production (2015)	% of total production	Reserves	Reserves/Year production*
Rwanda	600	50	-	-
Congo	200	17	-	-
Brazil	150	13	36,000	240
Other	140	12	-	-
China	60	5	-	-
Australia	50	4	67,000	1,340
<b>Total</b>	<b>1,200</b>		<b>103,000</b>	<b>1,600</b>

**Table 3. Mine production and reserves for Tantalum**

\*Estimated value taking 2015 production as basis. This value gives an idea of how many years a country could produce the same quantity with the known reserves. The value is approximate.

## MOLYBDENUM

Total annual world Mo production in 2015 was around 267,000 tons, of which 38% was produced in China, 21% in the USA and Canada, 30% in South America, 5% in Mongolia and the Commonwealth of Independent States (CIS), and less than 2% in other countries. Also of special note is the fact that Mo production increased by about 5,000 tons between 2011 and 2014. However, from 2014 to 2015, it decreased by 12,000 and 2,000 tons in North America and China, respectively [9]. The main consumers are China (35%) and Europe (25%). The consumption in North America is 11%, in Japan, 11% and in other countries combined, 12% [10]. Data on Molybdenum reserves is as follows [8].

Country	Mine production (2015)	% of total production	Reserves	Reserves/Year production*
United States	56,300	21	2,700,000	48
Armenia	7,300	3	150,000	21
Australia	-	-	150,000	-
Canada	9,300	3	260,000	28
Chile	49,000	18	1,800,000	37
China	101,000	38	4,300,000	43
Iran	4,000	1	43,000	11
Kazakhstan	-	-	130,000	-
Kyrgyzstan		-	100,000	-
Mexico	13,000	5	130,000	10
Mongolia	2,000	1	160,000	80
Peru	18,100	7	450,000	25
Russia	4,800	2	250,000	52
Turkey	1,400	1	100,000	71
Uzbekistan	520	0	60,000	115
<b>Total</b>	<b>266,720</b>		<b>10,783</b>	<b>540</b>

**Table 4. Mine production and reserves for Molybdenum**

\*Estimated value based on 2015 production data. This value gives an idea of how many years a country could produce the same quantity with the known reserves. The value is approximate.

## RHENIUM

The average value for Rhenium production is 50 tons per year. Mine production of Rhenium in 2015 was: 26 tons in Chile, 8.5 tons in United States, 7.8 tons in Poland, 1 ton in Uzbekistan and minor quantities in Armenia and Kazakhstan. Worldwide reserves are estimated to be [8]:

Country	Mine production (2015)	% of total production	Reserves (tons)	Reserves/Year production*
Chile	26	50	1,300	50
United States	8.5	16	390	46
Russia	7.8	15	310	40
Kazakhstan	0.2	0.4	190	950
Armenia	0.35	0.7	95	271
Peru	-	-	45	-
Canada	-	-	32	-
Others	2	4	91	45.5
Poland	7.8	15	-	-
<b>Total</b>	<b>52</b>		<b>2,453</b>	<b>1,402.6</b>

**Table 4. Mine production and reserves for Molybdenum**

\*Estimated value based on 2015 production data. This value gives an idea of how many years a country could produce the same quantity with the known reserves. The value is approximate.

## 2.1 CURRENT SITUATION IN EUROPE: SUPPLY AND DEMAND

The analysis performed above shows that refractory metal production in Europe takes place mainly in:

- Spain, Austria, UK and Portugal, all of which produce Tungsten but whose combined contribution represented only 3.24 % of total world production in 2015.
- Poland, which produces Rhenium and whose contribution represented 15% of world production in 2015. The extent of its reserves is unknown.

In order to obtain an overall figure concerning the impact of this data on the supply and demand balance, a thorough analysis by specific type of refractory metal was conducted.

### TUNGSTEN

The European countries which currently produce Tungsten from mines and their exports to non-EU countries in the form of ores and concentrates as well as Ferro-Tungsten are shown in the table below (data from Comtrade.org). The countries appearing next to export figures are the main countries to which EU countries exported.

Country	2015 Production (tons)	2015 W ores and concentrates exports to non EU countries (tons)	2015 FeW and FeSiW exports to non EU countries
Austria (Mittersill)	870	~0	~0
Spain	730	~1,600 (USA)	~0
Portugal (Panasqueira)	630	~780 (USA)	~0
UK (Hemerdon, Devon)	600	~255 (USA, China, Kenya)	~10 (USA, UAE)
<b>Total</b>	<b>2,830</b>	<b>~2,600</b>	<b>~10</b>

*Table 6. European Tungsten production*

As it can be inferred from the table above, a large part of the Tungsten produced in the EU was exported to non-EU countries, which does not imply a lack of need on the part of the EU; In fact, imports–exports for the year 2015 in EU were [11]:

W form	Total Imports (tons)	Total exports extra EU (tons)
Tungsten ores and concentrates	989	3,602
Tungsten oxides and hydroxides	3,895	382
Tungstates	4,987	24
Tungsten carbides	7,674	318
FeW and FeSiW	5,901	132
Tungsten powders	2,516	350
Tungsten waste and scrap	7,684	1,316

*Table 7. Tungsten imports and exports*

As can be inferred from the table above, demand of Tungsten in several forms in the EU is high. The main countries outside of the EU where Tungsten is imported as ores and concentrates are: Bolivia, Brazil, China, Vietnam, Australia, Kenya and Kazakhstan. Tungsten waste and scrap are imported in the vast majority by Germany, mainly from EU countries, but also in large quantities from the USA and Russia. The UK also imports large quantities of Tungsten waste and scraps, mainly from non-EU countries such as the USA, South Africa and China.

## NIOBIUM

The most widely used Niobium metallurgical product is Ferro-Niobium (employed in about 90% of applications), which is traded all over the world for use in steel alloys, mainly in High Strength Low Alloy Steels (HSLA).

In 2015, total Ferro-Niobium imports to the EU were 25,771 tons (513 M\$), while total extra-EU exports were 2,552 tons (41 M€). Imports came mainly from Brazil (based on data from Comtrade.org, which show some discrepancies with EUROSTAT data, indicating 46,166 tons. In any case, the data underscores the high demand for Ferro-Niobium in the EU and its high degree of dependence on Brazil to obtain it, with Niobium being as indispensable as it is for the EU steel industry.

The EU also imports slags, ash and residues containing Niobium and Tantalum. In 2014, total imports reached 21,575 tons, although in 2015 this figure decreased to 793. The country mainly identified as a major importer of these products was Germany, which imported 83% of its supply from Malaysia and 13% from Brazil. Of particular note, the German company H.C Starck has been identified as a major recycler of Nb and Ta compounds as well as those of other elements.

It is evident that EU demand for Niobium is high and totally dependent on Brazil and Canada. The Niobium market is well structured and should not be subjected to any significant change in the short to medium term. The Brazilian leader CB has good trade relationships with most of its partners and has invested in increasing its capability in order to keep up with the forecasted growth in demand. New players are unlikely to enter the market in this price range and no new mines will be able to enter into production. The company China Molybdenum is now the owner of the Boa Vista and Catalao mines in the states of Goiás and São Paulo (Brazil), sold to them by Anglo American in June 2016 and which accounts for 7-8% of total world mine production.

## TANTALUM

A review of the Tantalum trade into and from the EU 28 is provided below, using EUROSTAT data (tons).

Sector	Products	Ta content (%)	Imports	Exports
Mining/Extraction	Ores and concentrates	~0.1-10	0	0
Fabrication of intermediate products	Unwrought Ta, including bars, rods and powders	100	252.1	108.5
	Ta bars, rods, profiles, plates, sheets, strips and foils	100	25.3	29.9
Finished products	Articles of Ta, not otherwise specified	Unknown	62.4	59.7
	Fixed electrical capacitors	0.02g/unit	375.4	415.3
Residues	Ta waste and scraps	Unknown	151	244.5
	Slag, ash and residues containing mainly Ta and Nb	<1%	21,575	4.9

*Table 8. Tantalum imports and exports*

Tantalum is mainly imported in the form of intermediate or finished products, and a vast majority of them are slag, ash or residue-based products, containing mainly Ta and Nb (although the Ta content is under <1%).

## MOLYBDENUM

The International Molybdenum Association (IMOA) estimates that in 2015, Europe's consumption of Molybdenum amounted to 59,000 tons of contained Mo, which makes the EU the second worldwide Mo consumer, after China.

Between thirty and forty per cent of tech oxide production is processed into Ferro-Molybdenum (Fe-Mo), which contains between 60 and 75% Molybdenum. In the EU, Austria is the only country that produces Ferro-Molybdenum [12], reaching 4,000 tons in 2014, which means a minimum of 2,400 tons of Mo and a maximum of 3000 tons of Mo were imported (in the EU, only Norway produced Molybdenum, but the total quantity produced in 2014 was only 2 tons).

In 2015, non-roasted Mo concentrate imports reached 63,738 tons (with a value of 469 M€, and the total extra-EU export figure was only 826 tons (3M€). Roasted Mo concentrate imports were 76,123 tons (689 M€) and the total exports, 15,811 tons (52 M€). Total Mo oxide and hydroxide imports were 13,269 tons (139 M€) and extra-EU exports, 1,776 tons (18 M€). Total Ferro-Molybdenum imports were 69,745 tons (759 M€) and total extra-EU exports, 3,753 tons (36 M€). Lastly, Mo waste and scrap total imports were 4,886 tons (76 M€) and total extra-EU exports, 78 tons (1M€).

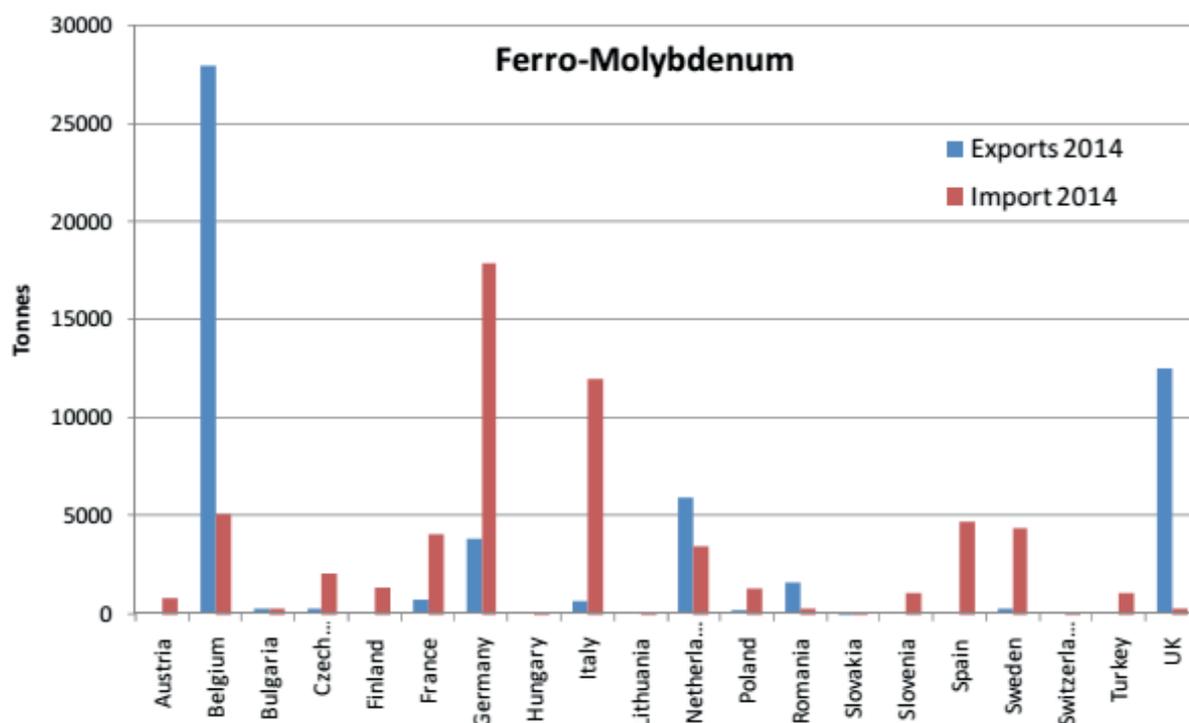


Figure 2. Imports and exports of Ferro-Molybdenum by different EU countries

## RHENIUM

Several difficulties have been found when assessing the EU's Rhenium demand using the traditional EUROSTAT international trade database access (ComExt):

- Rhenium products and wastes are reported in the same categories along with other metals such as Niobium, making it impossible to estimate Rhenium content for these flows.

- Rhenium is obtained mainly from Molybdenite concentrates. As the category reported in ComExt deals with only Molybdenum ores and concentrates, the Re content is unknown.
- Regarding intermediate products, Rhenium is reported along with Niobium and other metals. Super-alloys and catalyst categories join Rhenium containing products with non-Rhenium containing products.
- Finished products, such as turbine blades in turbojets, turbo-propellers and gas turbines are made of super-alloys containing Rhenium in the 3-6% range, but as the content in the case of turbines is around 0.03 kg/MW, it is not possible to obtain the Rhenium content based on weight or economic value as reported by ComExt.

It is clear that EU-28 is a net exporter for aerospace and gas turbines, which means that the Rhenium products imported seem to be mostly transformed into super-alloys by the EU industry. The development of the European aerospace industry has reduced the American market domination. Main consumers of super-alloys containing Rhenium are engine manufacturers, which account for 55% of total consumption. As for worldwide Rhenium demand, Lipmann Walton & Co Ltd [13] estimated that it was about 60-65 tons in 2013, of which 78% was for aerospace super-alloys, 6% for industrial gas turbine super-alloys, 9% for catalysts and the remaining 7% for minor uses (anodes for medical equipment, thin filaments for spectrographs and lighting, alloy spray powders, among others). Axens (France) is one of the main producers of catalysts used in oil refineries, representing 3% of the worldwide catalytic reforming capacity.

## 2.2 BALANCE BETWEEN SUPPLY AND DEMAND

Demand for Tungsten products is still expected to exhibit moderate but constant permanent growth through 2018, as next figure from HC Starck shows. Tungsten will remain an important component for tool steels, high speed steels, satellites and creep-resistant steels and alloys in the medium and long term. However, this demand is dependent on many industrial activities. Recently, the Tungsten market has suffered as a result of drops in the mining and oil and gas industries, hit heavily by the collapse of commodity prices, which have dropped by 30-40% since the 2012 highs. This has resulted in severe cut backs in the mining and oil industries, mine closures, reduced oil and gas drilling and reduced investment in major infrastructure projects. The two most important Tungsten markets, cemented carbides and specialty steels, have also suffered as a result.



**Figure 3. Tungsten Demand Perspectives. Source: H.C.Starck**

In 2010, the USGS estimated that global Tungsten ore reserves stood at 2.8 million tons of Tungsten-containing metal with more than 60% of it in China. A substantial portion (500,000 tons) of these reserves occurs in higher grade ores and is more

wrought (implying lower costs), as in the cases of wolframite porphyry stockwork and sheeted vein array systems. However, China has apparently been mining high grade deposits for over 15 years, which is damaging the resource itself and detrimental to long term mine economics. The remaining resources occur as skarn hosted scheelite which, in most cases, is of lower grade than the present wolframite resources. It is difficult to say how long this level of exploitation can be considered sustainable. Nevertheless, as of 2016, China still reigns strong over the Tungsten market and price-setting and has imposed export restrictions on Tungsten to prevent faster depletion of its resources.

New supply sources have been investigated. During the period 2008-2013, many new Tungsten exploration and mining projects were undertaken. The two largest new developments were the Drakelands (Hemerdon Ball) open pit deposit in the UK and Nui Phao in Vietnam, where major resources were drilled; both projects have come on stream during the last two years. However, the largest emerging Tungsten metallotect are the Variscan age belts of Portugal and Western Spain, where some 290,000 tonnes of extractable  $WO_3$  have been defined in five projects, three of which are currently in operation, with the remaining two expected to start production by 2018. Another potential source of higher grade ore is France, but this possibility will not be fully explored and evaluated until a definitive feasibility study can be conducted at some point between 2022 and 2025, with the mines themselves not becoming operational until the 2024-2028 time frame. Furthermore, former major producing centres, such as the Dolphin Mine at King Island, Tasmania, Australia are being re-evaluated for possible reopening in 2017.

The Ferro-Niobium market is an oligopoly dominated a few companies. The Brazilian leader CBMM, for example, has about 85% of the market share. However, important foreign players have a 15 % stake in the company through an intermediary investors' group comprised of JFE Steel Corporation (JFE), Nippon Steel Corporation (NSC), Sojitz Corporation (Sojitz) and Japan Oil, Gas and Metals National Corporation (JOGMEC) and a Korean investor group consisting of the major Korean steel producer POSCO and the National Pension Service (NPS) which ensure the security their Niobium supply for steel making [14]. Globally, the Niobium market is well structured and not many changes are expected in the short to medium term. On the demand side, it is likely that steel production will continue to drive demand for Niobium, which will continue to rise until Chinese, Indian, and Russian steels reach the same levels of Niobium content/quality as can be found in the EU and United States, Japan, South Korea, and Brazil.

As for Tantalum, its price/value escalates rapidly as it moves through the chain. Companies in the EU are at the higher end of the value chain. Even a superficial analysis reveals a differential between raw material cost and finished product value of at least 100%, while a deeper examination indicates that the unit value of tantalum imports into the Czech Republic in 2015 (mostly destined for capacitor manufacture) averaged US\$458/kg (ranging from US\$338 to US\$610, depending on the grade of powder employed). From the EU perspective, Tantalum unit inputs from non-primary sources are probably of greatest importance. Furthermore, the value of Tantalum to the EU lies not in raw materials but in processing and manufacturing, despite the risk of European manufacturers moving their production to lower-cost countries if economic conditions grow unfavourable. Strategic Mineral tin-mining and smelting projects in Spain, which could come into production in the first quarter of 2017, are a potential source of Tantalum supply (in slags), although the amounts produced by these activities would be modest.

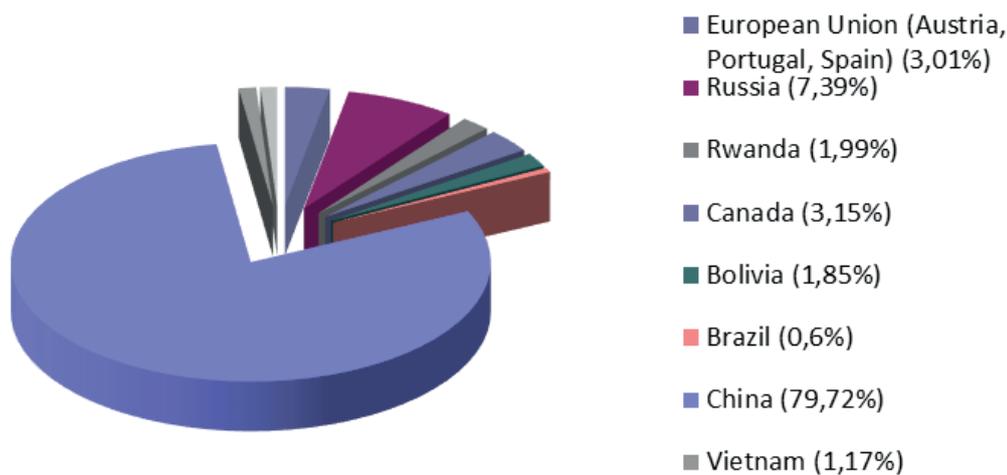
Molybdenum consumption in Europe and in the rest of the world is likely to continue being driven by the iron and steel industries. Molybdenum is primarily used as an alloying element in steel, cast iron and non-ferrous metals. The EU is the second largest producer of steel in the world after China. Due to its good trade relationships with producing countries, a strong industry, and due to the relatively low value and high abundance of Molybdenum, the balance between supply and demand would not be a major European concern in the medium term.

As a final point, demand for Rhenium is presently showing growth because of the demand for engines in both commercial and military jets. This is forecasted to continue to rise strongly over the next 20 years. The use of Rhenium catalysts in reforming is also growing but at a slower rate. Annual demand for Rhenium in fossil fuel power generation in the EU is forecasted at 0.6 tonnes/year between 2020 and 2030, which might imply a major material requirement [15]. However, in the last few years, the gap between supply and demand has been closed by tapping into tributaries and streams from salvaged units, thereby recovering the Rhenium that would have been wasted in the past. Thus, recycling of the metal has grown considerably over the past several years, particularly among the leading consumers, e.g. General Electric Aviation with its "Rhenium Reduction Program". In general, it is thought that, despite some worries within the industry as to future supply, "primary and secondary resources are sufficient to allow producers and potential producers to keep pace with demand".

### 3 REFRACTORY METALS MINING IN EUROPE: RESOURCES THAT ARE UNEXPLOITED OR LACKING

Europe possesses deposits of different types of refractory metals, for some of which there is reported data as to specific amounts present, while for others the occurrence and amounts are unknown. All of these deposits are presented in the map provided below, generated using MSP-REFRAM guidelines.

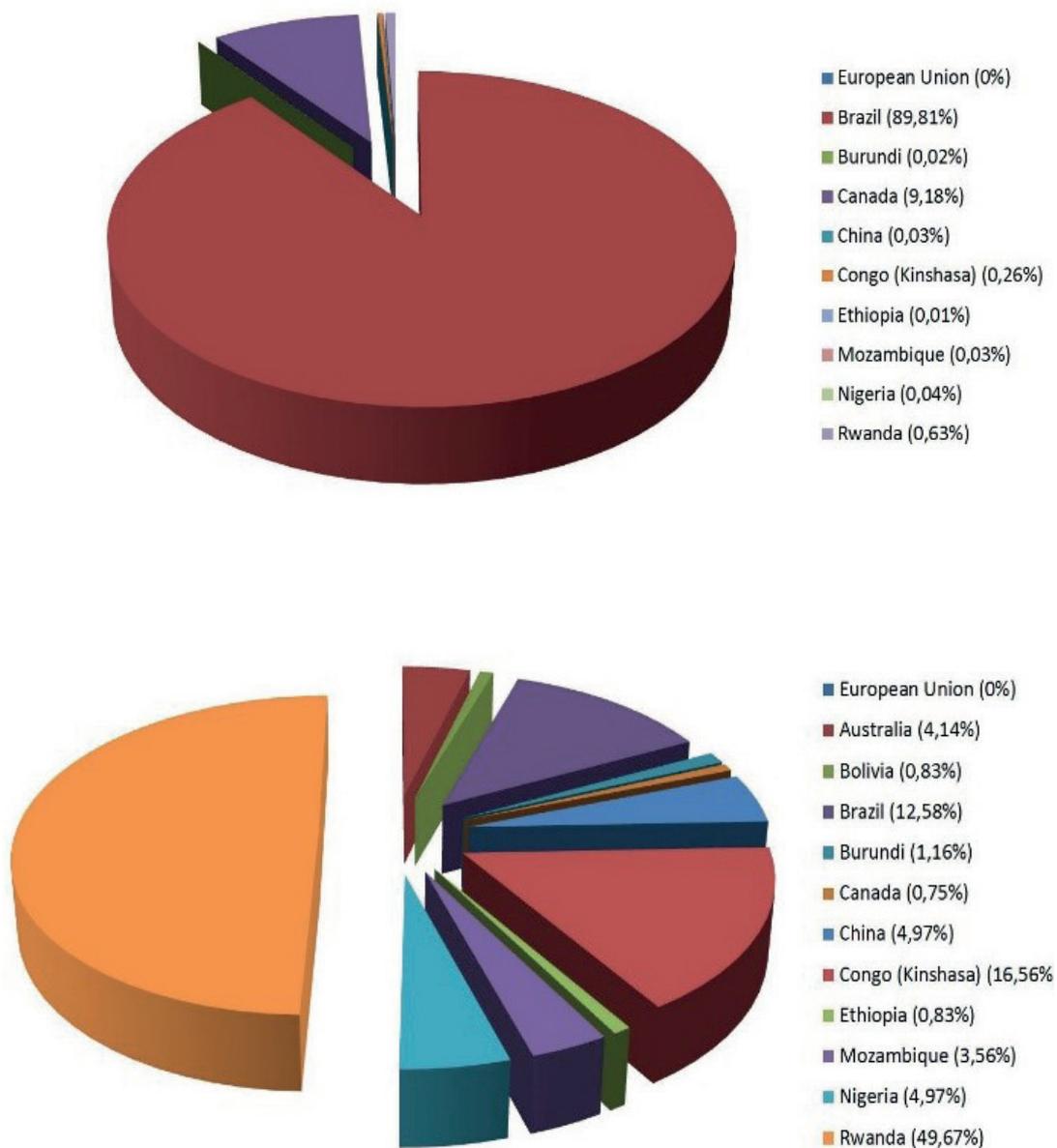
The three types of Tungsten deposits are: classical vein deposits, skarn deposits and bulk mineable deposits (greisen, porphyry, stockwork) [16]. For classical vein deposits, typical tonnages are from a few 10s to a few 100,000s of tonnes of ore with typical grades of 0.5 – 5% WO<sub>3</sub>. Examples of active mines are: Panasqueira in Portugal, San Fix in Spain, Pasta Bueno in Peru and Chollja in Bolivia. Skarn deposits (mineralisation might be mono-metallic Tungsten almost exclusively as scheelite or polymetallic, often with Mo or base metals: Pb, Zn, Cu), as is also the case with gold, fluorite or magnetite, have typical tonnages of few million, but sometimes much larger deposits can be found. Typical grades are 0.3 – 1% WO<sub>3</sub>. Lastly, bulk mineable deposits are either W-Sn or W-Mo deposits. Typical tonnages are dozens or hundreds of millions of tonnes with typical grades of 0.1 – 0.3% WO<sub>3</sub>. Examples of mines include Lianhuashan in China and Mittersill in Austria.



**Figure 4. Geographic distribution of the 2014 Tungsten production (in percent of the total world production), and contribution from the European Union**

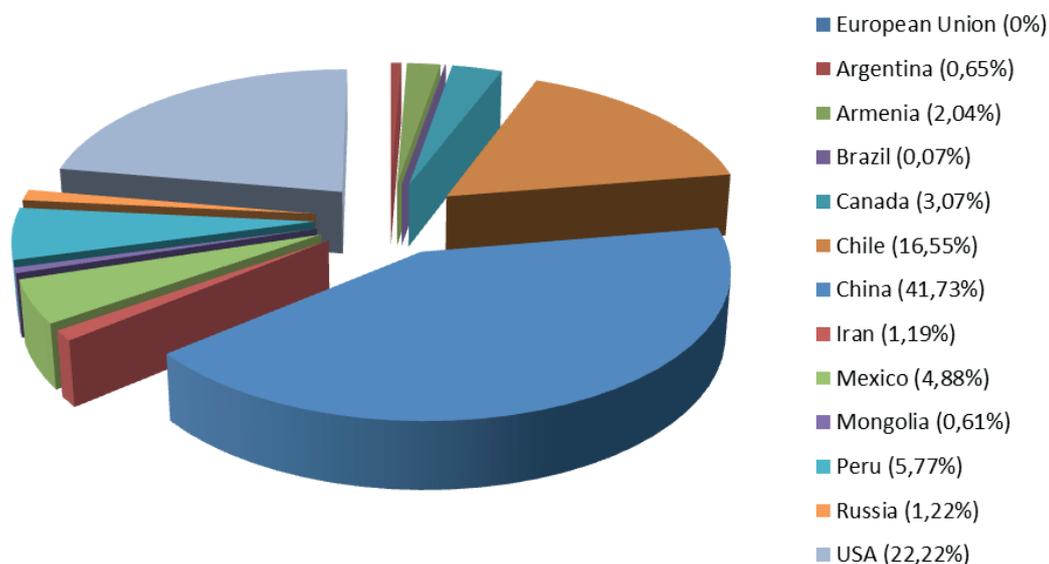
Tantalum usually occurs together with Niobium in the same type of mineral deposits and in minerals of similar characteristics. Very often, these metals are found in solid solutions, as is the case of columbite-tantalite or the minerals from the pyrochlore group. Mineral deposits from which Tantalum is extracted are associated with specific igneous rocks: Carbonatites and associated rocks, alkaline to peralkaline granites and syenites, and pegmatites.

The largest reserves of Tantalum are located in Brazil and Australia. However, the combination between demand, lack of control in production and commerce and small-scale mining have led to countries in the Great Lakes Region of Africa dominating the Tantalum production in recent years.



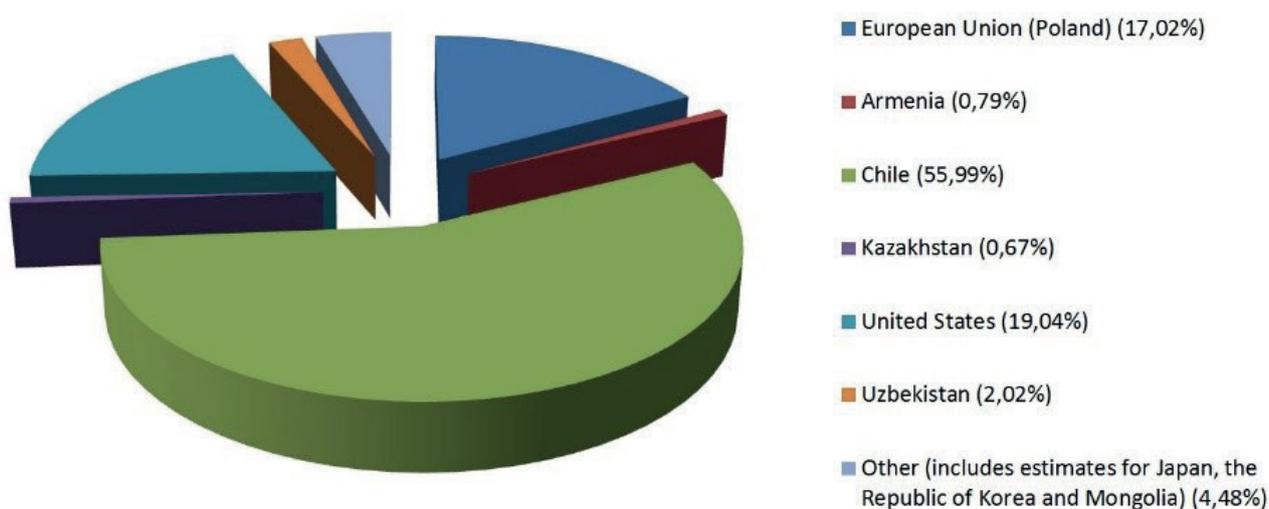
**Figure 5. Geographic distribution of 2013 production of Tantalum (top) and Niobium (bottom) concentrates (as a percentage of total world production), including the European Union's contribution.**

A further analysis of primary sources shows that Molybdenum is contained in various minerals, but only molybdenite ( $\text{MoS}_2$ ) is suitable for the industrial production of marketable Molybdenum products. Molybdenite can occur as the sole mineralization in an ore body, but is often associated with the sulphide minerals of other metals, notably copper. Mo content of viable ore bodies ranges between 0.01 and 0.25% [17]. Molybdenum ores are found in Chile, Sweden, Turkey, Canada, USA, China, Iran, Mongolia and Peru.



**Figure 6. Geographic distribution of 2014 Molybdenum mine production (as a percentage of total world production), including the European Union's contribution.**

Rhenium does not occur specially mineralized, but is carried essentially by molybdenite ( $\text{MoS}_2$ ). Accordingly, the world reserves of Re are primarily contained in molybdenite from porphyry copper deposits, making Rhenium a by-product of the Copper-mining industry. Some of the by-product molybdenite concentrates from Copper mines contain small quantities (<0.1%) of Rhenium. Molybdenum roasters equipped to recover Rhenium are one of the main commercial sources of this rare metal [18]. Poland is the EU's only Rhenium-producing country.



**Figure 7. Geographic distribution of 2014 Rhenium production (as a percentage of total world production), including the European Union's contribution.**



# 4 SECONDARY SOURCES AND URBAN MINING: RECYCLING AS A WAY TOWARDS SUSTAINABLE SUPPLY

## 4.1 SECONDARY SOURCES

When recycling, the main objective is to address the recovery of refractory metals in metallic or oxide form existing in waste (old mine tailing and industrial waste) and reduce the amount of waste put into landfill. To reach this objective, an analysis of the available resources containing refractory metals is needed. The waste rock, tailing mills, mine waste dumping, ashes and slag generated in different mines within Europe need to be identified. Information from the PROMINE Project (<http://promine.gtk.fi/>) has been complemented with additional information concerning possible sources of secondary resources of W, Ta, Mo, Nb and Re in different countries in Europe.

Sites with secondary resources of Tungsten and Molybdenum have been well identified throughout world. However, information concerning Ta, Nb and Re is not fully available. Molybdenum and Rhenium are mainly related to porphyry Cu deposits. An evaluation of these deposits in Europe has been conducted, but in some cases, there is not clear information about the tailing or waste rock. Information available for Niobium is very limited.

Information as to type of waste, mine companies, location, grade of metal, reserves, mineralogy and metal basis characterization is provided below.

In the EU, Tungsten-containing waste rock and mill tailings can be found in the Panasqueira Mine (Portugal) [19], the Barruecopardo mine (Spain) [20], the La Parrilla Mine (Spain), which has a 0,28%  $WO_3$  in coarse tailings and slimes [21], the Los Santos Mine (Spain) with a 0,14%  $WO_3$  in old tailings [16], the Milttersill mine (Austria) with 0,5%  $WO_3$  in mine tailings [22], smelting slags in Greece with a 3-76 ppm  $WO_3$  concentration and flotation tailings in Ylöjärvi (Finland) with a 0,02%  $WO_3$ - Mine waste dump at the Buchim Mine (Macedonia) is at 3-152 ppm  $WO_3$  while flotation tailings at Sasa (Macedonia) are at 655 ppm  $WO_3$ , along with several other unprocessed mine products and wastes in Portugal [23].

Niobium can be extracted as a by-product of tin smelter waste from sludge from the cemented carbide tool industry, in the form of mill scrap from alloyed and unalloyed metal fabrication and scrap from industrial alloys and super-alloys. The highest potential for Niobium recovery in Europe is ascribed to sites in Greece and Macedonia.

- The Buchim Mine Potential (Macedonia) is related to its active mineral extraction plants: Chalcocite, Chalcopyrite, Covelite, among others. This high potential (up to 313.3 t) is linked to the mine waste dump (surface storage) [24].
- The potential in Greece is much lower but still reaches a national average sum of 65.5 tons of Nb that may eventually be recovered. This tonnage is distributed among seven different locations in northern Greece. These wastes are associated with former smelter or refinery plants with smelting slag waste containing niobium.
- The Kiruna mine in Sweden is the largest underground iron ore mine in the world. In wet-sorted tailing, the niobium concentration is 11.9 ppm [25].

Tantalum can be extracted as a by-product of tin smelter waste. Tin smelter waste typically contains at least 8 to 10 per cent Tantalum oxide, sometimes reaching as much as 30%. Low grade smelter waste can be upgraded by electrothermic reduction yielding a synthetic concentrate with Tantalum and Niobium content of up to 50 %. In the EU, potential tailings and slags can be found in Spain, Portugal, France, the UK, Germany and the Czech Republic. In the EU, the only company of any real significance is H.C Starck, which might Malaysian and Brazilian slags at a plant in Germany, which is considering moving the processing to its plant in Thailand). A tin-mining and smelting operation in Spain is due to come into production in Q1 of 2017. That will create a new EU source of Ta feedstock (in slags) but there is no guarantee that it will be supplied to processors in the EU [26]. Tantalum can also be found in waste from uranium mining.

As for mine tailings, Molybdenum is recovered as a by-product of Copper and Tungsten mining. Recovery of copper-bearing ores is the primary objective and molybdenite recovery and provides added economic value. This accounts for 50% of the world's Molybdenum production [27].

- Boliden Aitik is the largest copper mine in Sweden (the Aitik mine is a porphyry Cu-Au-Ag deposit). Since 1968, over 632 Mt of ore has been mined. Molybdenite is sporadically observed in the ore zone and footwall of the deposit, usually in association with chalcopyrite and/or pyrite, in quartz veins of varying composition, and as coarse aggregates in pegmatite dykes [28]. The amount of tailings reaches 35676 kt with a 0.00027% percentage of Molybdenum.
- The Knaben Molybdenum mines in Norway have deposited more than 8 million tons of tailings in ponds with a high Mo concentration [29].
- The Garpenberg mine in Sweden produces 1.4 tons of ore per year and is expect to reach 2.5 million tons per year. Produced tailings reach 500000 tons/year, of which Mo content is 2.9 mg/kg [22].
- The Legnica-Glogow copper basin is located in Poland. Mo tailings composition is 15 g/t in Lubin, 12 g/t in Rudna, and 8 g/t in Plokowice [22].

Lastly, secondary sources of Rhenium in the EU are found in:

- Flue dust in Mansfeld smelter (Germany), where Re grade is 63g/t [23].
- Tailing waste in Iberian Pyrite Belt, where Re concentration is 3.4 ppm [30].
- Tailing and ashes in the Asarel Mine in Bulgaria, where Re concentration is 0.05 micrograms per gram of ash [31].
- Waste tailings and waste rock in the Aitik Mine (Sweden), where Re concentration is 1587 ppm [32].

## 4.2 URBAN MINING

As for recycling and urban mining, there are still significant gaps concerning reserves of refractory metals in end-of-life waste. There is however information concerning different applications and basic information on the distribution of the use of refractory metals among the applications, although in many cases it is difficult to find public data even for a coarse assessment of the quantities of refractory metals for end-of-life and manufacturing waste:

- Waste and product statistics are ill-suited for estimation, as individual statistical categories usually include products that contain and do not contain refractory metals. In many cases the percentages of refractory metals may vary even in the same kind of products. To give an example, very few of the capacitors used in portable electronics and vehicles are Tantalum capacitors and their quantities may vary from zero to several pieces per product. There are gaps in waste statistics as well, eg., WEEE and ELV statistics cover only the waste subjected to compliant treatment.
- Product development may cause relatively rapid changes in the use of components and metals. To give an example, the use of electronics in cars has developed quite rapidly. There are also applications with long life-times which are less subject to rapid changes, such as materials and equipment used in industrial plants.
- For many applications, there are very few studies or other publications which include reliable data on concentrations of refractory metals in end-of-life products.
- Recycling of manufacturing waste is in many cases less complicated than that of post-consumer waste. Recycling, however, is managed by private companies and there are usually no requirements to publish detailed information on the quality and composition of recycled materials.

Therefore, for all of the reasons outlined above, data on future development of the quantities and qualities of end-of-life products is limited. Although European waste legislation is the same for all EU countries, the practical implementation of e.g. collection systems varies from country to country. Thus there are no resources for more detailed evaluation of the collection systems. The economic feasibility of collection and recycling of refractory metals varies significantly depending on the type of waste. One example of a market that works quite well is the recycling of hard metal tools and different steels and alloys that have already been collected for recycling. Nonetheless, there are still a lot of challenges for the recycling of minor metals from consumer applications, and the recycling rates are near zero. Lastly, information concerning economic incentives for better management and the recovery of refractory metals from EoL and manufacturing waste is very limited.

As for Tungsten, the main sources of EoL are:

- Spent Ni-W catalysts: containing approximately 20.4 wt.% W and 3.3 wt.% Ni. In the EU, about 1000 tons of spent Ni-W catalysts are generated every year [33] [34].
- Other W bearing wastes are: burnt-out bulbs, electric contacts/devices, electrodes, bullets, surface coating materials. Recycling these materials is quite problematic, as they are quite dissipative and so far there is no efficient way to collect them.

Niobium containing end-of-life products can be found in [35]:

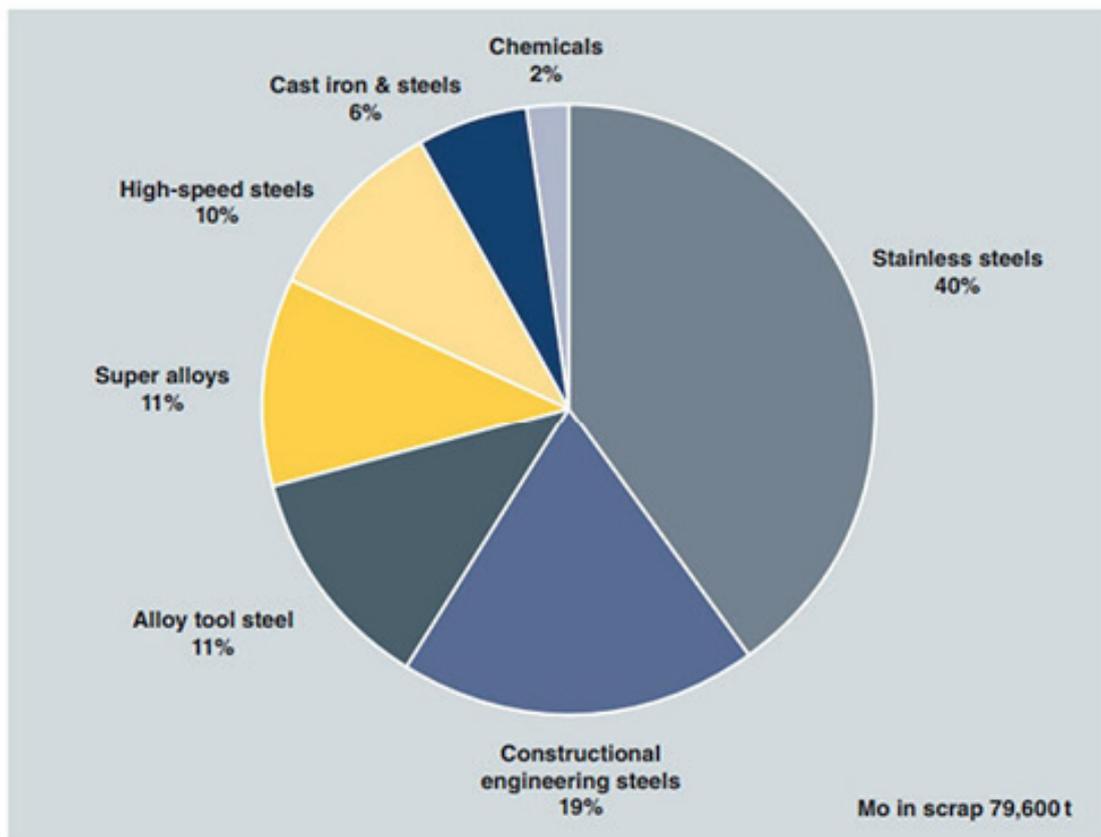
- Wastes of electric and electronic equipment (WEEE). It was estimated that a computer can contain up to 0.0002% of Niobium. Niobium recovered from the collected IT and telecommunications equipment could be as high as to 1.2 tonnes and that the grade of Niobium in PCB is approximately 36 g/t.
- End of Life Vehicles. The grade of Niobium in ELV can be estimated by the grades of Niobium used in stainless steels, which would be less than 0.04-0.08%.

Potential sources for Niobium recovery are mostly in steels, but the Niobium content is low (<0.5% in weight).

As for Tantalum, other potential sources are scrap from manufacturing of Tantalum powders and ingots as well as manufacturing of Tantalum-containing products and end-of-life scrap containing Tantalum [36]. Capacitors may be a potential source of Tantalum as they are its main application.

The following sources may be considered for urban mining of Molybdenum:

- Steel and alloy scraps returned to the furnace and melted together with primary Molybdenum and other raw materials to make steel. The recycling of stainless steel is currently a global market. It is reported that 39% of Mo used each year is recycled from scrap [37].
- Spent Ni-Mo catalysts from the petroleum refining industry typically contains 8-16% wt. of Molybdenum oxide. In the EU, about 25,000 tons of spent Ni-Mo catalysts are generated every year [38]. The recovery of metals from these catalysts has both economic and environmental incentives.
- Mo waste and scraps: in 2014, approximately 3,250 tons were imported to the EU.
- EOL vehicles contain various refractory metals, although no references have been identified as to their recovery.



**Figure 9. The use of Molybdenum from recycling scrap. SOURCE: IMO A**

Rhenium is mostly recycled from spent Pt-Re catalysts and Rhenium-containing spent super-alloys. The Rhenium content of a catalyst can vary from 0.25% to 0.9% by weight, typically 0.3% Rhenium and 0.3% Platinum. Several countries produce Rhenium from the recycling of these products: Germany (4 Mg of estimated Re production); Poland (0.5 Mg of estimated Re production); France (1 Mg of estimated Re production); Estonia (1 Mg of estimated Re production) and the Czech Republic (0.5 of estimated Re production) [39].

# 5 SUBSTITUTION: A TRICKY APPROACH?

Substitution has been considered as another alternative for managing the refractory material supply chain; removing one component and replacing it with another. Technically speaking, it can be done by substituting:

- One element for another element
- One product (material/compound) for another product (material/compound)
- A product for a service
- One product for another product
- One system for another system

The choice of the route depends on economic viability, sustainability, environmental friendliness, health safety and, last but not least, the quality of the proposed solution in terms of performance and thus the potential for either a reduction or an increase in RM use is considered for four possible scenarios:

1. The use of RM is reduced considerably or even substituted.
2. Potential and realistic substitutes are found in order to maintain or increase demand in current level and an increase in usage.
3. Current usage levels remain constant, no potential substitutes are found, and refractory metal demand increases.
4. The refractories will substitute the lower performing elements in large quantities.

Substitution is thus not a simple, straightforward approach. For example, most refractory metals can be substituted by another refractory metal, which creates a loop that makes it impossible to guarantee reduction in the use of refractory metals.

## 5.1 POTENTIAL SUBSTITUTES FOR REFRACTORY METALS

When assessing substitution, property analysis, applications, value chain and potential substitutes must all be taken into consideration. In the case of Tungsten, consumption continues to increase as the amount of carbide tool production increases with the expansion of markets in developing countries. As for the main application of Tungsten, WC-based cemented carbides, it would be difficult to substitute the Tungsten with another metal, as the potential substitutes increase production costs and diminish performance. Titanium carbide (TiC) and nitride (TiN) would be potential substitutes but the technology is not competitive at the moment. In steel products, Tungsten can be replaced by other refractory metals such as Nb (CRM) or Mo. In other application areas, possible substitution of Tungsten can be achieved by replacing super-alloys with Ceramic Matrix Composites (CMCs) made from a silicon carbide/nitride matrix for gas turbine engines. Furthermore, substitution with nanostructured n-alloys could be attained within the next 10 years, as current TRLs are very low (TRL 3-4). There are already some substitution paths in LEDs. The figure below represents the distribution of end-users and corresponding substitutability assessment for Tungsten [17].

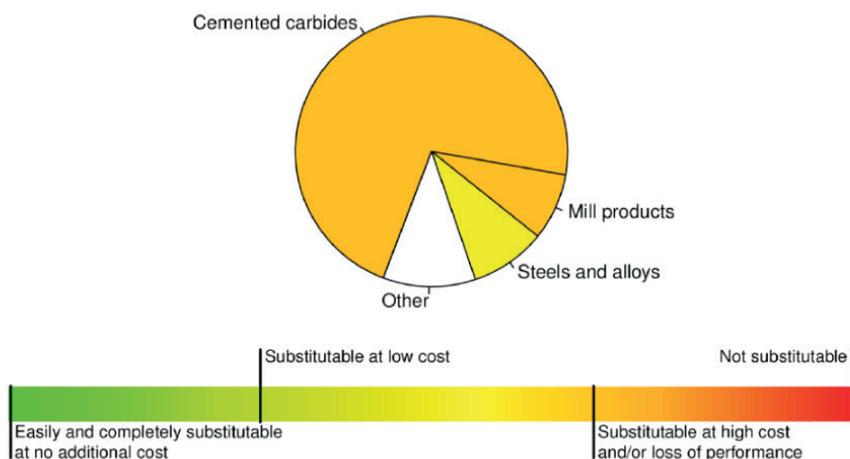
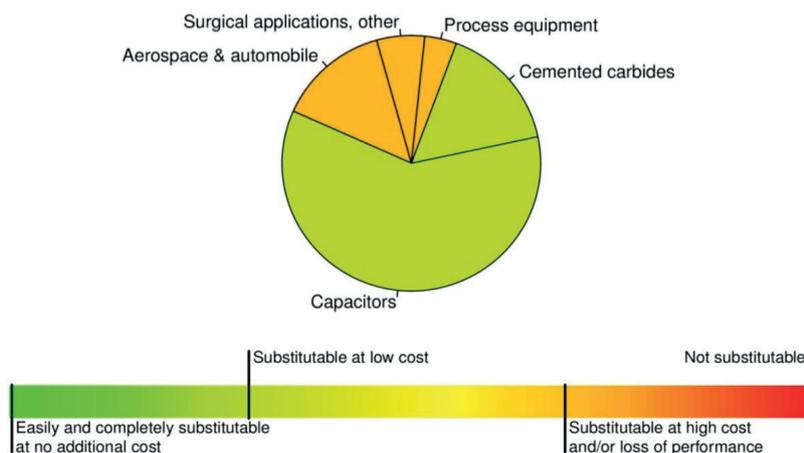


Figure 10. Distribution of end-uses and corresponding substitutability assessment for Tungsten [17]

Tantalum substitutability in capacitors and carbides is quite simple and economical. In super-alloys and mill products, substitutability is possible, but at a high cost and/or loss in performance. In sputtering targets and chemicals Tantalum remains unsubstitutable. Thus, while it is true that Tantalum can be replaced with other materials, most substitutes are either very costly or present adverse properties. Distribution of end-uses and corresponding substitutability assessment for Tantalum is presented below.



**Figure 11. Substitutability of Tantalum in its major applications**

Tantalum capacitors harness the beneficial quality inherent in Tantalum of forming a protective oxide surface layer as the dielectric. In Tantalum, the dielectric layer can be very thin which results in a high capacitance that can be achieved in small volumes. As for capacitors, aluminium and ceramic capacitors offer substitutes that are competitive in terms of both cost and performance in Tantalum. They also offer sustainable substitutes that do not employ critical raw materials. Ta capacitors are still used in applications which require high performance.

Murata Electronics first began to see industry acceptance of ceramic capacitors as substitutes for Tantalum in the late 1990s. By 2001, ceramics were proven to have enough advantages over Tantalum to become permanent replacements. The most important benefit is that ceramic capacitors offer a cost-effective solution to Tantalum capacitors. The design modifications have also led to several advantages in ceramic capacitors, including ease of placement, low equivalent series resistance (ESR), non-polarization, and high voltage [16]. Aluminium capacitors offer a lower cost and higher availability when compared with Tantalum capacitors. They also have shorter production lead times, low leakage currents and higher voltage range. [14]

Due to the physical and chemical similarities of Niobium and Tantalum, the two metals can be substituted for each other in a number of applications: cemented carbides, corrosion resistant coatings, optics and hard disc drives. Niobium is listed as critical raw material (CRM), so Niobium does not offer a sustainable substitute for Tantalum. Where strength at high temperatures is required in steels, metals such as Molybdenum and Vanadium could be used to substitute Tantalum. In super-alloys, Hafnium, Iridium, Molybdenum, Niobium, Rhenium and Tungsten could substitute Tantalum. Furthermore, these substitutes are not sustainable options and are typically more costly. In some electronic applications, such as SAW filters and SAW resonators, Lanthanum gallium silicate (La<sub>2</sub>Ga<sub>5</sub>SiO<sub>14</sub>) could be used as a substitute for Tantalum. Lanthanum and Gallium however are also listed as critical raw materials.

The substitution of Niobium is possible depending on the applications it is used for. For example, in the case of HSLA steels, it can be substituted with Ti, V or Mo. In the case of common stainless steels, Ti, Ta or high Nitrogen steels are the best options. As with other refractory metals, ceramic compounds have been also considered, as ceramic matrix composites are considered to be the best option for super alloys. Lastly, in the case of V-superconductors, both Ga alloys and BSSCO alloys offer promising solutions. The figure below shows the distribution of the uses of Niobium and their substitutability.

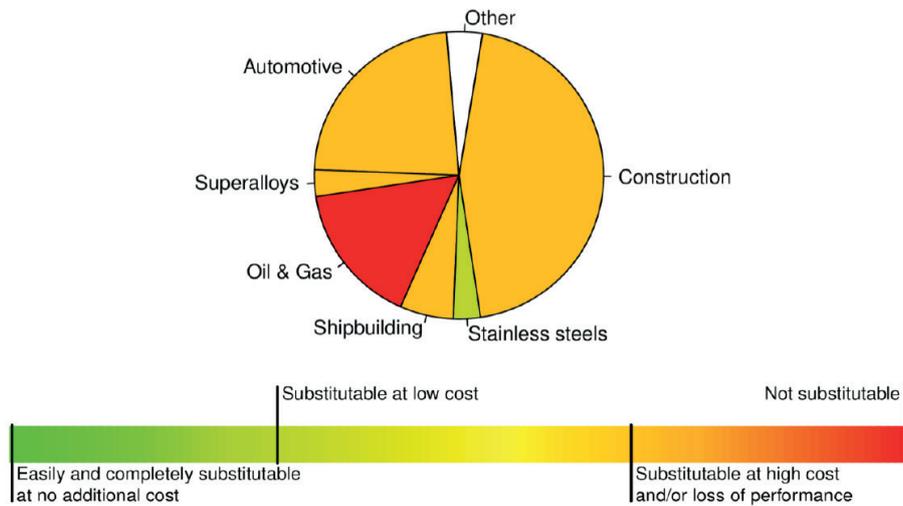


Figure 12. Distribution of end-uses and corresponding substitutability assessment for Niobium [2]

The substitutability of Molybdenum in present applications is rather low, with a high substitutability index, which may be due to the fact that most of the alternative applications are closely correlated to a reduction in performance, increased cost and the potential harmfulness of possible substitutes.

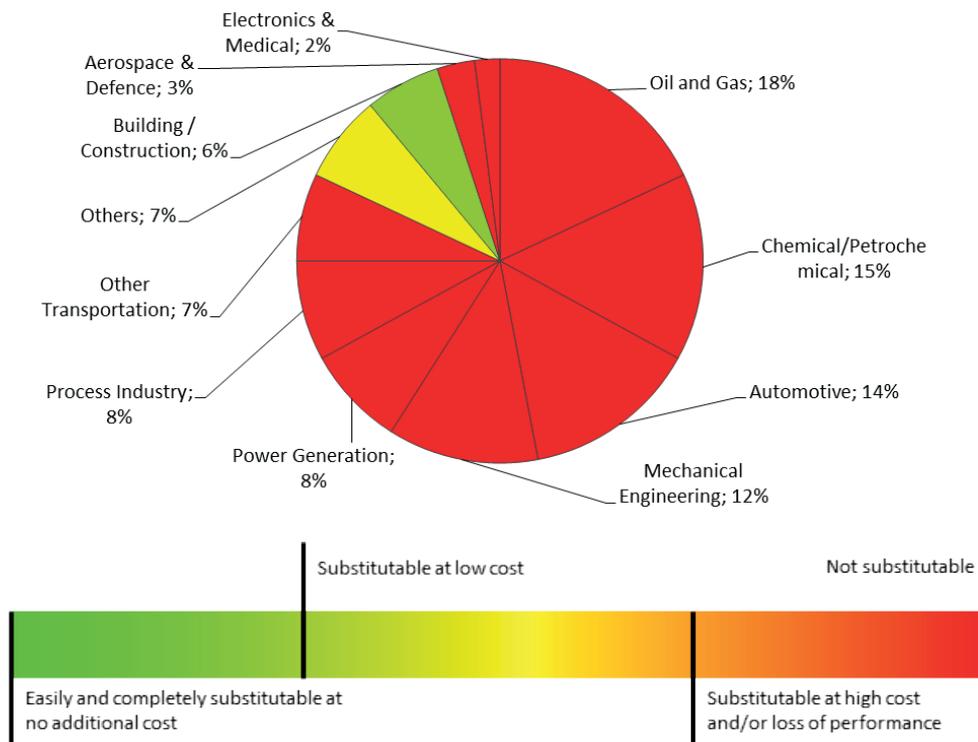


Figure 13. Distribution of end-uses and corresponding substitutability assessment for Molybdenum

Lastly, in the case of Rhenium, its main advantage in super-alloys is that Rhenium addition can be designed with closer tolerances, operating at higher temperatures, with prolonged engine life and increased engine performance and operating efficiency. Although substitution of Rhenium with other materials is difficult, General Electric announced in 2008 that they will aim to reduce Rhenium content in jet engine manufacturing by using more ceramic matrix composites (CMC). As for catalysts, Platinum-Rhenium applied to silica or silica-alumina bases is used in the reforming process in which low-octane refinery petroleum naphtha is converted into high-octane liquids for high-octane gasoline.

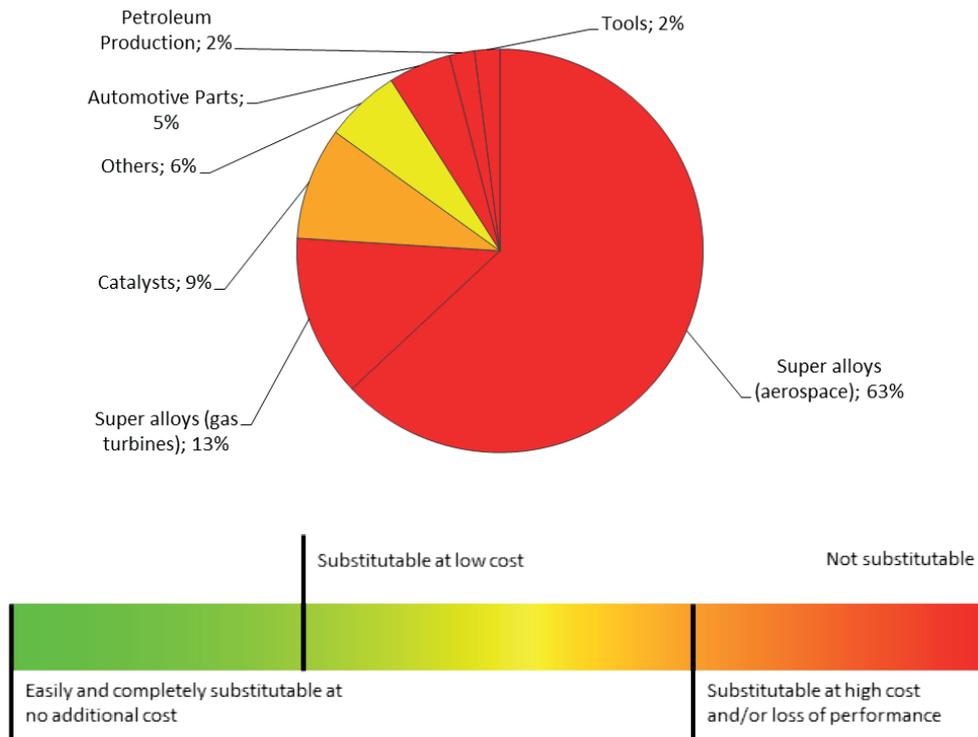


Figure 14. Distribution of end-uses and corresponding substitutability assessment for Rhenium [2]

# REFRACTORY METALS SUBSTITUTABILITY ASSESSMENT

The substitutability index is based on performance and price evaluations [10, 12]. However, it must be kept in mind that the driving forces behind substitution can change over time and are also affected by location-specific ethical issues, material conflicts and environmental concerns.

The procedure for assessing substitutability of many raw materials is briefly outlined in many documents on the identification and assessment of profiles, economics and risks related to critical raw materials [10, 11, 12]. The substitutability index is a quantitative comparison tool in which all of this type of information is concentrated. The substitutability index  $\sigma_s$  is first estimated for an element employed in a certain application so as to determine the element's functionality in a specific end-use sector. The estimated values are then used to calculate an overall substitutability index  $\sigma_{RM}$  of an element by calculating a weighted sum of sector indexes using the weight represented by the sector consumption share of an element as a portion of overall consumption of that element:

$$\sigma_{RM} = \sum_s A_{RM,s} \sigma_s$$

where  $A_{RM,s}$  is the net consumption share (in %) of a given RM (refractory metal) in a given end-use sector. The values of substitutability index are subjected to experts' judgement and estimated by them.

The values lie between 0 and 1 where selected values mean:  
 0.0 – easily and completely substitutable at no additional cost  
 0.3 – substitutable at low cost  
 0.7 – substitutable at high cost and/or loss of performance  
 1.0 – not substitutable

The tables below show the substitutability of the different refractory metals according to their different applications.

## TUNGSTEN

Application	Substitutability index
Tungsten alloys	0,7
Superalloys	1
Fabricated products	1
Alloy steels (mainly tool steel, >80%)	0,7
Cemented carbides	0,7

## TANTALUM

Application	Share	Megasector	Substitutability
Capacitors	40%	Electronics	0.3
Superalloys	21%	Metals	0.7
Sputtering targets	12%	Electronics	1.0
Mill products	11%	MechEquip	0.7
Carbides	10%	MechEquip	0.3
Chemicals	6%	Chemicals	1.0

## NIOBIUM

Application	Share	Megasector	Substitutability index
Steel: Structural	31	Construction	0.7
Steel: Automotive	28	Transport – Road	0.7
Steel: Pipeline	24	Oil	0.7
Superalloys	8	Metals	0.7
Others	6	Other	0.5
Steel: Chemical	3	Mechanical Eqpt.	0.7

## MOLYBDENUM

Application	Share	Megasector	Substitutability index
Oil and Gas	18%	Oil	1.0
Chemical/ Petrochemical	15%	Chemicals	1.0
Automotive	14%	Transport-Road	1.0
Mechanical Engineering	12%	MechEquip	1.0
Power Generation	8%	Electrical	1.0
Process Industry	8%	MechEquip	1.0
Other Transportation	7%	Transport-Other	1.0
Others	7%	Other	0.5
Building / Construction	6%	Construction	0.3
Aerospace & Defence	3%	Transport-Other	1.0
Electronics & Medical	2%	Electronics	1.0

## RHENIUM

Application	Share	Megasector	Substitutability index
Super alloys (aerospace)	63%	Transport-Other	1.0
Super alloys (gas turbines)	13%	MechEquip	1.0
Catalysts	9%	Chemicals	0.7
Others	6%	Other	0.5
Automotive Parts	5%	Transport-Road	1.0
Petroleum Production	2%	Refining	1.0
Tools	2%	MechEquip	1.0

More detailed information concerning advantages and disadvantages of main substitutes for refractory metals is provided in Annex B.

## 5.2 REFRACTORY METALS AS SUBSTITUTES

Tungsten may be a potential substitute in the following application:

- Refractory ceramics for aerospace: Transition metal borides and carbides with melting temperatures exceeding 2700°C are commonly referred to as ultra-high-temperature ceramics (UHTCs). Of these materials, hafnium diboride ( $\text{HfB}_2$ ) has shown the highest oxidation resistance. This material has been identified as a leading candidate for extreme environment thermal protection systems, for example, in the satisfaction of hypersonic vehicle requirements. However, oxide formed on the surface of this material allows future oxygen penetration. Silicon carbide additions (5-30% volume) had been used since in the 1960s, but was subsequently replaced by  $\text{SiO}_2$  glass, which improved oxidation resistance at moderate temperatures (<1700°C), but still not enough to prevent damage from the extreme conditions of hypersonic cruises, in which temperatures may exceed 1723°C. Most recently, Zhang et al. [40] have prepared  $\text{ZrB}_2$ -based UHTCs with additions of WC to promote liquid-phase sintering in the oxide scale. It was shown that the sample containing WC had a denser  $\text{ZrO}_2$  scale and the weight gain during oxidation was reduced at temperatures of 1600°C and below.
- Wear-resistant alloys with coatings: The erosive wear of materials caused by the impingement of solid particles is a well-known industrial problem, encountered for instance, in the case of compressor blades used in gas turbine engines in aeronautics. The deposition of W/W—C coatings can be accomplished by reactive magnetron sputtering which provides very highly erosion resistant coatings. Compared with Ti-based alloys, erosion resistance is improved by at least two orders of magnitude and this excellent behaviour seems to be a product of the achievement of physical vapour deposition PVD of very hard W—C solid-solution layers that can be closely combined with pure W layers. In general, the use of a tungsten carbide cobalt system is very reliable way to improve wear performance of less wear-resistant alloys and coatings. The tungsten carbide cobalt system (with different volume fractions of Co) has already been used extensively and seems to be a relatively strong candidate in terms of its ability to enhance wear performance, including toughness versus hardness property tailoring.

Some new applications for Rhenium alloys with Molybdenum or Tungsten include high-temperature reactor components and fuel-cladding materials. The beneficial properties of these alloys include good thermal properties, high strength at elevated temperatures and good room-temperature mechanical properties that simplify component manufacturing processes. Research shows that both Rhenium and Rhenium dioxide are chemically inert up to 2500 K [41] [42]. As for the prospects of nuclear applications of Rhenium alloys, it would first be necessary to investigate structural changes occurring in the alloys when heated or irradiated, significantly affecting their mechanical properties [43].

The search for super-hard materials, with diamond hardness but at a lower price, has revealed that Rhenium compounds figure among the possibilities. So far, the identified super-hard materials group is comprised of compounds made up of transition metals with light elements such as boron, carbon, nitrogen or oxygen. One example of these is Rhenium diboride  $\text{ReB}_2$ , but its properties are not isotropic. Theoretical investigation of its mechanical properties indicate that  $\text{ReB}_2$  has an extremely high shear modulus and its  $c_{44}$  elastic constant can be as high as 70% of c-BN. These properties suggest it is ultra-incompressible and therefore can be classified as super-hard [44]. Its high hardness is thought to be related to covalent double bondings of the B-B type as well as six Re-B strongly-directional covalent bondings [45] [46]. All this indicates that the best possible properties should be obtained in highly textured  $\text{ReB}_2$  materials, preferably in thin film form. However, the material's overall hardness is a product of coatings and the substrate used [47].

# 6 EUROPEAN VALUE CHAIN FOR REFRACTORY METALS

## 6.1 A CLOSER LOOK TO REFRACTORY METALS MAIN APPLICATIONS

Refractory metals are mainly applied as super-alloys in strengthening different types of steels for the automotive industry, the construction and oil and gas pipeline industries and the aerospace industry. They are also used for strengthening high speed cutting tools and electronic components. The fact that the EU's steel and aeronautical industries are among the best worldwide combined with its important role in the manufacture of everyday consumer products underscores the importance of refractory metals in the EU.

The main use of Tungsten is the production of hard materials based on Tungsten carbide, one of the hardest carbides, with a melting point of 2770°C. It is an efficient electrical conductor and it is used to make wear-resistant abrasives, and “carbide” cutting tools such as knives, drills, circular saws, milling and turning tools used in the metalworking, woodworking, mining, petroleum, and construction industries [48]. Tungsten is also used to make heavy metal alloys and is added, for example, to high-speed steels, which can contain as much as 18% Tungsten. These alloys are used in the aerospace and automotive industries, turbine blades and radiation shielding [49] [50]. Further applications of Tungsten include: lubricants (Tungsten (IV) sulphide), catalysts (for hydrodesulphurization [51]), ceramic glazes (Tungsten oxides), calcium/magnesium tungstates in fluorescent lighting, or crystal tungstates in scintillation detectors in nuclear physics and nuclear medicine applications.

Niobium is mainly used in the manufacture of steel for construction and high temperature applications. Recently, high-strength and low-alloy steels for the automobile industry, pylons, offshore platforms and pipelines have become a more important use of Niobium. It is also found to be important for carbon capture and storage of (pipelines) and nuclear technologies (stainless steels, and super-alloys). Approximately, 90% of Niobium production is transformed in standard grade Ferro-Niobium by adding iron and aluminium. Ferro-Niobium contains approximately 66% Niobium. The Ferro-Niobium content in grams per ton of produced steel is not always constant. In Europe, the Ferro-Niobium content in steel in 2014 was 84 g/t, higher than that of China, Russia and India [52]. Main global end-uses of Niobium are: (1) High-strength low-alloy (HSLA steels), (2) Construction, 31% of total Ferro-Niobium consumption; (3) Automotive, 28% of total Ferro-Niobium consumption (the automotive industry is increasingly looking for ways to reduce weight and costs, which is helped by the use of steels containing Ferro-Niobium); and (4) Oil and gas pipelines, 24% of total Ferro-Niobium consumption.

Moreover, super-alloys and stainless steel for the nuclear and aircraft industries count for 8% of all Niobium produced. Niobium is present in Nickel-based super-alloys in quantities varying from 3 to 5.5 wt.% percent (demand of Nickel based super-alloys containing Niobium is highly dependent on the aircraft engine industry). Despite the current low consumption of Nickel-based alloys, the automotive industry is becoming a more important end-user of these materials. Titanium alloys contain 0.2-6.5 wt.% of Niobium [53]. Niobium-Titanium and Niobium-Tin alloy are used in superconducting magnetic coils in magnetic resonance imagery (MRI), magneto-encephalography, magnetic levitation transport systems, and particle physics experiments. Cobalt and Iron-based super-alloys containing 1 to 5 % Niobium are used to make gas-turbine engine components, rocket nozzle sub-assemblies and heat-resistant combustion equipment [54]. In stainless steel industry, Niobium is consumed mainly in ferritic stainless and most notably that used for automobile exhausts [55]. Smaller quantities of Niobium are used in other applications, such as superconductors, jewellery, thermometers, chemicals, cutting tools (Niobium carbide), particle accelerators and catalysts. The large hadron collider requires 600 tons of Niobium-Titanium alloy and several tens of tons of pure Niobium for superconducting applications. The International Thermonuclear Experimental Reactor is estimated to use 600 tonnes of Niobium-Tin strands and 250 tons of Niobium-Titanium strands [56].

Tantalum is used in different sectors of the industry, thanks to its corrosion-resistance and its applicability as a capacitor (billions of units produced every year). To manufacture capacitors, key components of mobile phones and other communication systems, Tantalum is added in the form of metal powder. Other applications in EEE are the sputtering targets and surface acoustic wave filters, which are used in cellular and wireless telephones, TV sets, video recorders and tire pressure control and keyless entry systems [57]. In Medicine, Tantalum is used in several medical applications because of its non-toxicity quality for human tissue. Due to its passive oxide layer, the metal is completely bio-inert in the body. Moreover, in optical industry, Tantalum compounds, mainly Tantalum pentoxide, are used for special glass products (heat-reflecting, high refractive index, low optical scattering).

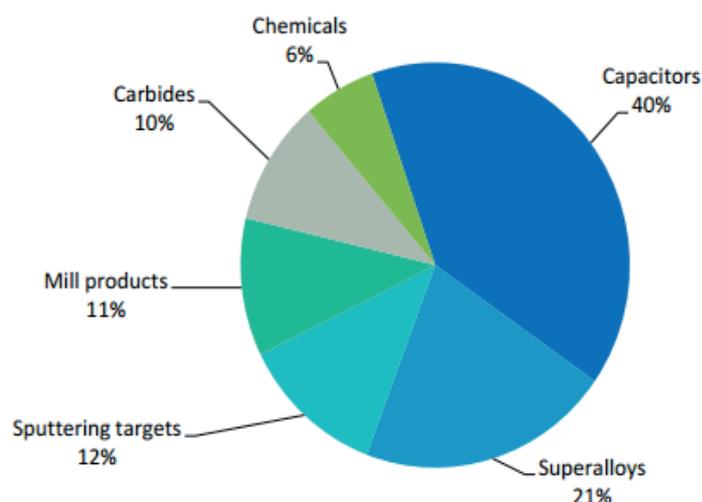


Figure 15. Roskill 2013 in Minor Metals Conference

In the case of Molybdenum, its widespread use in metallurgy applications is due to its effectiveness as an alloying element. Molybdenum is known as the least problematic metal among all the carbide forming elements, as regards specific challenges faced in powder metallurgy processing, due to its insensitivity to oxidation, its ability to influence the alloy's mechanical properties and its solid-solution strengthening and hardenability enhancement qualities, all of which make it effective in improving the mechanical properties of ferrous alloys significantly [58]. The Iron and steel industry are the biggest Molybdenum consumers. Molybdenum is primarily used as an alloying element in steel (engineering steels 45%, stainless steel 22% and tools and high speed steels 8%), cast iron (8%) and nonferrous metals (5%). The most important end-use applications of Molybdenum include machinery, electrical, transportation and automotive applications and the chemical and the oil and gas industries. There are different types of Molybdenum products and each of these products is used for different applications [59]: Mo oxide and FeMo are used in Stainless Steel, Alloy steel, Tool Steel and High-speed steel. FeMo is also used in cast iron, and Mo metal pellets are used in super-alloys. Ferro-Molybdenum is one of the most important Iron-Molybdenum alloys with a content of 60-75% of Molybdenum and it is the main source of Molybdenum alloying of High-Strength-Low-Alloy Steels (HSLA), and lastly, in chemical applications, ammonium heptamolybdate, ammonium octamolybdate, ammoniumdimolybdate, MoS<sub>2</sub> and sodium molybdate are used among others. To summarize, the main industries in which Molybdenum is used are: Oil & gas (17%), Chemical/Petrochemical (15%), Automotive (13%), and Mechanical Engineering (13%).

The main application of Rhenium is in alloys for aerospace industry (59%). Other applications of Rhenium are in gas turbines and catalysts (28%), the automotive industry (5%), and the oil/gas and tool industries (1%) [1]. Among the most important Rhenium-based products are: (1) Ammonium perrhenate used for the production of Rhenium metal and perrhenic acid, the manufacture of Pt-Re reforming catalysts and as an additive to super-alloys; (2) Perrhenic acid, used in the the manufacture of Pt-Re catalysts; (3) Rhenium metal powder and briquettes, which are added to super-alloys or used for sheet, foil, strip and wire production. Among all of these end products, Re content varies from 3% in Ni-based super alloys to 0.3% in Pt-Re reforming catalysts.

## 6.2 REFRACTORY METALS VALUE CHAIN

Refractory metals value chains are inextricably linked to major industries in Europe, especially to those who use super alloys, steel or catalysts. Some stakeholders, such as HC Stark or Treibacher Industrie, play an important role in this scenario as they act as processors/recyclers of different refractory metals at the same time.

In more specific terms, the EU is the leader in the development of many Tungsten products for automotive, aerospace, medical, and lightning applications (Total, Volkswagen, Airbus, BASF o Philips). The disappearance of EU Tungsten industry would result in full dependence of several key industries on imports from abroad [60]. This value chain would be enhanced by further exploitation of European Tungsten primary sources in Portugal, Spain and France.

The Niobium value chain is quite simple as the main sources coming into the EU are FeNb-based, at an average of 20000 t/year, mainly in the form of slags and ash residues, the tonnages of which vary between 1000-20000 per year. No ores, concentrates or wastes containing Niobium are imported into the EU and there are no Niobium mines currently in operation in the EU. There are thought to be other potential sources of Niobium, in ELV, WEEE and PCB, but there is no evidence of Niobium being recovered from these potential sources to date. Example of manufacturers are ArcelorMittal, a steelmaker, Treibacher Industrie, a carbides producer, or Shott, an optical lens manufacturer. HC Stark GmbH is one of the biggest Niobium processors, as it is with other refractory metals. There are also several companies in Europe that have been identified as Niobium recyclers: Buss&Buss Spezialmetalle GmbH, Innova Recycling GmbH, Jean Goldshmidt International SA, Metherma KG, ELG Utica Alloys Ltd, Metallum Metal Trading AG (Minor Metal Trade Association, Ta-Nb international study centre). As mentioned above, Niobium is mainly used in alloy steel in the automotive, aeronautic, and gas industries, so the end-users are mainly companies that work in these fields (Mercedes Benz, Exxon or Alstom).

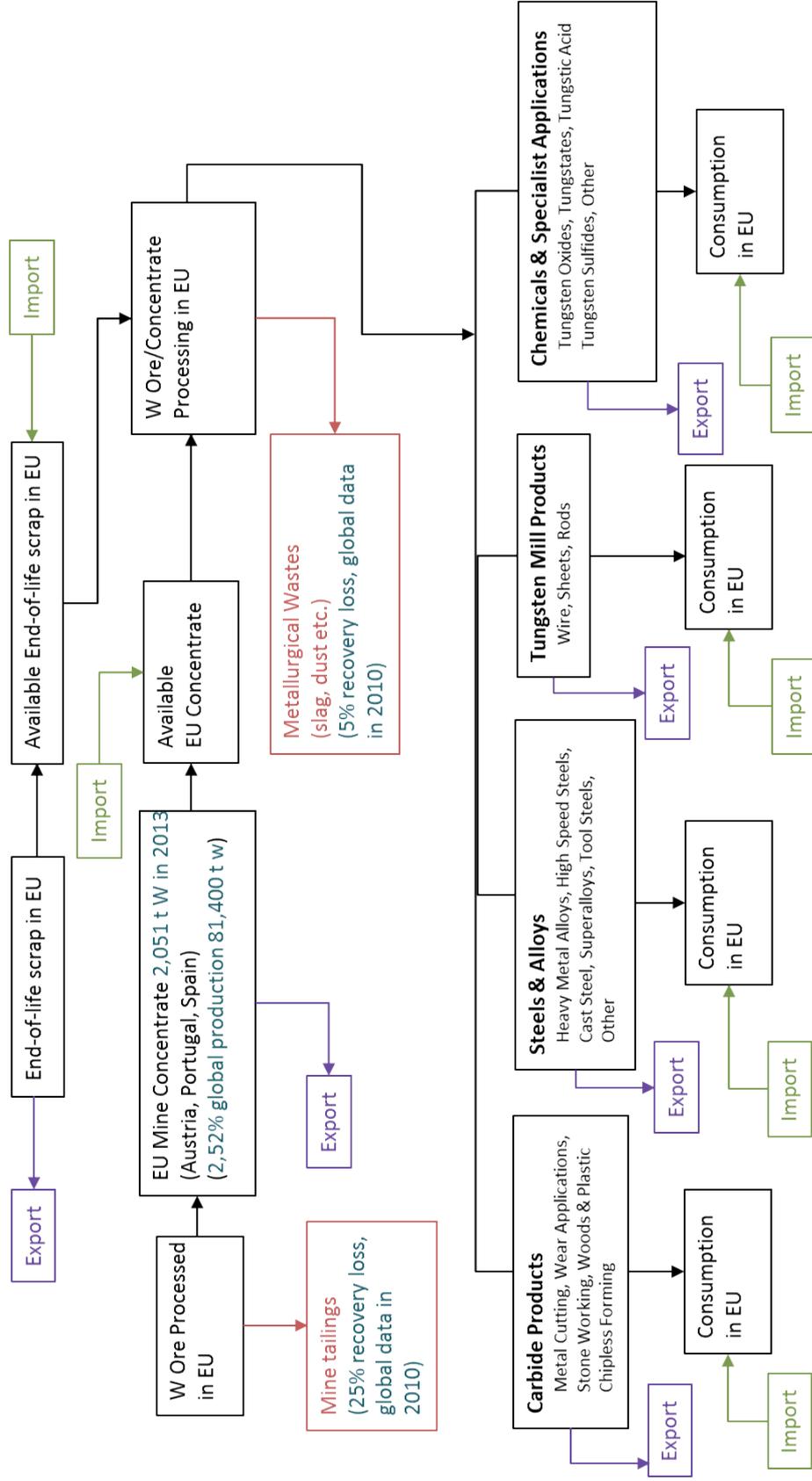
As for the Tantalum value chain, it is not a simple industry and it is certainly not transparent. The supply chain is complicated and often involves transfers within corporate groups, as most processors are either government or privately owned and the primary supply sector is shrouded in secrecy. Primary processors can use Tantalum concentrates, synthetic concentrates or scrap. Secondary processors rely on intermediate products, such as K-salt and Tantalum ingot. Two stakeholders worthy of mention are HC Stark, processor and recycler, and Scandmetal International, trader.

Imported Molybdenum ore concentrates are domestically processed following metallurgical procedures and are subsequently employed in the manufacture of various end-use products and intermediate products. Molybdenum is also imported in the form of finished products, ferro-alloys, scraps and external industrial wastes/residuals, although there is no statistical information on the amount of Molybdenum being extracted from waste/residuals. Molybdenum industrial value chain output is believed to be found mainly in various Mo-containing products or intermediate products, such as steels, metal/alloys. Some of these manufacturers are Sandvik or Plansee. Steels are used in the following industries: aeronautical and defence (EADS in Netherlands and Airbus in France), oil and gas (Royal Dutch Shell, Total and Eni), automotive (Volkswagen, Daimler, Fiat and BMW), and mechanical engineering (Sandvik, Outokumpu, Vaccumschmelze and Ceratizit Group). It is important to note that recycled Molybdenum satisfies between 25% and 33% total Mo demand as Molybdenum is a full recyclable metal.

Finally, the Rhenium value chain is quite complex as specific applications require specific intermediary products. The basic form, ammonium perrhenate (APR) is the starting material for the production of perrhenic acid and Rhenium metal in the form of powder, pellets or briquettes. A large proportion of the APR is used in the manufacture of reforming catalysts and then ultimately re-used within the petroleum catalysts industry. KGHM Ecoren is the only EU company that recovers Rhenium from molybdenite (around 6 tons per year), which it receives from its Copper-producing parent, KGHM Polish Copper. Among the major end-users of Rhenium in the EU are Airbus Group (the second-biggest aerospace manufacturer in the world) and Rolls Royce, one of the top four aircraft engine manufacturers.

A complete and detailed list of the main European stakeholders in each value chain is provided in Annex C.

# EU TUNGSTEN SUPPLY CHAIN



## Global Mine Production (Concentrate) 81, 400 Metric tons W in 2013

EU Mine Concentrate (Austria, Portugal, Spain) (2,52%), Australia (0,39%), Bolivia (1,54%), Brazil (0,47%), Burma (0,17%), Burundi (0,06%), Canada (2,62%), China (83,58%), Congo (Kinshasa) (1,02%), North Korea (0,08%), Peru (0,03%), Russia (4,42%), Thailand (0,12%), Uganda (0,02%), Vietnam (2,04%)

Figure 16. EU Tungsten value chain

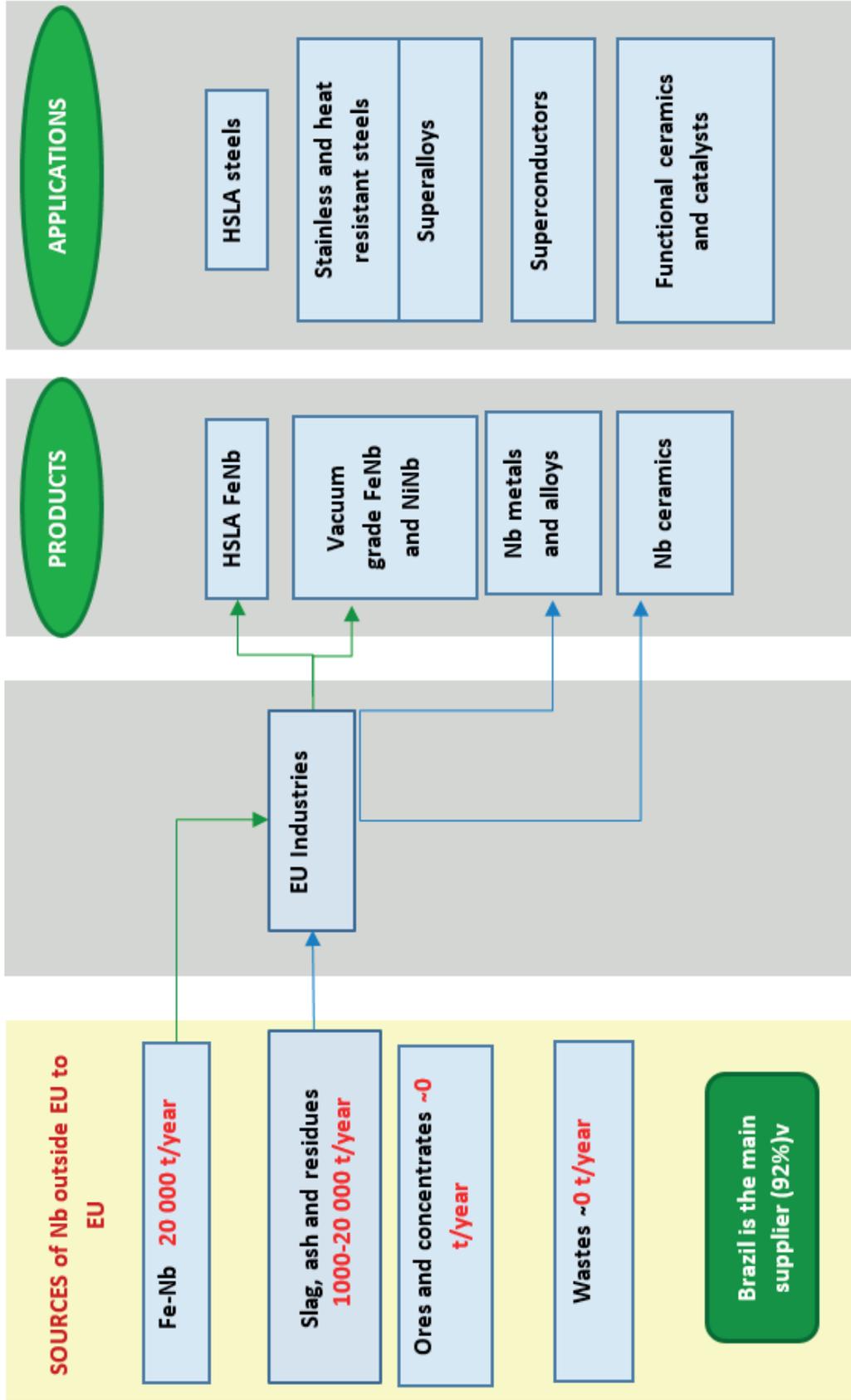


Figure 17. EU Niobium value chain

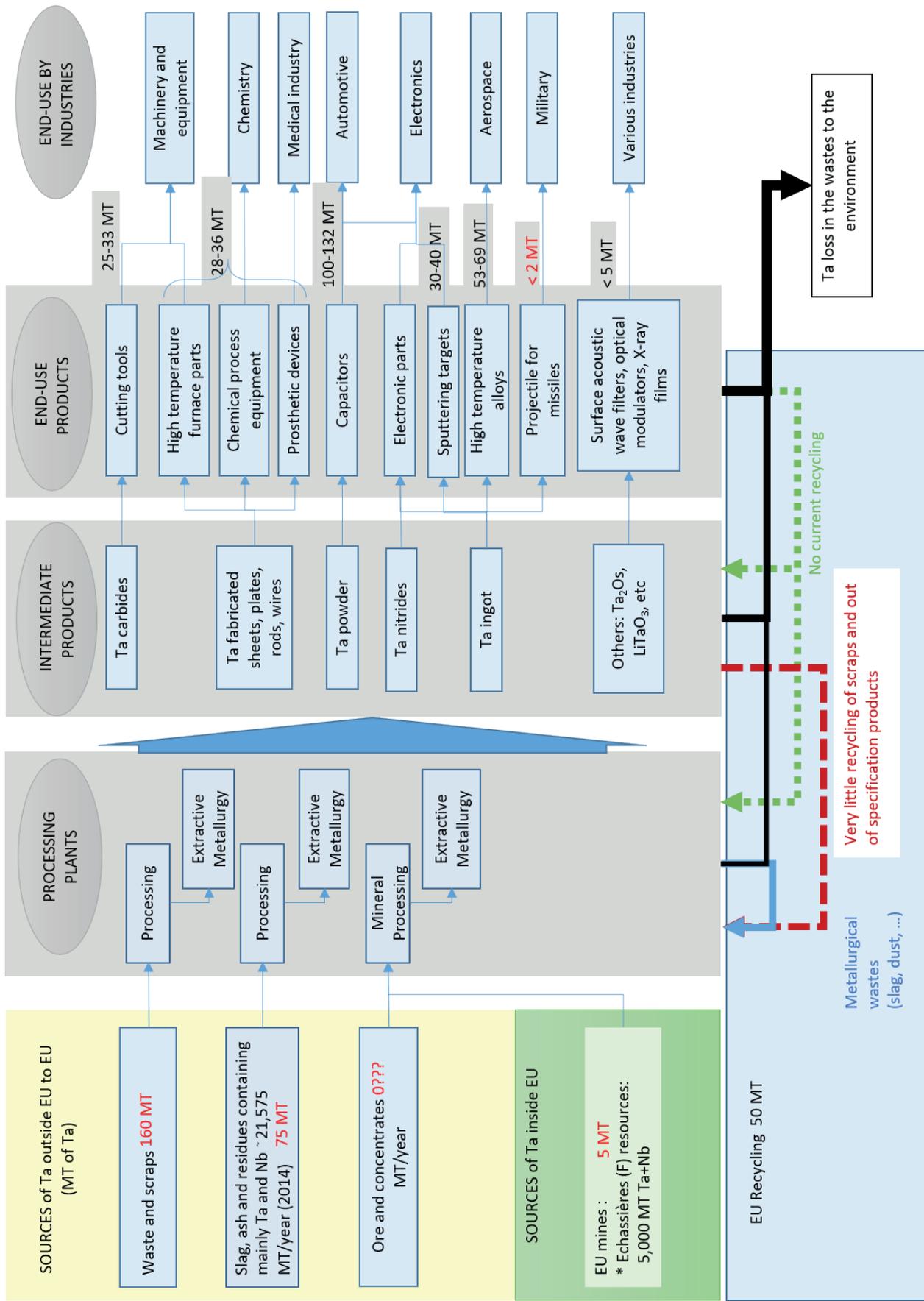


Figure 18. EU Tantalum value chain

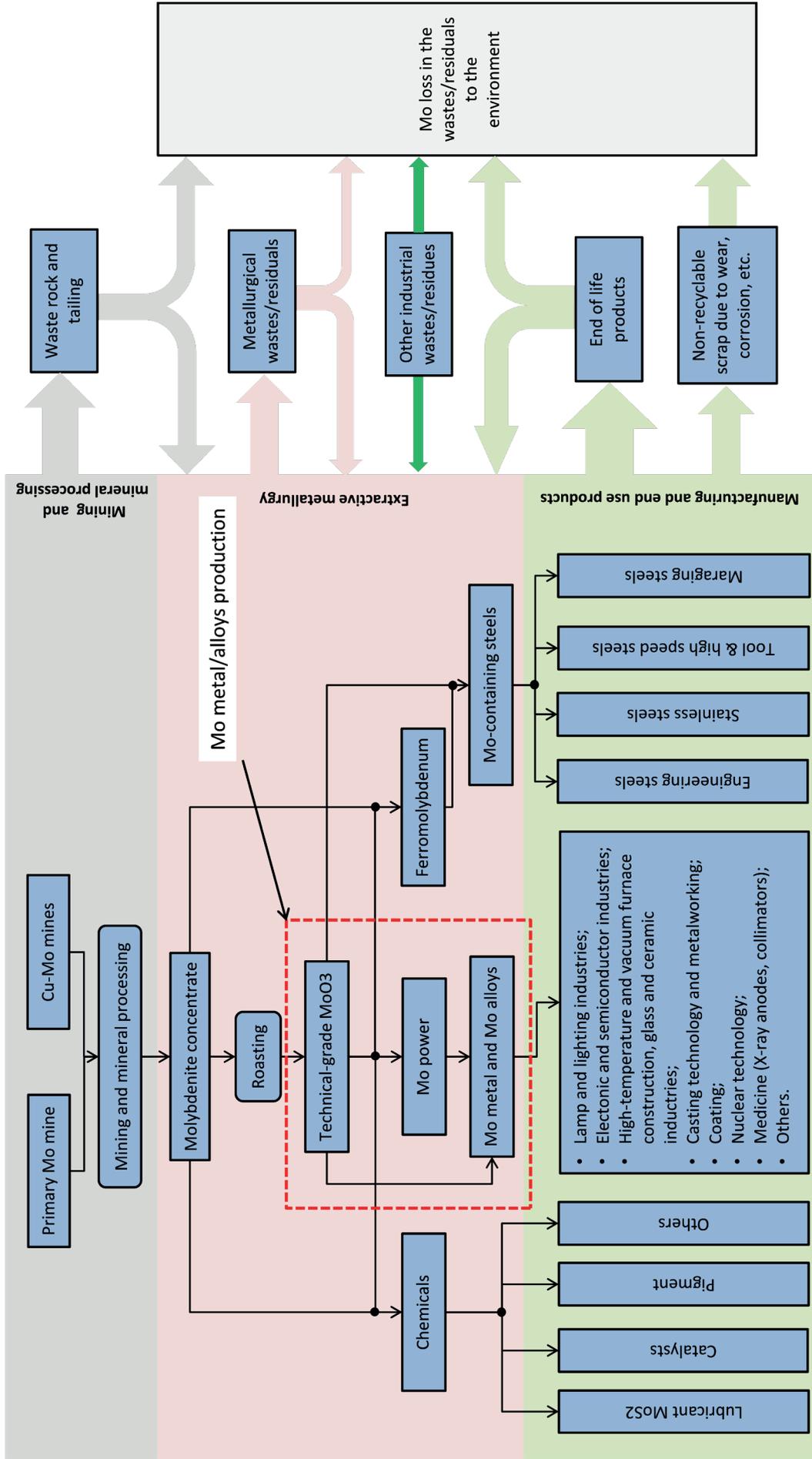


Figure 19. EU Molybdenum value chain

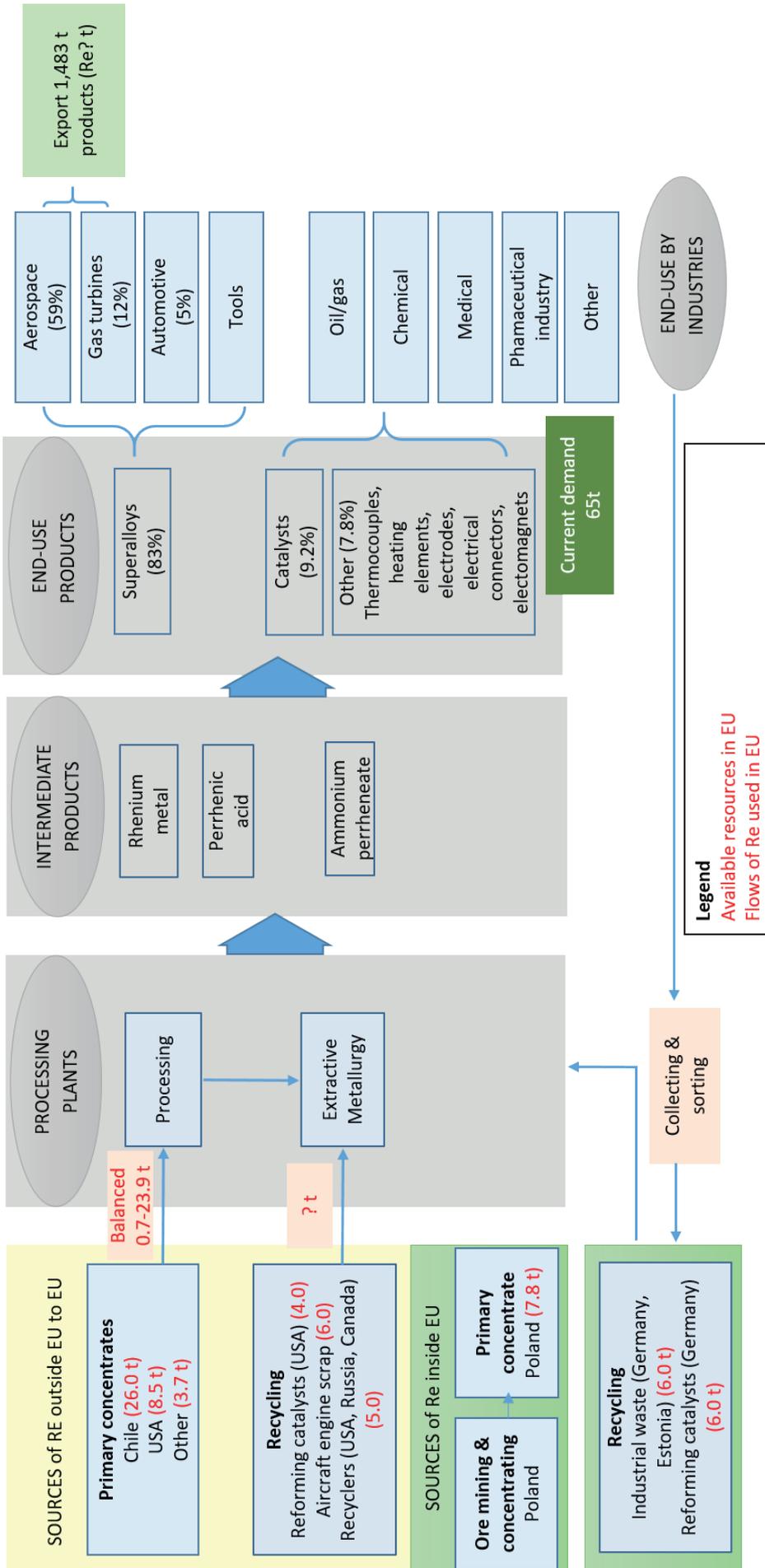


Figure 20. EU Rhenium value chain

## 7 ENVIRONMENTAL AND SOCIAL ASPECTS

As with any other resource extraction activity, refractory metals extraction may raise concerns among the public as to its about environmental and social impacts. These metals are not toxic, so the only two ways in which they may affect the environment are:

- When the ores are extracted from primary sources, the mining activity itself may have an environmental impact on the soil, fauna, vegetation, and may create noise pollution and dust.
- Their treatment and disposal after use may also have environmental impacts.

As stated in the table below, Rhenium and Tantalum are the most environmentally unfriendly of the refractory metals, with higher potential for contributing to global warming, high cumulative energy demand and their propensity to cause terrestrial acidification. On the positive side, their potential for causing freshwater eutrophication and human toxicity are very low, and these metals are considered non-toxic.

Impact category	Ta	Re	W	Nb	Mo
Global warming potential (kg CO <sub>2</sub> eq / kg)	260	450	12.6	12.5	5.7
Cumulative energy demand (MJ eq / kg)	4,360	9,040	133	172	117
Terrestrial acidification (kg SO <sub>2</sub> eq / kg)	1.7	11	0.29	0.053	0.16
Freshwater eutrophication (kg P eq / kg)	1.5E-01	3.5E+01	9.3E-6	3.7E-03	0.54
Human toxicity (CTUh/kg)	1.2E-04	5.9E-02	3.4E-05	6.4E-06	9 E-04

**Table 9. Comparative Environmental Impact of Refractory Metals (Life Cycle Assessment of Metals : A Scientific Synthesis Paper, Nuss P& Eckelman MJ 2014)**

As there is very little production of refractory metals in Europe (only primary production of Tungsten and Rhenium and a small amount of production from secondary sources), the environmental impact related to primary resources extraction is very limited in the EU:

- In the case of Tungsten from primary resources, closure plans and environmental bonds are typically required from the onset of mining to ensure that the mine site is adequately cleaned up and rehabilitated once the ore deposit is exhausted. Apart from the impacts of the mining operation itself (on nearby buildings and, in the case of open pitting, “hole in the ground” issues), the most significant impacts concern waste rock dumps and disposal of tailings (mill rejects). Tungsten deposits typically have a grade of less than 1% WO<sub>3</sub> and together with the swell factor (blasted rock occupies a much larger volume than in-situ material), Tungsten mines produce more waste in terms of volume than the quantity originally mined, and to that quantity must be added the waste rock that has to be removed to access the Tungsten ore. Landscaping of waste piles is a common approach, and there have been examples where the original landscape has been enriched by the legacy of mining activity. However, in many cases, at least part of the waste material needs to be backfilled into the voids created by the mining. In the case of underground mines, backfilling can be done concurrently with extraction, whereas for open-pit mining, adequate funds must be set aside to perform the backfilling operation after the mining is completed. The tailings produced in many Tungsten projects are benign as they do not contain chemical reagents (or only minor quantities of fatty acids) and low levels of heavy metals, resulting in their being classified as “Non-Class A” facilities in accordance with the standards established in the EU Mining Waste Directive.

Still, these tailings facilities are large engineered structures often containing millions of tonnes of fine-grained material and require adequate supervision and long-term stability planning. Many underground mining methods allow or require backfilling of voids, and depending on grain-size distribution and other physical properties, tailings may constitute a significant portion of the backfill material. However, the high slime content found in many tailings must be removed when backfill stability is uncertain, especially in cases where the consolidated backfill is generated by mixing the tailings with a binder such as cement and/or fly-ash. Just as mining operations can have an environmental impact on their surroundings, the natural environment can also pose extraordinary challenges for the mine itself. In remote areas, infrastructure might be totally absent and the mine operator might find it challenging (or very costly) to attract qualified personnel. Contrastingly, in densely populated areas, there might be virtually no place to locate the mine, or it would need to be completely concealed in order to be accepted.

- Concerning Rhenium, as its extraction is usually performed as a by-product in large-scale sulphide polymetallic mines, the main environmental impact of sulphide deposits is related to drainage issues.

All mining activities in Europe must be conducted in accordance with the requirements set forth in the European Directive 85/337/CEE concerning Environmental Impact Assessment. Unlocking the potential of refractory metal production in Europe would create more jobs in the metal mining sector and improve access to metal product markets. In addition, the 2006/21/EC Directive provides several references for measures, procedures and guidance aimed at minimising any adverse environmental effects (on water, soil, air, fauna, flora and landscape) stemming from extractive industry waste management activities. One of the objectives of this directive is for member states to take the necessary measures to ensure that extractive waste is managed without endangering human health and without using processes or methods which could harm the environment and that uncontrolled disposal of extractive waste is avoided.

The reference manual entitled “Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities” is based on ores that have a potentially significant impact on the environment. As for refractory metals, Tungsten is the only one for which information is included in this publication. Tungsten mining and exploitation processes often result in high losses (10 – 40 %) and produce large amounts of waste rock and landfill. While primary production cannot be entirely substituted by recycling due to the fact that demand is growing year by year [29], recycling methods do require less processing energy and hence reduce carbon emissions and eliminate the creation of waste rock, waste water and leachates that occur as a result of mining operations.

The “Best Available Techniques Reference Document for the Non-Ferrous Metals Industries” reference manual is focused on secondary metal sources. Of the metals identified, only information on FeMo is included as far as refractory metals are concerned. This document addresses several important issues concerning environmental performance:

- In the production of FeMo, fluorspar may be used to improve slag and metal separation. Fluorspar is a calcium fluoride ore that is used as a flux and lowers the melting point and the viscosity of the slag, resulting in enhanced slag fluidity. Additionally, when mixed with lime, it reduces the phosphorus and sulphur content of the metal. The use of fluorspar as a fluxing agent results in emissions of fluorides within the range of 150 – 260 mg/Nm<sub>3</sub>. Due to the biotoxic nature of fluoride, the use of fluorspar should be minimised.
- In FeMo production, 1.5-3 tonnes of slag are produced per tonne of alloy. To minimise the environmental impact of slag treatment and disposal, slag can be used as a construction material. Also the dust generated in the process can be recycled into the smelting process or sent to special waste disposal or processed to recover Molybdenum.

In case of treatment and disposal of refractory metal end-of-life products, recycling is the best way to reduce environmental impact and move towards the circular economy approach and zero-waste concept. In the MSP-REFRAM project, two life-cycle analyses have been performed: the first one compares the environmental performance of Ta production from different secondary sources, while the second one compares primary Re extraction with a method (hydrometallurgical process) that is used to recycle Re from super-alloy production and processing wastes. In the first case, the results indicate that, when considering all of the important issues (Global warming, cumulative energy demand, terrestrial acidification, freshwater eutrophication and human toxicity) there is an important gap between the impact of the secondary recovery process and the primary extractive process, with secondary process amounting only to approximately 15 % of the primary process effects.

In the second LCA performed, the environmental performance results of the recycling process compared with the virgin primary process of Re extraction led to the following conclusions:

- Global warming potential was identified in about the half of virgin process, with the most significant stages being leaching, elution and washing after elution.
- Terrestrial acidification was associated with about 15 % of the virgin process, mostly as a result of leaching.
- Almost null freshwater eutrophication, (35 kg P eq/kg).
- Almost null human toxicity, (6E-02).

These results represent a significant opportunity for the EU as there is currently no primary production of Nb, Ta and Mo, and very limited production of W and Re. Therefore, recycling could be identified as a very good solution for strengthening the refractory metals value chain, and even more so in light of the low environmental performance demonstrated.

Although there is currently no primary Tantalum production in Europe, Tantalum is still mined in Africa by traditional methods and its related social aspects must be addressed, as they may alert stakeholders and create insecurity. In fact, in 2016, Tantalum production in the Democratic Republic of Congo, DRC, (Kinshasa) was 450 tons (from Coltan), higher than Brazil's, at 115 tons [61]. The DRC is one of the most politically unstable countries on earth (Gootnick 2008). Coltan in the DRC is "mined" from stream beds by hand, in a process similar to that used by prospectors during the American gold rush. A small team can collect about a kilogram of coltan per day and labourers are paid a maximum of \$50 per week. Moreover, the uncontrolled, unregulated mining erodes the land and pollutes the water, and miners are killing critically-endangered gorilla species and destroying their habitats [62].

The United States, through the enactment of Section 1502 of the Dodd-Frank Wall Street Reform and Consumer Protection Act (Dodd-Frank Act) in 2010, made it a statutory obligation for all companies registered with the U.S. Securities and Exchange Commission (SEC) to perform due diligence to determine whether the products they manufacture, or the components of the products they manufacture, contain Tantalum, tin, Tungsten and (or) gold (3TG minerals), and if so, to determine whether these minerals were sourced from Congo (Kinshasa) and/or bordering countries.

# 8 HEADING TO THE FUTURE

## 8.1 FUTURE USES

In recent years, the need for a more energy-conscious society has led to more intensified activity in the area of efficient production and consumption of energy and will become increasingly important in the future. Currently, worldwide energy use is growing much faster than supply can match. The efficiency of conventional technologies must be improved in order to reduce losses in transmission and distribution of energy, and new strategies and technologies must be developed for “doing more, using less”.

Current discussions on global warming and the conclusion that anthropogenic greenhouse gases are mainly responsible for the observed rise in average temperatures since the middle of the twentieth century have brought calls for reductions in emissions, which will require a more conscientious handling of fossil energy worldwide. The search for alternatives will be intensified, as coal, oil and natural gas reserves are depleted and the need to use existing natural and renewable resources steadily rises.

This global phenomenon represents another great opportunity for Tungsten-based materials and components, which have been used extensively in the past in functional materials and advanced tools with outstanding properties. Tungsten-containing products are strategically important in the field of fossil energy production, fossil energy and renewable power generation, power transmission and power distribution because of their outstanding properties [61].

In the case of Rhenium, the new developments are in compounds, materials and composites for applications in developing economic sectors such as the weapons industry, aviation, the pharmaceutical industry and medicine, the chemical industry (for catalytic processes), the drilling industry and the mining industry. Innovative Rhenium products include: electrochemical Rhenium-Nickel and Rhenium-Cobalt alloys and coatings with W and/or Mo, Rhenium and non-ferrous metal powders, Rhenium carbonyl and its derivatives, homogeneous and heterogeneous Rhenium catalysts and inorganic Rhenium compounds with application properties that can be exploited in many different types of industries [62].

## 8.2 SUPPLY AND DEMAND ESTIMATIONS

### TUNGSTEN

Worldwide Tungsten mine production in 2017 was predicted in the Merchant report [63]. China is predicted to continue dominating the world Tungsten market both in terms of production and exports. Global Tungsten production is expected to have an average annual growth of 3.8% over the next few years and reach 100,100 tons by 2017.

EU Tungsten mine production in 2013, 2014 and 2015 were 2051, 2341 and 2830 tons, respectively. According to this forecast for the EU, Tungsten mine production would reach 3049 tonnes in 2017. Total Tungsten production, if production from the end-of-life scraps recycling is to be included, would reach over 8000 tons.

According to this analysis, Tungsten demand in Europe over the next 10 years would remain stable at approximately 10000 tons/year, which means that the Tungsten produced in Europe could meet 80% of the demand. In 2015, Wolf Minerals opened its Hemerdon Tungsten mine in the UK and produced 600 tonnes of Tungsten. According to Investing News, mine production in the UK is estimated to be 5000 tons of Tungsten concentrate annually in the future. In Spain, the company W Resources conducted a mine development study at the La Parrilla mine which projects a 150% increase in production there. The mine will be fully developed by 2017 or 2018, and production is expected to increase to 5,000 tons of Tungsten concentrate annually, which represents a production increase of 1000 tons of Tungsten from mining over a three-year period, bringing total Tungsten production to over 9000 tons, thus getting ever closer to overall target of 10,000 tons.

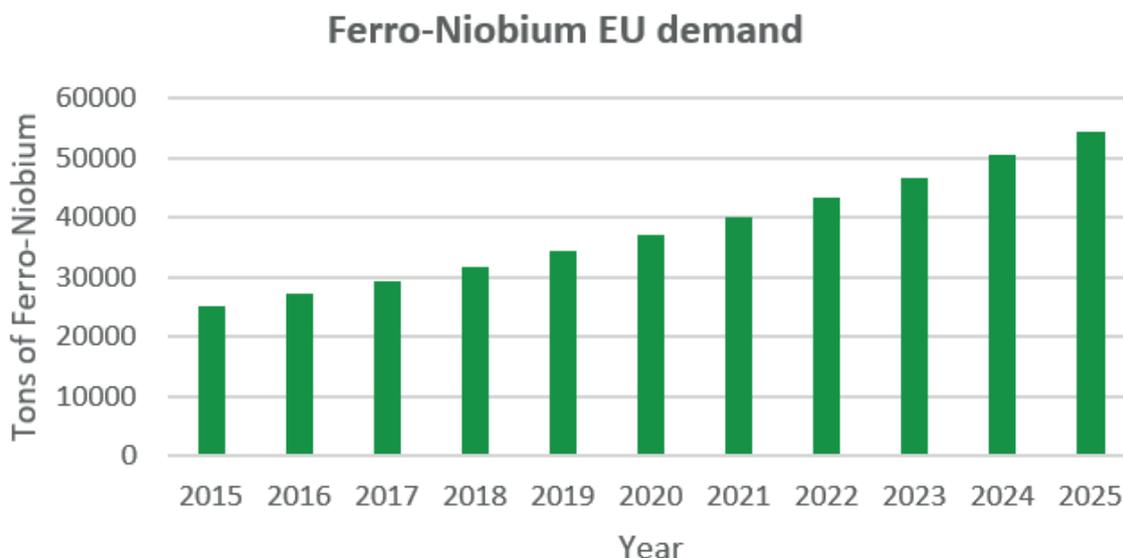
Tungsten carbide is the most important application of Tungsten produced on a large scale in Europe, which in 2005 accounted for half of worldwide global Tungsten carbide production. There are over 19 suppliers of Tungsten in Europe, producing concentrates, hard metal/cemented carbide, oxides and acid, tungstates and other Tungsten chemicals, Ferro-Tungsten, scrap/recycling, Tungsten/Tungsten carbide powder and sintered Tungsten products.

In the longer term, the Tungsten industry looks especially bright for Europe, especially as its own substantial Tungsten mineral endowment will finally be explored and brought into production. Given the geology of Europe, there is every chance that Europe should be wholly self-sustaining with respect to internal primary (mine) Tungsten supplies by 2040–2050, assuming Governments are supportive of mine development. This should then permit expansion of downstream manufacturing facilities in Europe providing a secure Tungsten resource base well into the future and underpinning a key element of Europe’s high technology manufacturing base.

## NIOBIUM

World production of Niobium is rising rapidly. Apart from Ferro-Niobium, the increasing demand can be attributed to its use in heat-resistant alloys, functional and construction ceramics and mobile phones [64].

Ferro-Niobium is by far the largest market for Niobium, as previously stated. A sharp growth in demand (over 8% annually) for Ferro-Niobium is expected between now and 2020. There are two main factors driving this strong growth rate. Firstly, there is the general high global demand for steel in construction, infrastructure and automotive applications. Secondly, there is also a trend towards greater use of HSLA steels. Increasing demand for natural gas is expected to result in increased demand for pipeline steel. The combined effect of the two trends means that the growth in worldwide demand for Ferro-Niobium is likely to exceed the overall trend for steel due to a projected increase in Niobium use [65]. Therefore, it is clear that given the current economic situation, demand for Ferro-Niobium in the EU will remain high. The projected 8% annual increase rate makes it possible to estimate the Ferro-Niobium demand for 2025, based on 2015 EU import figures:



**Figure 21. Ferro-Niobium EU demand**

Brazil has planned an increase in production for 2017, mainly due to the increasing demand from emerging countries.

Estimations indicate that worldwide Niobium reserves and resources are abundant and more than sufficient to meet global demand for the foreseeable future, possibly for the next 500 years [66], and it appears for the moment that Brazil will continue to be the world leader in Niobium production, even though deposits have been identified in other parts of the world [67].

Taking all of the above into account, Niobium demand is expected to continue to rise in the European Union over the next few years for several reasons: its unique characteristics and growth in terms of its main applications (rising consumption of HSLA); an improved economy and consequent increase in investment in infrastructure, rapid growth of the world's population and the resulting rise in demand for new products. Moreover, the lack of substitutes and the current ease with which Niobium is imported from Brazil and Canada (whose reserves for the future are well established) ensure that Niobium will continue to be a highly traded commodity.

## TANTALUM

With many uncertainties concerning current Tantalum needs for EU industries, it is much more difficult to assess future needs. It is projected that demand for Tantalum in 2035 will be 4 times that of 2013 production, driven by the need for it in the manufacture of micro-capacitors and in medical technology. For micro-capacitors, the world demand was 128 tons in 2013 and has been estimated to be between 360 and 1,070 tons in 2035, with annual growths of 4% and 7%, respectively, and other assumptions concerning prices and efficiency.

The core use of Tantalum in capacitors has several possible substitutes (aluminium, ceramic capacitors) that are likely to be able to satisfy most common needs, but with a loss in performance. Only niche capacitor applications with heavy size and robustness/tolerance requirements may be more difficult to replace, but with lower demand volumes and possibly higher values.

## MOLYBDENUM

The analysis of the world mine production of Molybdenum for the years 2014 and 2015 has shown a decrease of 5%. This reduction is mainly related to the significant fall in demand due to low oil prices and consequent impact on exploration and production activities in which Molybdenum-bearing steels are widely used [68]. Despite this reduction, the International Molybdenum Association (IMOA) estimates that the end-user demand for Molybdenum could increase by an average of 3.6% annually between now and 2024 [69] due to a number of sectors expected to generate future demand for Mo through use in applications influenced by global trends. The «Molybdenum Market Outlook» report has estimated that growth rates of worldwide Mo demand in 2020 will be similar to those of copper, iron ore and other mineral raw materials pumped by the industrialization process taking place in emerging economies, led by China, India and Brazil, and it will increase by 4.6% (total demand: 355,000 tonnes) [70] Additionally, this report estimates the world mine production in the same year to be 254,000 tonnes, meaning an insufficiency of 100,000 tonnes, which will lead to the development of new mining industry projects. According to The Roskill Report, demand for Mo in Europe is expected to increase by some 105 kt per year between now and 2025, and the current capacity is insufficient to meet this growth in demand [71].

The applications that will increase Mo demand are:

- The steel industry: In 2015, demand from the steel industry represented 70% of global Molybdenum demand, and is expected to increase to 73% by 2025;
- Automotive light weighting using Molybdenum for high strength steels;
- Hydrodesulphurization of fuels, using Molybdenum-based catalysts. This technology has already achieved a 100-fold reduction in sulphur dioxide emissions in the European vehicle sector since 1993. This will play an important role in the future as emissions standards are tightened across the world;
- Industries that manufacture catalysts, lubricants and pigments are also expected to increase Molybdenum use by 2025, though at a lower growth-rate;
- Uses in power generation: boosting the efficiency of coal-fired power stations and solar, wind and hydroelectric power stations as well. Molybdenum provides resistance to corrosion, strength and performance at high temperatures as an alloy. Non-fossil energy generation has grown considerably in recent years and is predicted to more than double between now and 2020.

The fall in the price of Molybdenum led a number of primary Molybdenum producers to halt production in 2015. Longer term price prospects for Molybdenum appear uncertain, though prices are expected to remain stable throughout the first half of 2016. Despite the low prices, the development of Molybdenum deposits continues, with projects in the USA, Kazakhstan, Peru and a number of other countries scheduled to go into production before 2025. Supply from these new producers is forecast to represent 22% of global production by 2025, which is necessary if the growing demand for Molybdenum products from consumers is to be met [71].

## RHENIUM

Rhenium consumption is dominated by nickel-based super-alloys that are used in gas turbines, aero engines and, to a lesser extent, in industrial gas turbines (IGT). Roskill, in their market forecast (2015), states that demand for Rhenium will experience a period of strong growth between 2015 and 2018 followed by a period of stability through 2020. Growth in demand for the forecast period will average 6% per year and reach about 85 mt/year. Super-alloy turbine parts for aero engines and industrial gas turbines will remain by far the largest end market for Rhenium, accounting for over 80% of total Rhenium consumption.

Airbus estimates a demand for 6508 new aircraft in Europe for the period 2016-2035, which means a 20% share of world demand for new aircraft. On the other hand, Boeing estimates that 7450 new airplanes will be needed in Europe between 2014-2033. Considering an average demand of 50 kg of Rhenium per aircraft, the demand for Rhenium could be as high as 1450 tons in 2033. In addition, DERA (2016) predicts a new demand for Rhenium in the emerging technologies sector, which will require 120 t of super-alloys per year by 2035, which means a 250% increase over 2013 Rhenium production figures (46 tons).

## 8.3 RESEARCH TRENDS

### TUNGSTEN

Future challenges lie in decreasing Tungsten losses in conventional precipitation, purification, reducing chemical consumption and improving the efficiency of conventional ion exchange and solvent extraction methods. As for pyrometallurgy methods, Tungsten recovery of over 95% has been attained by directly alloying steel with Tungsten using Tungsten ore: Tungsten ore and carbonaceous material are charged into the melting furnace and the steel is directly alloyed with the Tungsten. This is a one-step process which is economical and energy efficient [72].

European Projects currently aimed at addressing these issues are:

- **OPTIMORE:** Optimization of crushing, milling and separation in ore- processing technologies used in Tungsten and Tantalum mineral processing, by means of improved, faster and more flexible fine-tuning production process control based on new software models, advanced sensing and a more thorough examination of the physical process, which will result in a 7-12% yield increase and a 5% energy savings increase on the best production processes and best techniques available today.
- **BASHYCAT LIFE PROJECT:** The aim of the Bashycat project is to propose the regeneration of used NiMo and NiW catalysts in order to achieve the most comprehensive recycling possible of the chemical elements they are composed of.

### NIOBIUM AND TANTALUM

Research in hydrometallurgical technology for processing Niobium and Tantalum concentrates is aimed at making the following improvements: (1) the application of more robust extractants with higher stability and lower water solubility; (2) less HF or no HF used for the digestion of concentrates and metal separation with SX; (3) recycling reagents as much as possible to reduced liquid and solid wastes.

As for tin slags, carbochlorination at 500°C has allowed complete extraction and recovery of Niobium and Tantalum [73]. Alloy scrap is seen as being a promising approach. In the case of electronic waste, oxidation in the air of the scraps followed by mechanical collection of the sintered Ta electrodes in the scraps in combination with chemical treatment allows high-purity Ta<sub>2</sub>O<sub>5</sub> recovery.

Projects conducted in Europe in this area are:

- OPTIMORE, previously described
- E4-CritMat: Engineering of Energy Efficient Extraction of Critical Materials – Application to the Processing of Niobium and Tantalum Minerals

## MOLYBDENUM

Research in Molybdenum extraction from primary resources has been developed mainly using flotation processes and flotation reagent development. Hydrometallurgy processes such as alkaline pressure leaching, oxidant additives leaching and bioleaching are also being studied.

In the area of secondary resources, of particular note is a research project that has resulted in a high level of Mo recovery from molybdenite extracted from ultrafine waste tailings using oil agglomerate flotation (OAF). Neutral oils like kerosene, diesel, transformer and rapeseed oil were used as collectors or bridging reagents in OAF. From steel making dusts, water leaching has been applied to obtain an alkaline solution containing about 2 g Mo/L, followed by solvent extraction to obtain a pure Mo solution [74].

For recycling Mo-containing mill scale, microwave heating is a potentially effective process, as the reaction rate is very high and there is no need to pelletize the mill scale.

Related EU projects are:

- BASHYCAT LIFE PROJECT, described above.

## RHENIUM

Research activities in Rhenium extraction are and will continue to be focused on:

- The development of the synthesis of new extractants for Rhenium that are more selective, durable, ecological and less expensive. [4].
- New and more efficient methods for Rhenium recovery based on solvent extraction and ion exchange that require profound examination of the newest available ion-exchange resins and organic extractants in order to optimize the Rhenium recovery process. Both methods generate lots of waste solutions. The membrane techniques have high industrial potential for reducing the amount of waste solution and providing a more energy-efficient process [4].
- Recovery of Rhenium from dust [5], mainly by hydrometallurgical methods that employ acid, base and sodium salts as leaching agents. An interesting alternative is to use the pressure method for recovery of Rhenium from dusts. This technique significantly improves Rhenium recovery efficiency while minimizing leaching time and decreasing the leaching temperature [6].

Recent studies have been conducted in the following areas: (1) Rhenium extraction as a by-product of Copper/Molybdenum production; (2) Rhenium extraction from spent catalysts; and (3) Rhenium from scrap, or spent catalysts.

Among EU Projects conducted in this area is:

- SPIN-PROJECT: Technology that makes it possible to obtain ammonium perrhenate (VII) from solutions with very low Rhenium concentrations.

## 8.4 REDESIGNING THE VALUE CHAINS

### TUNGSTEN

When it comes to metals and materials that have a wide range of benefits and uses, it is hard to argue with the effectiveness of Tungsten carbide. There is a great number of benefits that come from using this reliable and very tough material and the number of different industries that rely on Tungsten carbide indicates just how important it is. From its superior cutting skills, making it highly valuable in the mining and milling industries, to the reliable yet stylish nature which makes tungsten carbide a natural choice for so many jewellers, there is no doubt that Tungsten carbide is hugely important.

Like all metals, there is significant commercial potential and demand for scrap Tungsten carbide. The recycling of scrap metal is important for many reasons and whether you are trying to protect the environment or simply aiming to maximise cost effectiveness, there are strong arguments for taking the recycling of Tungsten carbide very seriously.

One of the reasons why it is important to recycle Tungsten carbide is that it has been listed as a metal that is of great importance to the EU and Europe's economy in general. It is believed that there are very few materials that can provide the quality and reliability of Tungsten carbide, which makes it very difficult to find a worthy substitute. There is also a lot of doubt as to how much Tungsten carbide supplies there are left in the world, which means that there is an increasing need to ensure that tungsten carbide scraps and residues are recycled on a regular basis.

There are several reasons for recycling Tungsten scrap. Firstly, most scrap materials are richer in Tungsten than ore concentrations, making Tungsten scrap a worthy material for recycling. Secondly, the demand for tungsten products is increasing; consequently, the demand for tungsten resources is rising. Companies can lower their raw material costs and make greater profits by recycling Tungsten scrap, and lastly, recycling Tungsten scrap has many environmental benefits, such as reducing land-fill waste, saving valuable and finite virgin raw materials and energy, as well as reducing pollution.

Methods for recycling Tungsten can be broadly divided into two types: direct methods and indirect methods. Direct methods mean that Tungsten scrap is transformed into powder of the same composition by either chemical or physical treatment, or a combination of both. A typical example of the direct methods is the zinc treatment method (*Clean cemented carbide inserts and compacts are converted to powder through the zinc process, i.e. molten zinc forms an alloy with the contained cobalt, which disrupts the integrity of the cemented carbide. The zinc is then removed by distillation, leaving a spongy material which is easily crushed. This material is added to new, ready-to-press tungsten powder. This process not only allows tungsten carbide to be recycled but the carbides of cobalt, tantalum and other metals as well*). This method has many advantages, such as limited energy consumption and chemical waste, as well as low production costs. The disadvantages of this method are the restrictions on the recycled materials. Indirect methods, such as the wet chemical treatment method, are generally used in the ore-refining process. This way of recycling has no restrictions on materials, but large quantities of chemicals and energy are needed.

The estimated increases in primary mine supply are predicted to be outpaced by the use of secondary recycled Tungsten raw materials between now and 2018. Tungsten recycling is expected to continue to rise at a rate of about 8% per year over the next five years, which will increase global production of recycled Tungsten materials from 23% of total supply in 2012 to 28% of global supply in 2018. The main regions for growth in Tungsten recycling are most likely to be Europe and Asia as collection programs for Tungsten products are improved and construction of new Tungsten recycling facilities is undertaken.

### NIوبيUM AND TANTALUM

Globally, it has been estimated that 10-20% of the global Tantalum supply is produced from tin slags and 20-30% from different types of manufacturing and end-of-life scrap. According to the Tantalum-Niobium International Study Center (TIC), production from secondary resources grew considerably between 2008 and 2012. The best quality slags have been identified in Brazil, Thailand and Malaysia, which are the biggest producers of slag-based Ta. Due to the downturn in tin mining, the best sources are old slag dumps.

The potential for old tin slags and other waste materials has also been studied in Europe. Based on information available, potential tailings and slags can be found not only in the “Tin-belt” countries of Spain, Portugal, France, and the UK, but also in Germany and the Czech Republic. Tantalum can also be found in waste from uranium mining, which usually contains radioactive thorium. Very little public data is available as to the characteristics and Ta potential in mine waste areas in Europe.

In addition to mine waste areas, Ta can also be found in municipal waste landfills, industrial landfills (such as WEEE recycling company landfills) and from incineration slags. It has been estimated that about 5% of WEEE ends up in municipal landfills or incineration plants. Because Ta containing components are mainly used in high-tech electronics, in portable electronics, for example, it is likely that the Ta concentrations in MSW landfills and slags are very low.

Other potential sources are scrap from manufacturing of Ta powders and ingots as well as manufacturing of Ta-containing products as well as end-of-life scrap containing Ta. The most important applications of Ta are capacitors and other electronic components, different Ta-containing alloys and hard metal, where a small percentage of Ta can be used in addition to W. Although, for example, the largest capacitor manufacturers are found in the USA and Asia. According to Eurostat Prodcom statistics, there is still considerable manufacture of Ta-containing products in Europe, which means that both manufacturing and end-of-life are available in Europe.

The highest potential for Niobium recovery in Europe is thought to be in Greek and Macedonian sites. The potential for the Buchim Mine (Macedonia) is evident in its active plant, where many different minerals are extracted, including Chalcocite, Chalcopyrite, Covellite, Cuprite, Galena, Hematite, Goethite (limonite), Magnetite, Pyrite, Sphalerite, Tenorite and Native metal. This high potential (up to 313,27 t) is linked to mine waste dump (surface storage) [75]. Greek potential is much lower but nonetheless has an average national total of 65,44 tons of Nb that may eventually be recovered. This tonnage is distributed among seven different locations in northern Greece. These wastes are associated with former smelter or refinery plants with smelting slag waste containing Nb.

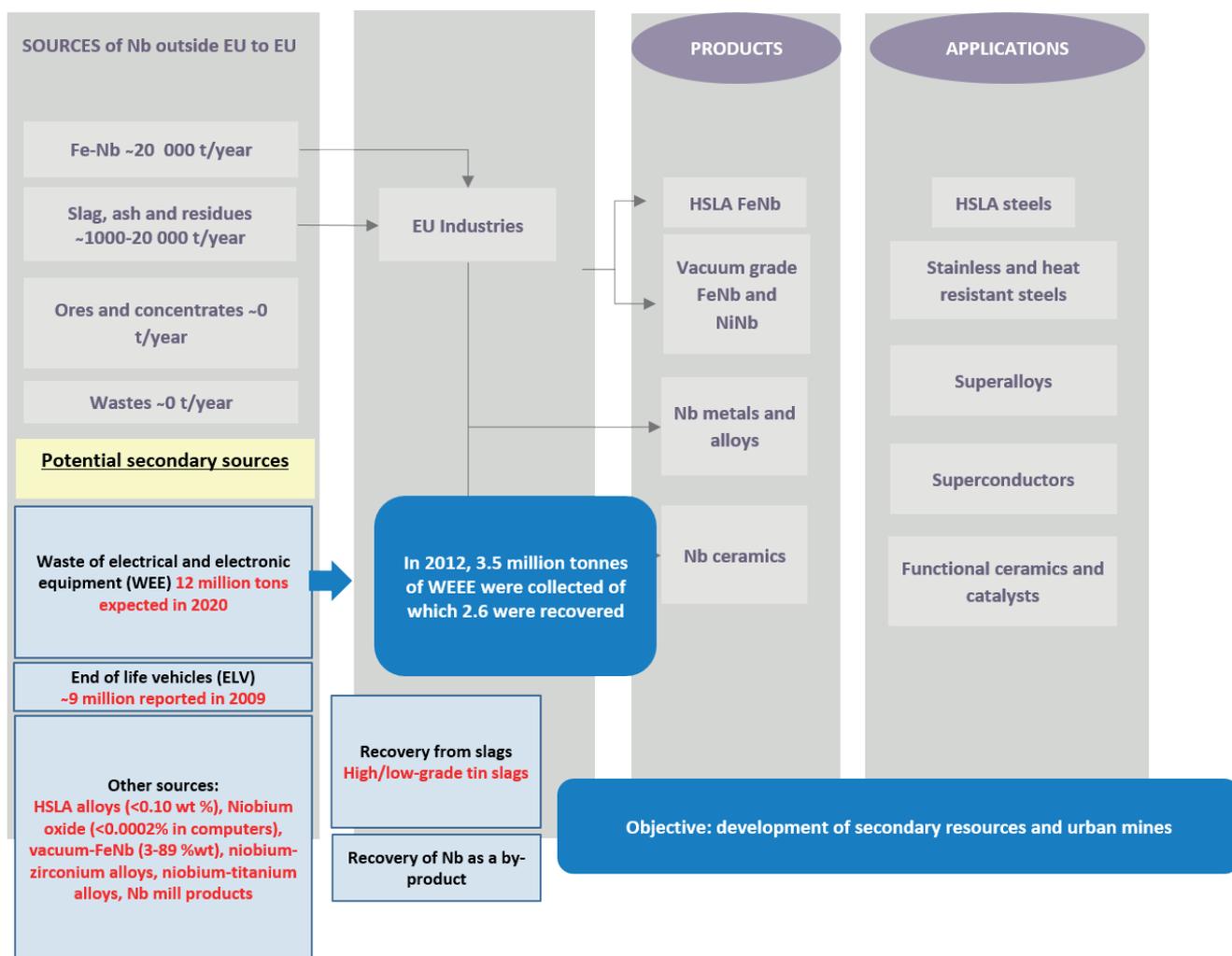


Figure 22. Future value chain of Niobium

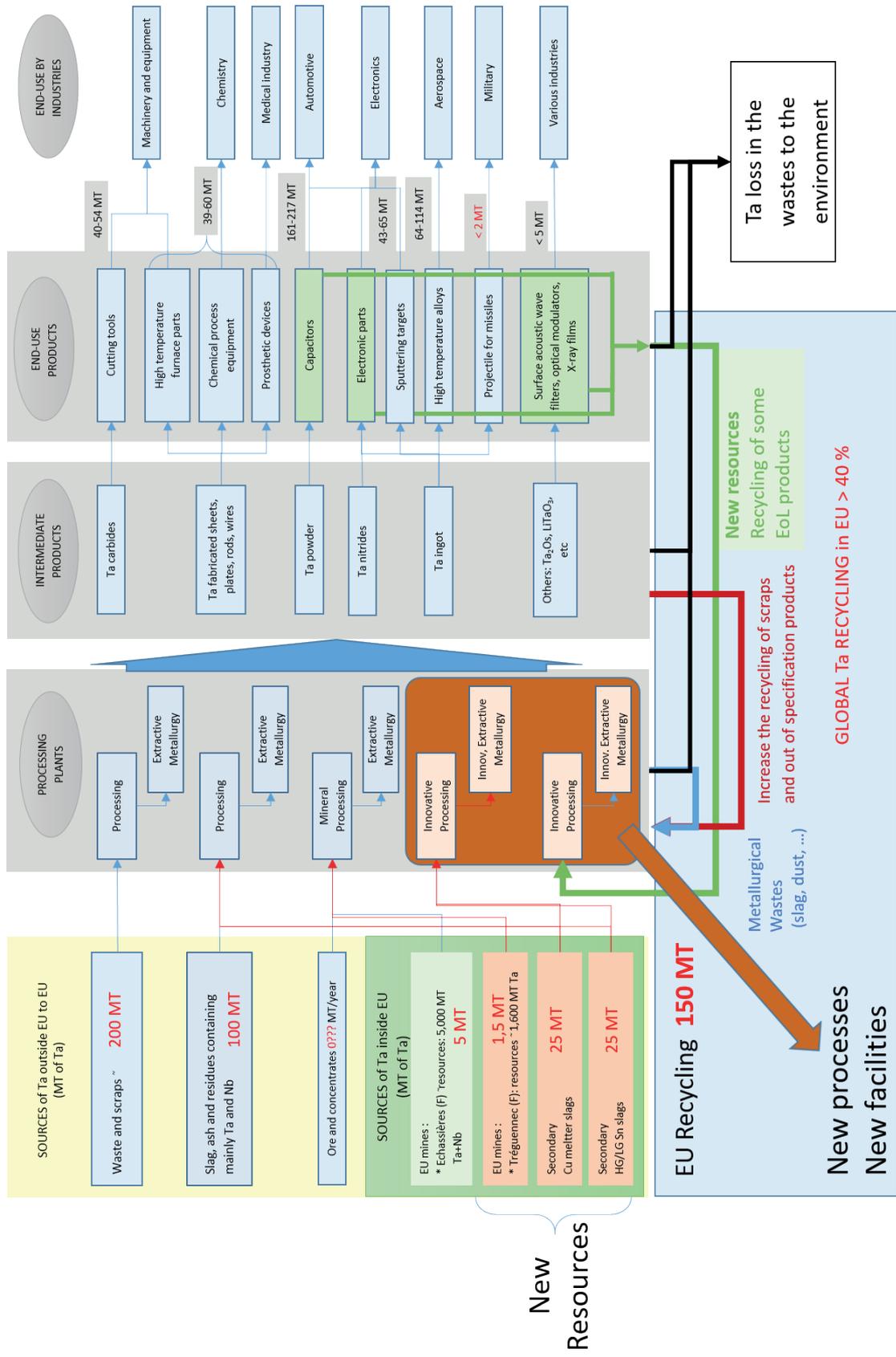


Figure 23. Future value chain of Tantalum based on 500 Mt/y

## MOLYBDENUM

The critical transition steps in the re-design of the current Molybdenum value chain include the following aspects:

1. Zero hazardous emission: development of a more environmentally friendly process to replace the present oxidative roasting process. This may change the present Mo industrial panorama in the EU and increase its competitiveness.
2. More recovery: establishing a more efficient sorting and collection infrastructure for EOL products. This will reduce the dependence of the EU on Mo supply from non-EU countries.
3. Higher integration of the processes. This will increase the competitiveness of the Mo industry in the EU.
4. No wastes: Increasing the added value of wastes generated by using them as by-products. This will increase the competitiveness and sustainability of the Mo industry in the EU.

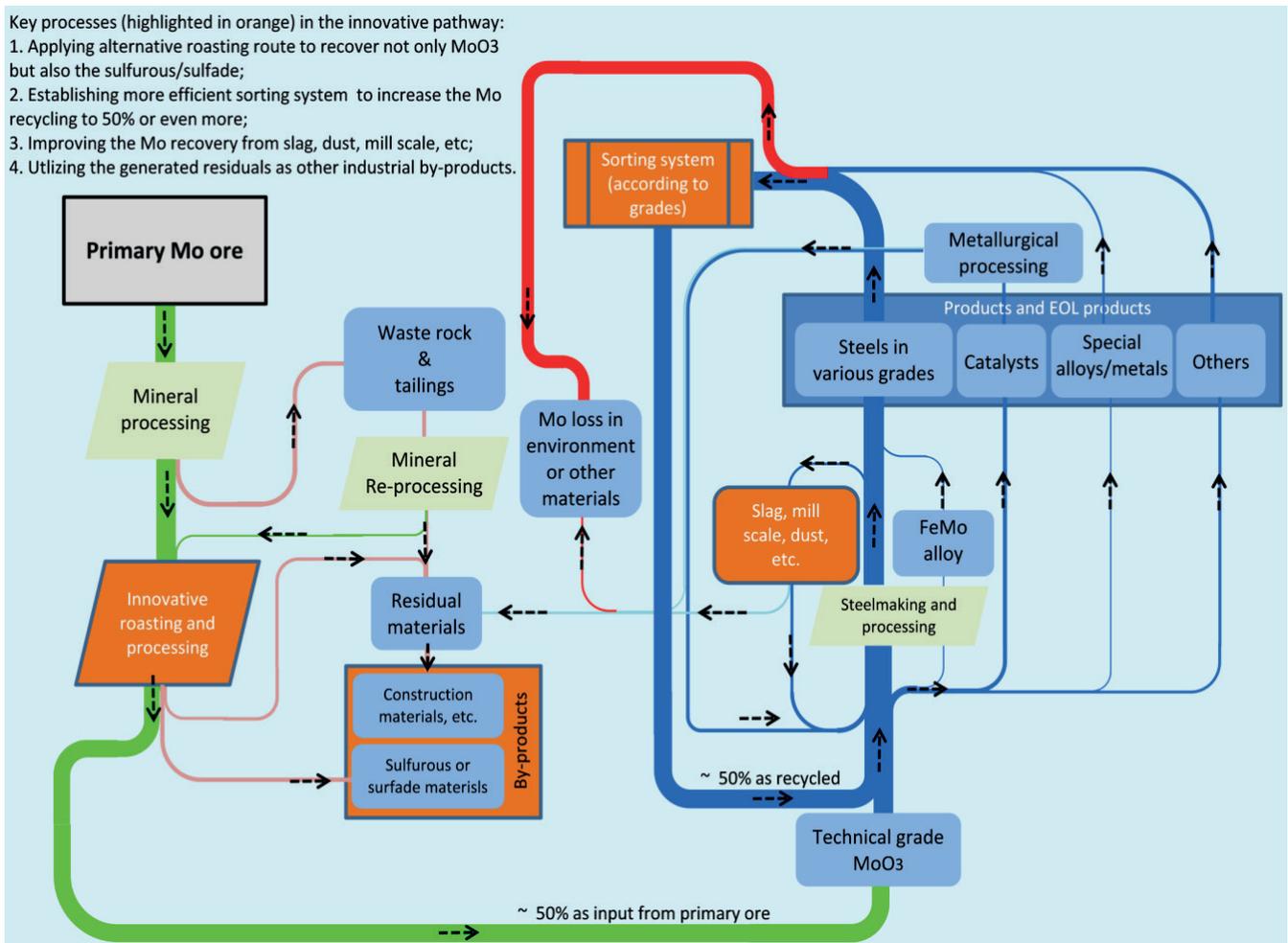


Figure 24. Future Mo value chain

## RHENIUM

Promoting primary Re production by increasing the recovery of Re in mining, enrichment, smelting and refining, while reprocessing Re-containing secondary wastes (tailings, residues) could be significant innovation paths.

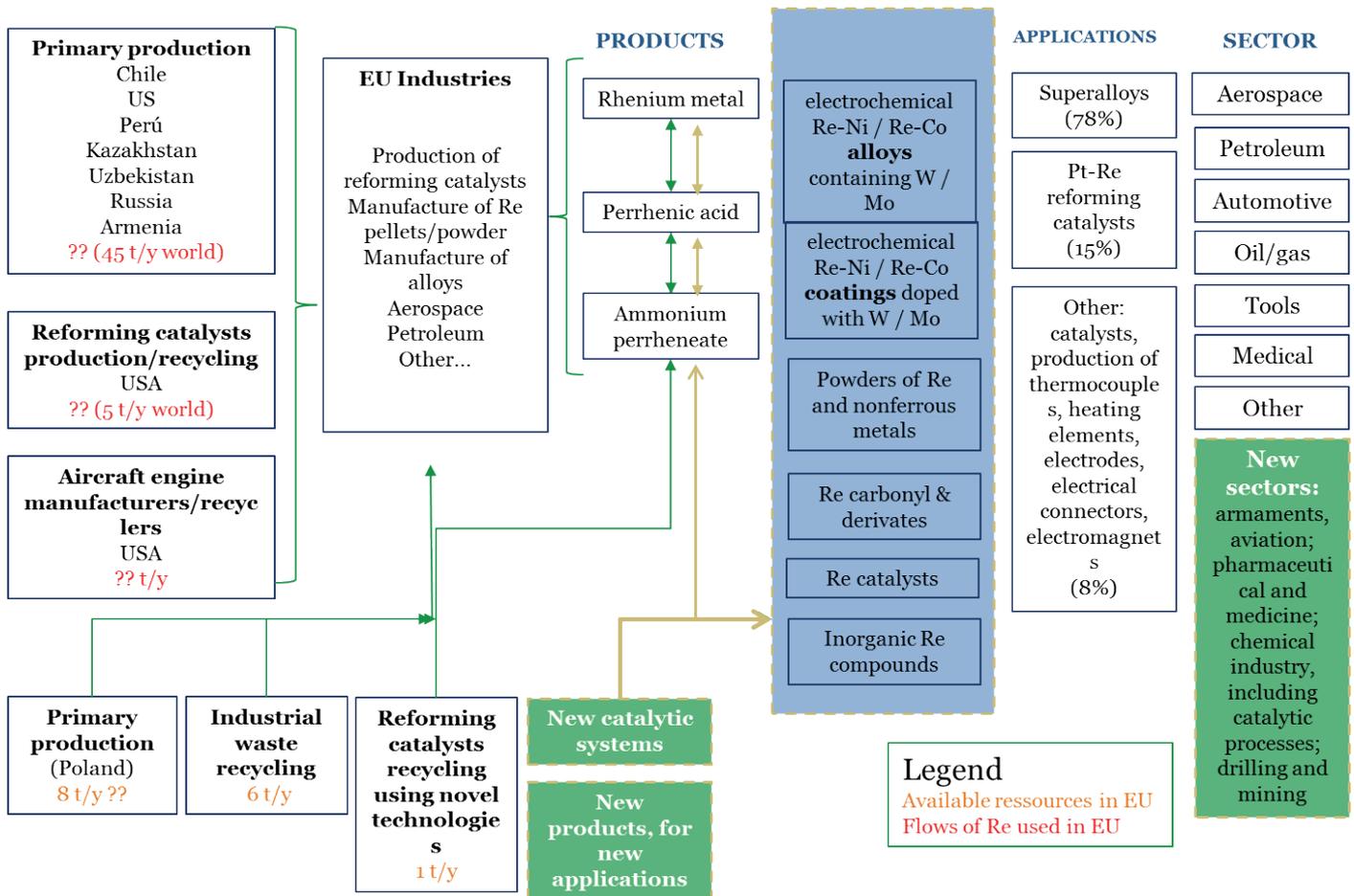


Figure 25. Rhenium future value chain

Rhenium has a great innovative potential due to its application in numerous new products and materials. Hence, it is important to address technological issues that are important and innovative in the global Rhenium market, including increasing the amount of rhenium-containing wastes stemming from the processing of large-volume materials, e.g. dross formed during super-alloy smelting, scraped super-alloy products and other wastes formed during super-alloy product manufacturing. Currently, Rhenium is not recovered from such components. Moreover, there are not many companies in the world which are dealing with recycling of this metal. Nowadays, Rhenium is recovered mainly from wastes formed during the processing of super-alloys of diameter  $\leq 30$  mm. Development of Rhenium recovery method for materials with diameters  $> 30$  mm which are not currently processed will make it possible to increase global ammonium perrhenate production, which represents a breakthrough process that will result in the opening up of the small, hermetic and impenetrable Rhenium market [76] [77] [78].

# 9 CONCLUSIONS AND POLICY RECOMMENDATIONS

The outstanding properties of refractory metals, an improving EU economy, the leading role of the EU in steel production and in the entire range of steel applications, the growth of the aeronautical and electronics sectors and the use of refractory metals in these industries, among other factors, will ensure that the demand for refractory metals in the EU remains high. Several challenges and problematic issues have been identified in refractory metals panorama and they must be addressed in the coming years if Europe is to strengthen its position in the worldwide refractory metals value chain.

China's actions and its export restrictions on Tungsten which are aimed at preventing accelerated depletion of the resource in China must be closely monitored as it is the world's main producer of Tungsten and Molybdenum. In parallel, political development in countries like Rwanda, which is also a major supplier of Tantalum, must be analysed as conflicts in that area of Africa might affect metals production. Ethical issues must also be monitored as, in most cases, working conditions in the region are lacking in terms of respect for human rights.

As for secondary sources, it has been reiterated throughout this report that scrap is imported into the UK and Germany and then is subsequently used in recycling efforts throughout Europe, which underscores the need for better collection systems for secondary sources. By implementing the right incentive policies and strategies, Europe could avoid having to import secondary sources and boost self-sufficiency. Another challenge is the lack of proper systems for the identification of the metals contained in EoL products, which makes a well-targeted and tailored sorting and processing industrial process difficult.

Regarding substitution, the main challenge is to find substitutes that are not another refractory metal as this creates a loop that might provide a temporary solution for a certain refractory metal shortage but will not be sustainable in the long term if supply risk is extended to all refractory metals.

Lastly, the wide array of data available on refractory metals is often conflicting. Some discrepancies have been found for example concerning Niobium information from Comtrade and EUROSTAT. Rhenium data are also hard to analyse as products and wastes are often reported together and at times even with other refractory metals such as Niobium. Hence, more transparency is needed in order to be able to accurately assess the current status of European markets.

## 9.1 POLICY RECOMMENDATIONS AND ACTIONS NEEDED

Different pathways have been identified in MSP-REFRAM to improve performance in the EU refractory metals supply and to address the challenges outlined above. The pathways concern technical performance and policy recommendations. In general, increased investment in new extracting technologies and subventions for recycling will be needed as well as more transparency in actions undertaken in Europe, such as recycling rates. More research on metal extraction from secondary resources and recycling methods is needed as well as further studies and pilot-plant demonstrations for promising technologies developed on the lab scale.

### TUNGSTEN

- Recycling Tungsten Carbide is essential as most scrap materials are richer in Tungsten than ore concentrations. Demand for Tungsten products is increasing, and companies can lower their raw material costs and make greater profits by recycling Tungsten scrap. Also of importance, although not so related to dependence issues, are the environmental benefits to be gained from recycling. Recycling of Tungsten carbide may be performed by direct methods rather than by indirect methods, i.e. transforming Tungsten scrap into powder of the same composition through chemical or physical treatment, or a combination of both. Recycling can be very effective provided there are good collection programs of products and new Tungsten recycling facilities, which underscores the need for investment in new recycling technologies.
- Investing in the development of new mines.

- A thorough knowledge of the EU panorama and value chain, which could be gained through a study of the arrangements and agreements between the different companies, is indispensable. It has been observed that Asian funds sometimes take large shareholdings in mining companies whose resources are essentially outside of China. One example is the Drakeland project, which hosts the RCF Capital fund. When participation is not capital-intensive, raw materials are purchased through off-take contracts, as is the case with the Barruecopardo project in Spain, where Noble group, which is Singaporean, buys production in advance.

## NIOBIUM

- In 2020, 12 million tons of electrical and electronic equipment waste is expected and there are expected to be 9 million end-of-life vehicles in 2019. The recycling of Niobium from these applications could satisfy part of the EU Niobium demand for the foreseeable future, which does not however eliminate the need for increased investment in extraction facilities and methodology.
- The extraction of Niobium from High Strength Low-Alloy Steels (HSLA) is always a promising source of Niobium, as this is the main application of Niobium. Research is needed in this field.
- Investing in research for the recovery of Nb and Ta from Tungsten carbide sludge ([Nb] = 5.6% and [Ta] = 7.2%).

## TANTALUM

- Another solution lies in considering capacitors and electronic parts as new resources, which would lead to a 40% Ta recycling rate in the EU. To increase recycling, central waste collection centres and channelling waste streams would be needed. Current recycling rates, which fluctuate between 10% and 30% would need to be improved to prevent scarcity of the products. The recycling industry could focus not only on old scraps (cemented carbides and alloys) but also on end-of-life products with high Tantalum grades (electrolytic capacitors: 36.7 %, wavefilters: 33 %, semiconductors: 28.6 %).
- New deposits could be exploited. Resources are present in Europe (see the MSP\_REFRAM diagram), including among others, Treguennec in Brittany (France) with a potential of 1600 tons of Tantalum.
- Old tin tailings containing Tantalum (or Niobium) could be exploited for Tantalum extraction using improved technologies (they represent only 10% of the world Tantalum production in 2012).
- Investment in new innovative processing and innovative extractive metallurgy for secondary resources and recycling would be highly beneficial as 60 tons Ta recycled/year could be obtained given a 20% recycling rate.
- Penalties for companies importing from conflict-affected regions or countries with poor working conditions.

There is currently no real supply risk for EU industry in terms of technological needs, but the situation could change with stricter regulations on supply from conflict-affected regions or countries with poor working conditions or as a result of heightened environmental concerns. Moreover, increased transparency concerning the declaration of real production figures should be promoted among EU processors, as it would facilitate more accurate estimation of the EU's needs and weaknesses.

## MOLYBDENUM

- Potential innovations in secondary-resource recovery (mill scale, dust, slag, etc.) are needed. For example, smelting reduction Mo-containing mill scale in EAF ~ 5 wt.% mill scale can be charged into EAF with no operational problems.
- Implementation of more efficient sorting and recovery systems (improving Molybdenum recovery to > 50 %).
- Using the generated residual materials as by-products rather than wastes.

## RHENIUM

- Creation of a database of Rhenium-containing product inventories, sales, product info on components, expected wastes.
- Promotion of sorting logistics and collection efficiency of Rhenium- containing end-of-life products and identification of a stable supply source.
- Improvement of pre-processing efficiency using innovative and scale-up technologies.
- Increased facilitation of market access and involvement of large companies, suppliers and specialised groups in Re-recycling programmes.
- Encouraging manufacturers to improve product design by taking features such as easy disassembly, reuse and recycling into account.
- Development of a Rhenium recovery method for materials of diameters >30 mm, which are not currently processed.
- Innovative technologies for conversion of commercially prepared Rhenium compounds (mainly ammonium perhenate) into more technologically advanced and processed functional compounds, materials or components.
- Promote the recycling of super-alloys (83.3% of the Re production).

# ANNEXES

# REFERENCES

- [1] E. Observer, "Http://Euobserver.Com/884 /28943," [Online].
- [2] C. o. t. E. N.-f. M. I. ECORYS, "Final\_report\_5\_april\_en".
- [3] "Tungsten," [Online]. Available: [www.tungsten.com/materials/tungsten](http://www.tungsten.com/materials/tungsten).
- [4] R. E. Krebs, "The history and use of our earth's chemical elements: a reference guide," Greenwood Publishing Group, 2006.
- [5] RPA, "Study on data needs for a full raw materials flow analysis. Prepared for Directorate-General Enterprise and Industry. London, UK, Risk and Policy analysis limited," 2012.
- [6] "Deliverable 1.5 MSP-Refram European Funded Project, 2016".
- [7] A. N. E. Naor, "Properties and applications of Rhenium and its alloys," The AMMTIAC Quarterly, vol. 5, no. 1.
- [8] USGS, "USGS," 2016. [Online]. Available: <http://minerals.usgs.gov/minerals/pubs/commodity/molybdenum/mcs-2016-molyb.pdf>.
- [9] "International Molybdenum Association," [Online]. Available: [www.imoa.info/index.php](http://www.imoa.info/index.php).
- [10] "Deliverable 1.1 MSP-REFRAM EUROPEAN PROJECT," 2016.
- [11] "D1.3 MSP - Refram European Funded Project," 2016.
- [12] B. e. a. T.J, "European Mineral Statistics 2010-14. A product of the world mineral statistics database," British Geological Survey, 2016.
- [13] "Lipmann co," [Online]. Available: <http://www.lipmann.co.uk/articles/metal-matters/metal-statistics-rhenium-an-overview/>.
- [14] L. Moreno, "Tantalum and Niobium Primer," JacobSecuritiesInc, 2011.
- [15] Z. Zhu and C. Cheng, "A review, Hydrometallurgy, Solvent Extraction technology for the separation and purification of Niobium and Tantalum," 2011.
- [16] "Molybdenum Mining & processing [www.imoa.info](http://www.imoa.info)".
- [17] [Online]. Available: [www.imoa.info/molybdenum/molybdenum-mining.php](http://www.imoa.info/molybdenum/molybdenum-mining.php).
- [18] D. Clemente and et al, "Reprocessing slimes tailings from a Tungsten mine," Minerals Engineering , vol. 6, pp. 831-839, 1993.
- [19] O. MINING, "Update on Barruecopardo Tungsten Tailings Project," 2006.
- [20] N. A. T. Corporation, "North American Tungsten Investigates Tailing Reprocessing Potential At the Cantung Mine Site," Cantung Mine, 2013.
- [21] European Commission, "Reference document on Best Available Techniques for Management of tailings and waste-rock in mining activities," 2009.
- [22] ProMine, "AC\_Mo\_Nb\_Re-Ta-W resources".
- [23] D. R. Leal-Ayala and et al., "Mapping the global flow of Tungsten to identify key material efficiency and supply security opportunities," Resources, Conservation and Recycling, vol. 103, pp. 19-28, 2015.
- [24] E. Commission, "Reference document of Best Available Techniques for Management of tailings and waste-rock in mining activities.," EC, 2009.
- [25] ROSKILL, "EU TANTALUM SECTOR OVERVIEW," 2016.
- [26] S. Bulatovic, "Handbook of Flotation Reagents: Chemistry, Theory and Practice: Flotation of Sulfide Ores, vol! Elsevier B.V.," Amsterdam.
- [27] C. Wanhainen, W. Nigatu, D. Selby, C. McLeod, R. Nordin and N. Bolin, "The Distribution, character, and Rhenium Content of Molybdenite in the Aitik Cu-Au-Ag-Mo Deposit and Its Southern Extension in the Northern Norrbotten Ore District," Minerals, vol. 4, pp. 788-814, 2014.
- [28] M. Lengedal, "Dispersion of tailings in the Knabe na-kvina drainage basin," Journal of Geochemical Exploration, vol. 58, pp. 157-172, 1997.
- [29] M. Figueredo, T. Silva, M. Batista, J. Veiga and D. de Oliveira, "Opportunities for recovering critical raw materials from mine wastes: the type-case of Rhenium in residues from the exploitation of old portuguese mines.," Wastes: solutions treatments and opportunities, Second International Conference, September 11th-13th, 2013, Braga, Portugal.
- [30] O. Bozhkov, C. Tzvetkova and T. Blagoeva, "An approach of Rhenium Phytrorecovery from soils and waters in ore dressing regions of Bulgaria," in International Conference on Waste Management, water pollution, air pollution, indoor climate , Corfu, Greece, 2008.
- [31] C. Wanhainen, W. Nigatu, D. Selby, C. McLeod, R. Nordin and N. Bolin, "The Distribution, character, and Rhenium Content of Molybdenite in the Aitik Cu-Au-Ag-Mo Deposit and Its Southern Extension in the Northern Norrbotten Ore District, Northern Sweden, Minerals 2014, 4".
- [32] A. Dehghani, K. Forsat, K. Mohammadbeigy and S. Borojjerdi, "Experimental Study on Recovery of Spent Hydrocracking catalysts," Petroleum&coal, vol. 51, pp. 176-180, 2009.

- [33] Layman, "Recycling used catalysts through a combination of hydro and pyro-metallurgical processes: a sustainable development project," 2006.
- [34] S. Casanovas, "Mapping\_of\_secondary\_Nb\_resources\_(EOL\_products)," in WorkShop1 MSP REFRAM, Barcelona, 2016.
- [35] S. Cuesta-Lopez, R. Barros, M. Ulla-Maija, S. Willersinn and Y. X. Sheng, "Mapping of the secondary resources in the EU (mine tailings, industrial waste)," MSP REFRAM, 2016.
- [36] "Stainless Steel in Figures 2015. International Stainless steel forum".
- [37] Layman, "Recycling used catalyst through a combination of hydro and pyro metallurgical processes: a sustainable development project," 2016.
- [38] W. Kurylak, U.-M. Mroueh, S. Casanovas, R. Barros and S. Cuesta, "Mappin the secondary resources in the EU (urban mines)," in MSP REFRAM EU PROJECT pp67, 2016.
- [39] "The Canadian Encyclopaedia" 2009.
- [40] "Tungsten applications, www.wolfmet.com".
- [41] "Tungsten applications-Steel Azom, 2000-2008," 2008.
- [42] B. G. Delmon, "Hydrotreatment and hydrocracking of oil fractions: proceedings of the 2nd international symposium, 7th European workshop, Antwerpen, Belgium, November 14-17 pp. 351-. ISBN 978-0-444-50214-8. R," Elsevier, 1999.
- [43] MDNinc, "Niobaymetals," 2015. [Online]. Available: <http://niobaymetals.com/wp/wp-content/uploads/2015/09/FeNb-Market-MDN-Web.pdf>.
- [44] T. G. Carneiro T., "Niobium plays role in strengthening superalloys," American Metal Market, vol. 108, p. 164, 2000.
- [45] R. S. D. Crockett, "International Strategic Minerlas Inventory Summary Report - Niobium (Columbium) and Tantalum," USGS, 1993.
- [46] ROSKILL, "PR Newswire Europe Including UK Disclosure," 20 March 2009. [Online]. Available: <http://www.prnewswire.co.uk/news-releases/roskill-expects-global-niobium-demand-to-recover-early-152914985.html>. [Accessed 10 October 2016].
- [47] R. N. Crockett and D. M. Sutphin, "International Strategic Minerals Inventory Summary Report - Niobium (Columbium) and Tantalum," U.S.Geological Survey, Denver, 1993.
- [48] A. Audion and P. Piantone, "Panroama 2011 du marché du tantale, BRGM," 2012.
- [49] S. Ratore, M. Salve and V. Dabhade, "Effect of Molybdenum addition on the mechanical properties of sinter-forged Fe-Cu-alloys," Journal of Alloys and COmpounds, 2015.
- [50] T. Brown, C. Wighton, N. Idoine, E. Rayfract, R. Shaw, E. Deady, J. Rippingale and T. Bide, "World Mineral Production 2008-12 British Geological Survery, Keyworth, Nottingham, 2016".
- [51] H.C.Starck, "High Tech Recycling for Refractory Metals, www.hcstarck.com".
- [52] International\_tungsten\_industry\_association, 2011. [Online].
- [53] J. Yang and W. Kurylak, "MSP Refram Third Workshop Presentation," in Potential innovation pathways in the recovery of refractory metlas from secondary resources, Brussels, 2016.
- [54] Mcgroup, "World Tungsten Produciton to Reach 100100 tons in 2017," 14 March 2014. [Online]. Available: <https://mcgroup.co.uk/news/20140314/tungsten-production-reach-100100-tonnes.html>.
- [55] E. Nikishina, D. Drobot and E. Lebedeva, "Niobium and Tantalum: State of the World Market, Application Fields and Sources of Raw Materials Part 2," Metallurgy of Rare and Noble Metals, vol. 1, pp. 29-41, 2014.
- [56] EC, "Report on Critical Raw Materials for the EU," European Comission, 2015.
- [57] "USGS," [Online]. Available: <https://pubs.usgs.gov/fs/2014/3054/pdf/fs2014-3054.pdf>.
- [58] M. Pinkham, "The vital roles of ferro-niobium," Metal Bulletin, vol. 3, 2014.
- [59] [Online]. Available: <http://www.argusmedia.com>.
- [60] "International Molybdenum Association," [Online]. Available: [www.imoa.info/index.php](http://www.imoa.info/index.php).
- [61] B. P-, "Molybdenum Market Outlook," 2010. [Online]. Available: [www.Molyexp.com](http://www.Molyexp.com).
- [62] [Online]. Available: <http://roskill.com/product/Molybdenum>.
- [63] "Technique for alloying steel making directly from tungsten ore". 2007.
- [64] I. Gaballah, E. Allain and M. Djona, "Extraction of Tantalum and Niobium from Tin Slags by Chlorination and Carbochlorination," Metalluyrgical and Materials Transaction B, vol. 28B, pp. 359-369, 1997.
- [65] S. Virolainen, R. Salmimies, M. Hasan, A. Häkkinen and T. Sainio, "Recovery of valuable metals from argon oxygen decarburization (AOD) dusts by leaching, filtration and solvent extraction," Hydrometallurgy, vol. 140, pp. 181-189, 2013.
- [66] [Online]. Available: [http://rudemet.net/media/articles/Article\\_EM\\_01\\_15\\_pp.38-40.pdf](http://rudemet.net/media/articles/Article_EM_01_15_pp.38-40.pdf).
- [67] "Deliverable 4.2 MSP-REFRAM «State of the art on the recovery of refractory metals from urban mines»".
- [68] "D3.3 MSP-REFRAM «INNOVATION POTENTIAL IN THE RECOVERY OF REFRACTORY METALS FROM SECONDARY RESOURCES» MSP REFRAM PROJECT," 2016.

- [69] P. Taylor and C. Anderson, "Extractive Metallurgy of Rhenium: A review," *Minerals and Metallurgical Processing*, vol. 1, pp. 59-73, 2013.
- [70] B. Heshmatpour and R. McDonald, "Recovery and refining of Rhenium, Tungsten and Molybdenum from W-Re, Mo-Re and other alloy scrap," *Journal of the Less Common Metals*, vol. 86, pp. 121-128, 1982.
- [71] Arcelormittal, "Arcelor Mittal Automotion," [Online]. Available: [http://automotive.arcelormittal.com/europe/1509/Product\\_Safety\\_Toxicology/EN](http://automotive.arcelormittal.com/europe/1509/Product_Safety_Toxicology/EN). [Accessed 5 September 2016].
- [72] Niocorp. [Online]. Available: <http://niocorp.com/index.php/press-releases/218-niocorp-completes-offtake-agreement-with-thyssenkrupp-for-50-of-its-planned-ferro-niobium-production>. [Accessed 5 September 2016].
- [73] "APERAM," [Online]. Available: <http://www.aperam.com/about-2/aperam/what-is-stainless-steel/discover-stainless/properties>. [Accessed 2016].
- [74] "Outokumpu," [Online]. Available: <http://www.outokumpu.com/en/products-properties/more-stainless/stainless-steel-types/ferritic/14521/Pages/default.aspx>. [Accessed 5 September 2016].
- [75] "ssab," [Online]. Available: <http://www.ssab.com/company/about-ssab/the-abc-of-steel-language>. [Accessed 5 September 2016].
- [76] "vallourec," [Online]. Available: <http://www.vallourec.com/fossilpower/EN/Products/Pages/tp92.aspx>. [Accessed 5 September 2016].
- [77] H. Mohrbacher, "Niobium microalloyed automotive sheet steel - a cost effective solution to the challenges of modern body engineering," *International Symposium on Niobium Microalloyed Sheet Steel for Automotive Application*, 2006.
- [78] M. MINES. [Online]. Available: <http://mdn-mines.com/wp/wp-content/uploads/2015/09/FeNb-Market-MDN-Web.pdf>. [Accessed 5 September 2016].
- [79] "Acerinox," [Online]. Available: [http://www.acerinox.com/opencms901/export/sites/acerinox/Galeria\\_documentos/aceria.swf](http://www.acerinox.com/opencms901/export/sites/acerinox/Galeria_documentos/aceria.swf). [Accessed 5 September 2016].
- [80] D. Porter, "Zmm," [Online]. Available: <http://www.zmm.mk/doc/DQUHSS.pdf>. [Accessed 5 September 2016].
- [81] K. STIL. [Online]. Available: <https://www.salzgitter-ag.com/en/press/press-releases/artikel-aus-dem-konzernmagazin-stil/2015-08-25/man-nehme.html>. [Accessed 5 September 2016].
- [82] CBMM, 5 September 2016. [Online]. Available: <http://www.cbmm.com.br/en/Pages/Uses-EndUsers-Niobium.aspx>.
- [83] "Sigma Aldrich," [Online]. Available: <http://www.sigmaaldrich.com/catalog/search?term=niobium&interface=All&N=0&mode=match%20partialmax&lang=es&region=ES&focus=product>.
- [84] "H.C.Starck," [Online]. Available: [https://www.hcstarck.com/en/hc\\_starck\\_group/press/press\\_releases/press\\_archive/2011/hc\\_starck\\_and\\_cabot\\_announce\\_patent\\_cross-license\\_agreement.html](https://www.hcstarck.com/en/hc_starck_group/press/press_releases/press_archive/2011/hc_starck_and_cabot_announce_patent_cross-license_agreement.html). [Accessed 5 September 2016].
- [85] "American elements," [Online]. Available: <https://www.americanelements.com/nb.html>. [Accessed 5 September 2016].
- [86] J. S. Inc., "Tantalum & Niobium primer - two critical metals," *Jacob Securities*, 2011.
- [87] B. G. Survey, "World Mineral Statistics," [Online]. Available: <https://www.bgs.ac.uk/mineralsuk/statistics/worldStatistics.html>.
- [88] D. Mackay and G. Simandl, "Geology, market and supply chain of Niobium and Tantalum-a review," *Miner Deposita*, vol. 49, pp. 1025-1047, 2014.
- [89] L. Rudnick, "Lubricant Additives," *Chemistry and Applications*, Second Edition, 2009.
- [90] J. F. Papp, "2014 Minerals Yearbook. Niobium (Columbium) and Tantalum [Advance Release]," *USGS science for a changing world*, p. 52.2, 2016.
- [91] A. International, "High-Strength Low-Alloy Steels," *ASM International*, Ohio, USA, 2001.
- [92] M. Pinkham, "The vital roles of ferro-niobium," *Metal Bulletin*, 3 2014.
- [93] C. Gibson, "Niobium, The envy of the gods," *EDISON*, 2016.
- [94] J. Gray, "Niobium bearing steels in pipeline projects," *Microalloying International*, Inc..
- [95] T. Carneiro and G. Tither, "Niobium plays role in strengthening superalloys," *American Metal Market*, vol. 108, no. 164, p. 8A, 2000.
- [96] Roskill, "PR Newswire Europe Including UK Disclosure," 20 March 2009. [Online]. Available: <http://www.prnewswire.co.uk/news-releases/roskill-expects-global-niobium-demand-to-recover-early-152914985.html>. [Accessed 10 October 2016].
- [97] J. Papp, "2014 Minerals Yearbook. Niobium (Columbium) and Tantalum," *USGS*, p. 52, 2016.
- [98] R. Moss, E. Tzimas, P. Willis, J. Arendorf and L. Tercero Espinoza, "Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies," *Institute for Energy and Transport Oakdene Hollins Ltd Fraunhofer Institute for Systems and Innovation Research ISI*, 2013.
- [99] "CBMM," [Online]. Available: <http://www.cbmm.com.br/en/Pages/Uses-EndUsers-Niobium.aspx>.

- [100] "Lipmann Co," [Online]. Available: [www.lipmann.co.uk/articles/metal-matters/metal-statistics-rhenium-an-overview](http://www.lipmann.co.uk/articles/metal-matters/metal-statistics-rhenium-an-overview).
- [101] BGS, "Niobium-tantalum mineral summary," 2011.
- [102] E. Nikisina, D. Drobot and E. Lebedeva, "Niobium and tantalum:state of the world market, fields of application, and raw sources Part I," *Metallurgy of rare and noble metals*, vol. 5, pp. 28-34, 2013.
- [103] M. Pickham, "«The vital roles of ferro-niobium»," *Metal Bulletin*, vol. 3, 2014.
- [104] "CRM\_InnoNet substitution of CRM".
- [105] S. Zhang, "Titanium carbonitride-based cermets processes and properties.," *Materials Science and Engineering*, vol. 163, pp. 141-148, 1993.
- [106] T. Lindroos, P. Lintunen, M. Karhu and J. Kemppainen, "Novel Ti carbide based hard metal alternative for traditional WC-Co".
- [107] T. Ishida and e. al, "Development of Cemented Carbide tool of reduced rare metal usage," *Industrial Materials*, vol. 73, pp. 52-56, 2011.
- [108] E. P. Rothman, G. B. Kenney and H. K. Bowen, "MIT Materials Processing Center Poferrt@ of Ceramic Laaterlak 10 Replace CobaH C/IUornwn Manganese and Plafflum In Wlca/App/ICatlorM OTA Contract study," January 1984.
- [109] G. E. GE.
- [110] J. Papp, "Niobium (Columbium) and tantalum," USGS, 2013.
- [111] A. Chapman, J. Arendorf, T. Castella, P. THompson, P. Willis, L. Tercero, S. Klug and E. Wichmann, "Study on Critical Raw Materials at EU Level," 2013.
- [112] Y. Liu, H. Zhong and Z. Cao, "Molybdenum removal from copper ore concentrate by sodium hypochlorite leaching," *Mining Sci.Technol. China*, vol. 21, pp. 61-64, 2011.
- [113] G. Olson and T. Clark, "Bioleaching of molybdenite," *Hydrometallurgy*, vol. 93, pp. 10-15, 2010.
- [114] J. Fu and e. al., "Recovering molybdenite from ultrafine waste tailings by oil agglomerate flotation," *Minerals Engineering*, vol. 39, pp. 133-139, 2012.
- [115] S. Cho and J. Lee, "Metal recovery from stainless steel mill scale by microwave heating," *Met.Mater.Int*, vol. 14, pp. 193-196, 2008.
- [116] K. Niwa, I. Ichikawa and M. Motone, "Method of separating and purifying tantalum and Niobium-containing compounds," Patent JP82487/86, EP0241278, 1987.
- [117] M. Kabangu and P. Crouse, "Separation of Niobium and Tantalum from Mozambican tantalite by ammonium bifluoride digestion and octanol solvent extrction," *Hydrometallurgy*, vol. 129, pp. 151-155, 2012.
- [118] J. D. Lessard, L. Shekhter, D. Gribbin and L. F. McHugh, "A new technology platform for the production of electronic grade Tantalum nanopowders from tantalum scrap sources," *Intenration Journal of Refractory Metals and Hard Materials*, vol. 48, pp. 408-413, 2015.
- [119] [Online]. Available: <http://www.agence-nationale-recherche.fr/?Projet=ANR-13-CDII-0010>.
- [120] J. Hiskey and N. Nebeker, "Recovery of Rhenium from copper leach solution by ion exchange," *Hydrometallurgy*, Vols. 125-126, pp. 64-68, 2012.
- [121] A. Khoshnevisan, H. Yoozbashizadeh, M. Mohammadi, A. Abarzappor and M. Maarefvand, "Separation of Rhenium and Molybdenum from Molybdenite laeach liquor by the solvent extraction method.," *Minerals Metallurgical Process*, pp. 53-58, 2013.
- [122] D. Jafarifara, M. Daryanavardb and S. Sheibani, "Ultra fast microwave-assited leaching for recovery of platinum from spent catalyst," *Hydrometallurgy*, vol. 78, pp. 166-171, 2005.
- [123] T. Angelidis, D. Rosopoulou and V. Tzitzios, "Selective Rhenium recovery from spent reforming catalysts," *Ind.Eng. Chem.Res*, vol. 38, pp. 1830-1836, 1999.
- [124] ROSKILL, "The Economics of Rhenium," 2006.
- [125] Snakowski T., Golas K. and Ewicka E., *Mineral Yearbook of Poland*, 2014.
- [126] Z. Abisheva, A. Zagorodnyaya and N. Bekturganov, "Review of technologies for Rhenium recovery from mineral raw mateirals in Kazakhstan," *Hydrometallurgy*, vol. 109, pp. 1-8, 2011.
- [127] E. G. Naor, "Properties and applications of Rhenium and its alloys," *The AMMTIAC Quarterly*, vol. 5.
- [128] Churchward, Rosenbaum, "Sources and recovery methods for Rhenium," *United States Bureau of Mines, Report of Investigations*.
- [129] Chen, Dongdong and et al, "Experimental Research on the Separation of a Carbonate-vein-type Wolframite-Scheelite Ore by the Combined Process of Gravity-Flotation-Magnetic Technologies," vol. 30, pp. 18-23, 2015.
- [130] W. Zhang, J. Yang, Z. Zhao, W. Wang and J. Li, "Coordination leaching of Tungsten from scheelite concentrate with phosphorus in nitric acid," *J.Cent Sout Univ.*, vol. 23, pp. 1312-1317, 2016.
- [131] "D.3.3 MSP REFRAM «INNOVATION POTENTIAL IN THE RECOVERY OF REFRACTORY METALS FROM PRIMARY RESOURCES»".
- [132] J. Drobnick and C. Lewis, "Recovery and Purificiation of Tungsten by Liquid Ion Exchange Process," *Unit Processes in Hydrometallurgy*, pp. 504-514, 1964.
- [133] G. Zhang, W. Guan, L. Xiao and Q. Zhang, "A novel process for W hydrometallurgy based on direct solvent extraction in alkaline medium," *Hydrometallurgy*, 2016.

# TECHNICAL ANNEX A: MAIN PROCESSING TECHNOLOGIES

## TUNGSTEN

### PRIMARY RESOURCES

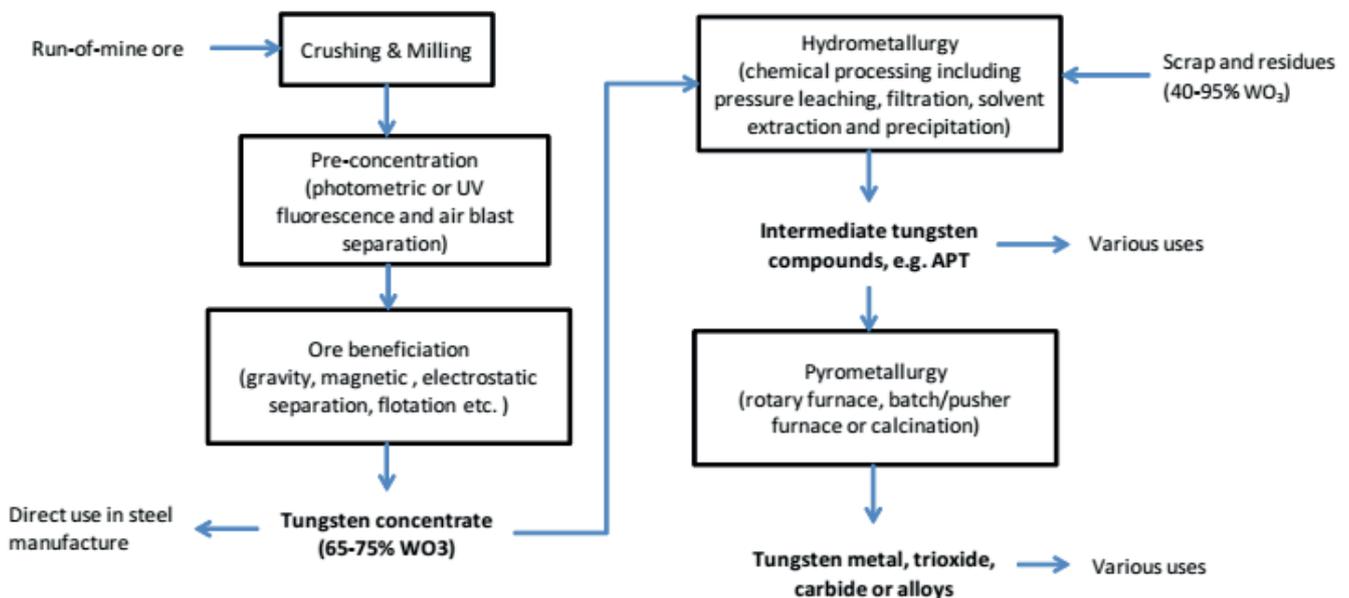
#### MINING

The selection of a suitable mining method, open-pit or underground mining, depends on the physical and chemical properties of the mineral, tonnage and grade, the physical form in which it occurs, the geometry and the depth of the ore body. Owing to variation in deposit types, both open pit and underground mining methods are used in tungsten mine operations.

Open pitting is used for example at Los Santos mine (skarn, Spain), at the Kara mine (skarn, of which tungsten is by-product, Australia), for part of the production at Cantung mine (skarn, Canada) and in various Chinese operations. In fact, most of the other tungsten mining projects that are currently in operation throughout the world also use open pitting. Tungsten open-pit mining rarely exceeds 100 meters.

Underground mining techniques are used at the Panasqueira mine in Portugal, the Chollja mine in Bolivia, the Mittersill mine in Austria, the Cantung mine in Canada and at the Pasta Bueno mine in Peru, among others.

#### MINERAL PROCESSING



*The general flowsheet of tungsten production*

The beneficiation process normally includes a pre-concentration step after the crushing and grinding of the run-of-mine ore, which is followed by pre-concentrate processing, concentrate cleaning or up-gradation step and, lastly, a final purification stage to meet market specifications. Only scheelite is readily amenable to flotation. Wolframite is paramagnetic. Thus, the beneficiation techniques of gravity concentration and flotation are applied for scheelite ore, whereas gravity and/or magnetic separation techniques are used for wolframite. Furthermore, pre-concentration methods are usually used to discard a portion of the run-of-mine ore and increase the head grade prior to the traditional beneficiation stages. The beneficiation flow-sheet depends on the nature of the mineralization in the ore body and on the liberation size of the Tungsten minerals.

## **EXTRACTIVE METALLURGY**

### *Hydrometallurgy*

After digestion and purification of the raw material, the concentrated leachates enter the solvent extraction cycle. There are several processes to produce high-purity ammonium paratungstate (APT), which is the most important intermediary in pure Tungsten production:

1. Digestion: alkali leaching, pressure leaching with soda and acid leaching.
2. Purification: filtration and precipitation. Silicates are common impurities, which can be precipitated using aluminium sulphate or magnesium sulphate solution at pH 8-11. Phosphates and fluorides are co-precipitated. Molybdenum is precipitated using sodium sulphide in a neutral or slightly alkaline environment forming triomolybdate. It is then precipitated as trisulfide by adding sulphuric acid with a pH of 2.5-3. This is also selective for other sulphides: As, Sb, Bi, Pb and Co.
3. Solvent extraction: tertiary or secondary aliphatic amines are the most important extractants. Extractants are dissolved in kerosene or other aliphatic solvents. Phase modifiers like isodecanol can be added.
4. Ion exchange: sodium tungstate solution is placed into contact with a strongly alkaline ion exchange resin in chloride form, where the tungstate is adsorbed. Desorption is carried out with ammonium chloride solution.
5. Crystallization: the isopolytungstate solution is evaporated and the water and ammonia are distilled, which are then recycled in the solvent extraction step. Its solubility is thus reduced and APT crystallizes into recirculating batch crystallizers.

### *Pyrometallurgy*

Tungsten concentrates, after processing of the ore, may be directly converted into Ferro-Tungsten (through aluminothermic and carbothermic reduction processes), steel (in an EAF) and Tungsten chemicals or indirectly into metal powder (through a hydrogen reduction process of Tungsten oxide at 600-1000°C) and carbide (producing high-purity Tungsten powder and Tungsten powder carbonization with high-purity carbon black, soot or graphite).

## **SECONDARY RESOURCES**

### **MATERIAL PROCESSING**

From waste rock and tailings: Waste rock generally consists of coarse, crushed, or block material covering a range of sizes, from very large boulders or blocks to fine sand-sized particles and dust. Mill tailings consist of extremely fine particles that are rejected from the grinding, screening, or processing of the raw material. Typically, mill tailings range from sand to silt-clay particle sizes, depending on the degree of processing needed to recover the ore. At the Panasqueira Mine in Portugal, flotation, magnetic separation and gravity concentration test work has been undertaken at the laboratory and pilot scales. Current tailings were well floated using froth flotation. At La Parrila mine in Spain in 1986, tailings were processed using cyclones, spirals, and shaking tables and resulted in 70% Tungsten recovery. Contaminated cemented carbide scrap, turnings, grindings and powder scrap are oxidized and chemically processed in a way similar to that applied to the ores.

Grinding sludge/swarf: The main problem is the oil contained in the swarf. It must be removed by using, for example, a high pressure filter. Moreover, non-metallic and phosphorous content in the sludge/swarf also needs to be reduced to no more than 5% and 0.03%, respectively, if the swarf is to be sent for smelting recycling. Phosphorous removal may be achieved by controlling the oil content and by employing a water-washing process. Non-metallic removal is carried out using gravity concentration and magnetic separation. The cleaned residues are then sent to smelting furnaces.

Mill scale: It must first be crushed or ground into fine powder and then formed into briquettes before undergoing charging in the reduction reactor to extract Tungsten.

## **EXTRACTIVE METALLURGY**

Waste rock and tailings are treated hydrometallurgically:

- Digestion: In concentrated NaOH (40-50%) at 100-150°C or by high-pressure digestion with diluted NaOH.
- Purification: Sodium tungstate solutions are filtered and precipitated to remove impurities. Sodium ion concentration must be reduced from 70 g/L to < 10 mg/L. After purification, it is subjected to a Tungsten concentration process.
- Solvent extraction: The same procedure as that used for primary resources.
- Ion exchange resin: Sodium tungstate solution is placed into contact with a strongly alkaline ion exchange resin in chloride form, where the tungstate is adsorbed. Desorption is carried out with an ammonium chloride solution. Elements such as Si, P, As and Mo can also be removed.

In the case of grinding sludge/Swarf, after proper processing, grinding sludge/swarf briquettes can be charged into the smelting furnace to produce Ferro-Tungsten or Tungsten alloy. In this way, the Tungsten in the scrap is recovered in the steel in the end. Alternatively, it is also possible to apply NaOH pressure leaching to extract Tungsten and the Tungsten is thus recovered as ammonium paratungstate (APT), an important intermediate product for Tungsten metal powder and carbide production.

From mill scale, reduction can be applied and the Tungsten can be used in the steel, by charging the mill scale in the EAF. The same leaching technique as is used for swarf can also be applied.

Lastly, in the case of Tungsten carbides, the most common method involves separation of the carbides from the binder phase or oxidation followed by alkali leaching. However, coarse powders are formed, the cost is high and large amounts of chemicals are required.

## **TANTALUM AND NIOBIUM**

### **PRIMARY RESOURCES**

#### **MINING**

Almost all mines in carbonatites and other steeply-dipping intrusive rock structures are mined in open pits. The Araxá mine starts mining in the most surficial weathered part of the deposit. However, the Niobec mine plays underground mining. Underground mining is restricted to deep deposits (the Tanco Mine in Canada and the Greenbushes Mine in Australia for Tantalum extraction).

#### **MINERAL PROCESSING**

Beneficiation of the ores at the industrial scale relies upon the combination of:

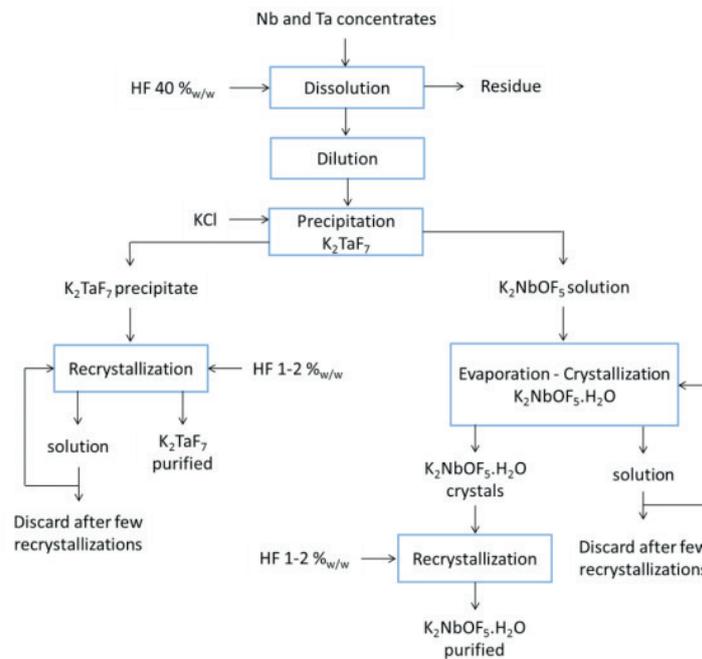
- Crushing (jaw, cone or impact crusher) to, say, <15-20 mm
- Grinding (ball or rod milling) and classification (screens and hydrocyclones) in a closed circuit to <1mm
- Conventional (jig, shaking table), centrifugal (spiral) and enhanced gravity separation (MGS, Falcon concentrator), depending on the size of the liberated particles
- Selective reverse flotation to concentrate the finest material, normally at a controlled pH. The high consumption of additives is a significant cost factor for the flotation processing of T-Nb fines and has pollution issues as well.

- Regular and high magnetic separation to remove companion magnetic phases
- Thickening circuit to recycle the process water

## EXTRACTIVE METALLURGY

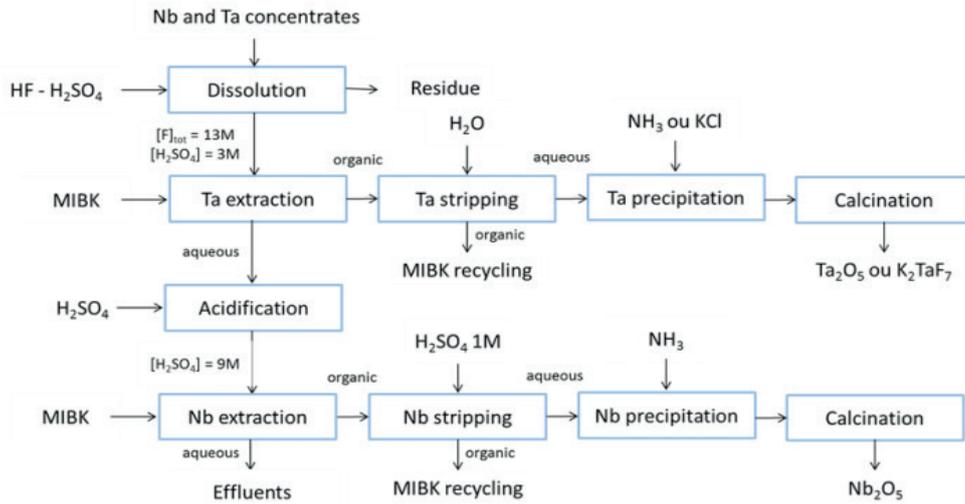
### Hydrometallurgy

- Leaching: Acid digestion of ores in a mixture of hydrofluoric acid with other mineral acids, generally sulphuric acid.
- Fractional Crystallization: The separation should be carried preferably at an acid concentration of about 1 to 7% HF, where the solubility of Niobium complex is nearly 10 to 12 times more than that of Tantalum. Apart from acidity, many other factors, such as temperature and the presence of other ionic species, affect the solubility of the complex species. The separation of Niobium and Tantalum by fractional crystallization is accomplished using double fluoride complexes with potassium. Since the solubility of potassium fluotantalate ( $K_2TaF_7$ ) is low, it crystallizes out. The crystalline solid is redissolved and recrystallized. The process is conducted in several stages. The process works quite satisfactorily and is conducted with relative ease as far as the preparation of pure Tantalum complex  $K_2TaF_7$  is concerned.



**Fractional crystallization flowsheet**

- MIBK extraction: The key parameter is the  $H^+$  concentration, which controls the degree of separation as well as the recovery of the two metals. Normally, operated mixer-settlers are used. Niobium and Tantalum remain in the organic phase, which is washed with concentrated sulphuric acid and re-extracted with water or dilute sulphuric acid to obtain Niobium. Niobium oxide hydrate is then precipitated using gaseous or aqueous ammonia. Then, they are filtrated, dried and calcined at up to 1100 °C. The precipitation, drying and calcination parameters can be modified to obtain different particle sizes of the oxides, depending on the desired application. Impurities are not extracted and left in the raffinate. Very pure Ta and Nb products are obtained.



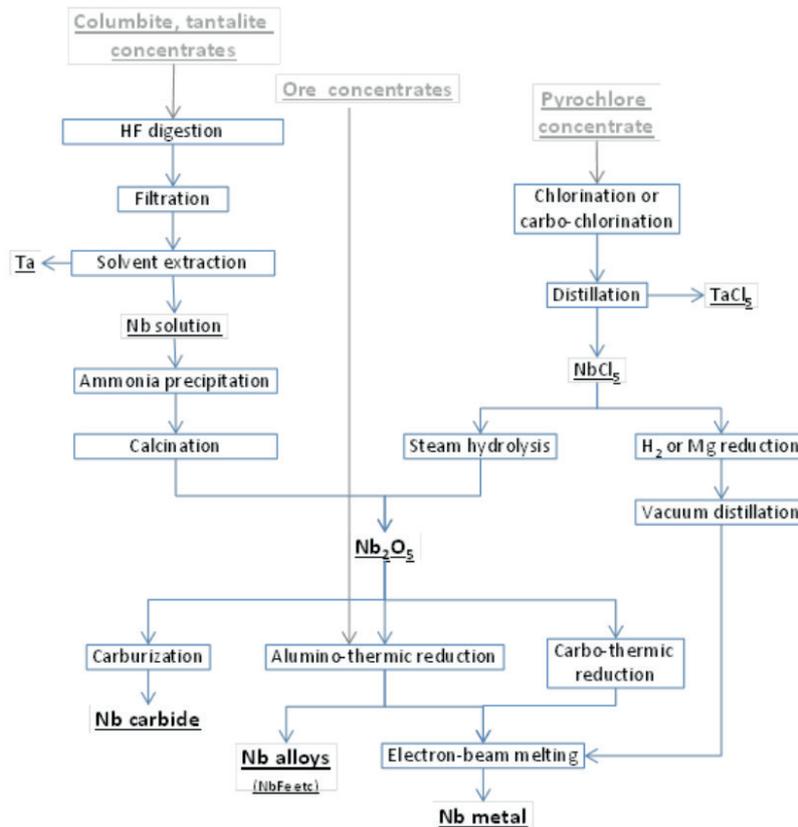
**MIBK extraction flowsheet**

**Pyrometallurgy**

The pyrochlore concentrate obtained after physical beneficiation followed by chemical leaching to remove impurities is of the right specification and it can be used directly for the production of ferroNiobium by aluminothermic reduction process.

One of the simplest methods for breakdown treatment of concentrates of Niobium is direct reduction with aluminium and carbon with or without the addition of iron and iron oxides. In aluminothermy, all the oxides that have free energy of formation less negative than that of alumina are reduced to the metallic state and joins the ferroalloy, giving especially a Ferro-Niobium alloy. In carbothermic reduction, Niobium reacts with excess carbon and form carbides, forming an alloy carbide. This process is usually performed in a smelting electric arc furnace.

However, if the objective is to separate Tantalum from Niobium, a selective reduction of the chlorides can be applied. Niobium pentachloride is more readily reduced by hydrogen (or by metals such as aluminium) to the lower chlorides. Then, NbCl<sub>5</sub> reduction takes place at 450-550°C to trichloride. TaCl<sub>5</sub> is not reduced under these conditions.



**Pyrometallurgical route for W production**

## SECONDARY RESOURCES

### MATERIAL PROCESSING

- Municipal and Industrial Landfill waste: The first stages include crushing and separation of fines from larger particle using, for example, a rotary screen. Typical methods are magnetic, density and ballistic separation methods and in some cases, an eddy current.
- Incineration bottom ash: Usually the slag is treated at the incineration plant. Before treatment, slag is stored at least one day for integration of CO<sub>2</sub> and to make it less wet and sticky. Metal pieces and particles are separated in several mechanical processing stages: sieving, crushing and mechanical separation (magnetic, eddy current). Sensor separators are also used.
- Tin slags and silt-like tailings: Strong chemical digestion or electro-thermic reduction are usually needed.

### TANTALUM EXTRACTIVE METALLURGY

#### *Hydrometallurgy*

The organic solvents that are appropriate for Niobium and Tantalum extraction are of two categories:

1. neutral oxygen-containing extractants, such as ketones, TBP, TOPO and octanol, among others;
2. anion exchangers, such as trioctylamine (TOA). Industrially, MIBK, cyclohexanone, TBP and 2-octanol are used. Generally, the extraction and refining of Tantalum is accomplished by hydrofluoric and sulphuric acid leaching at high temperatures, which produces complex fluorides. After filtration and solvent extraction (MIBK) or ion exchange (amine extractant in kerosene), highly purified solutions of Tantalum and Niobium are produced. Tantalum values in solution are generally converted into potassium Tantalum fluoride or Tantalum oxide.

#### *Pyrometallurgy*

Tantalum oxidizes easily and moves into the slag produced in pyro-metallurgical processes. By using an electrothermic reduction process, the slag is upgraded with up to 50% of Tantalum oxides. Carbothermic, metallothermic, and hydrogen reduction can be applied to extract Tantalum. Also molten salt electrolysis is applied. After these processes, Tantalum metal can be refined by molten salt electro-refining, vacuum sintering, electron beam or plasma refining.

### NIOBIUM EXTRACTIVE METALLURGY

Well-classified metal scrap can be reused by pulverizing it after hydriding, acid leaching to remove contamination of iron, if any, and then reusing in the fabrication stream. Similarly, well-classified scrap of cemented carbide tools consisting primarily of alloy carbide cemented with a cobalt binder can be reused within the fabrication plant after separating the carbides from the cementing material. This can be achieved by a simple process involving treatment of the scrap with molten zinc. Cobalt and zinc form an alloy which has a higher specific volume. This disintegrates the cemented carbide shapes. Then, the carbide powder can be reused and cobalt can be recovered using vacuum distillation of zinc.

Niobium and Tantalum separation by solvent extraction is normally performed in the presence of fluorides. Sulphuric and hydrochloric acid solutions are characterized by association and polymerization of complexes of these elements, which prevent their selective isolation.

Niobium extraction processes from tin slags can be divided into three phases:

1. Upgrading the Niobium content of the slag: separating some of the constituents by leaching (acid leaching of slag with 2 % sulphuric acid at 50°C).
2. Preparing synthetic concentrate.
3. Recovering Niobium directly from medium-grade slags.

As for recycling of iron and steel scrap, scrap is collected by scrap dealers and processed into a physical form and chemical

composition that can be consumed by steel mills in their furnaces. Baling presses are used to compact the scrap into manageable bundles. Scrap dealers sort scrap materials, and steelmakers carefully purchase scrap that does not contain undesirable elements that exceed acceptable levels. The scrap is mainly melted in basic oxygen and electric arc furnaces (BOF and EAF). In recycling of high-strength, low-alloy steel one must be aware that about 0.05% of Niobium will most likely be oxidised to the slag phase and lost during recycling to EAF or BOF. In the fabrication of new steel products, new steel scrap with known chemical composition is produced. Preparation of the new scrap for recycling is usually limited to cutting, cleaning, and baling prior to shipment back to the steelmaker.

## MOLYBDENUM

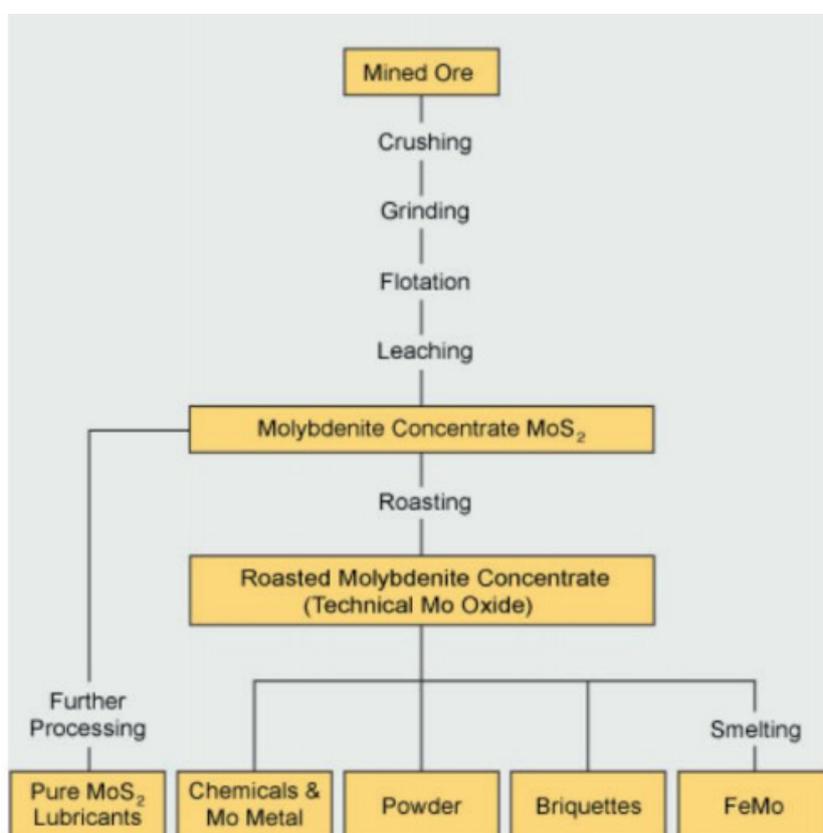
### PRIMARY RESOURCES

#### MINING

Molybdenum is mined as a principal ore and is also recovered as a by-product of copper and tungsten mining. Molybdenum is contained in various minerals, but only molybdenite ( $\text{MoS}_2$ ) is suitable for the industrial production of marketable molybdenum products.

Depending on the minerals contained in the ore body and their quality, molybdenum mines are grouped into three types: 1) Primary mines; 2) By-product mines, 50% of the world's molybdenum production comes from Cu-Mo ore as a by-product; and 3) Co-product mines.

If the ore lies close to the surface, open cast pit technology is employed. The overburden is excavated to reveal the ore body for easy extraction. If the ore lies deep underground, the underground block caving technique is employed, and large blocks of ore are undercut and allowed to collapse under their own weight. The resulting rock is brought to the surface for processing.



*Typical flowsheet for Mo production from ores*

## **MINERAL PROCESSING**

Normally, crushing and grinding are performed, converting the ores to fine particles and sending them to flotation to separate the metallic minerals including molybdenite from the gangues. In the case of Copper/Molybdenum ores, molybdenite is further separated by flotation from Copper sulphide. The resulting concentrate contains between 85 and 92% MoS<sub>2</sub>. Further treatment by acid leaching can be used to dissolve impurities like copper and lead if necessary. The concentrate is roasted in air at temperatures between 500 and 650°C, and the resulting molybdenite usually contains a minimum of 57% Molybdenum, and less than 0.1% sulphur.

## **EXTRACTIVE METALLURGY**

Once a concentrate is obtained, a small part of it is directly used to produce pure molybdenite chemicals and the larger portion of the concentrate is transformed into Molybdenum oxide, an important starter compound for powders and ferroMolybdenum. Most of the concentrate is roasted to a technical grade and afterwards used directly in the steel and iron industries and the rest is further processed to produce a high-grade Molybdenum oxide suitable for use in catalysis, pharmaceuticals, fertilizers, pigments, etc.

There are several hydrometallurgical techniques that can be employed to recover Molybdenum from beneficiation concentrates. In many cases pretreatment stages are performed to reduce the impurities before roasting. Normally sodium cyanide is used to remove copper and gold, ferric chloride for copper, and lead and calcium and hydrochloric acid to remove Lead and Bismuth. Pressure oxidative leaching is becoming the most popular hydrometallurgical technique for the recovery of Molybdenum because of its environmental friendliness and versatility in treatment of high/low-grade concentrates.

## **SECONDARY RESOURCES**

### **MATERIAL PROCESSING**

For flotation tailings from a copper-molybdenum mine, a combined process was studied to recover copper, molybdenum, sulfur and iron minerals. The procedure involved pre-desliming, bulk flotation of copper and molybdenum of the coarse fraction, separation of Cu-Mo, separation of sulfur from bulk flotation tailings and low-intensity magnetic separation of iron from sulfur flotation tailings. Recovering molybdenite from ultrafine waste tailings by oil agglomerate flotation was also studied.

Mo-Cu is separated by flotation and the rougher Mo concentrate goes to Mo recleaner flotation to obtain final Mo concentrate. Jet flotation systems are recommended for old tailings and the initial slurry is separated into 3 flows: Rough concentrate from flow 1 is mixed with the initial feed from flow 2, rough concentrate from flow 2 is mixed with initial feed from flow 3, and rough concentrate from flow 3 is fed for scavenging. It is efficient to use flotation with a heat saturated water steam and air mixture [79].

### **EXTRACTIVE METALLURGY**

For the recycling of steel scrap containing Molybdenum, the most common method consists of re-melting the steel scrap, for example, in an electric arc furnace (EAF). Before the re-melting procedure, the scrap normally needs to be pre-treated to: 1) ensure that the scrap is of a suitable size to make it possible to be charged into the furnace; 2) ensure a homogenous composition of the scrap; 3) remove the impurities from the scrap.

In the case of spent catalyst recycling, they are normally roasted to eliminate the C and S content (de-oiling and de-coking) and/or to facilitate the transformation of the refractory metal oxide into other forms. Crushing and/or grinding is performed in order to obtain finer materials, which are then subjected to leaching [80].

# RHENIUM

## SECONDARY RESOURCES

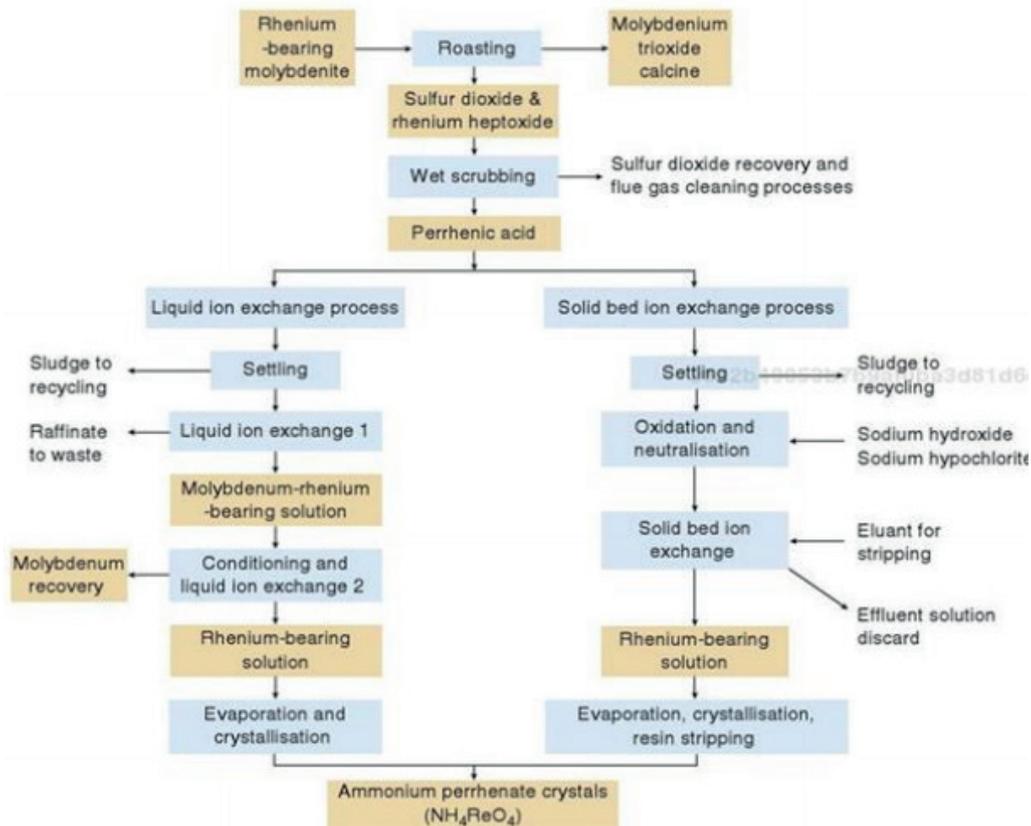
### MATERIAL PROCESSING

Due to high volatility of the oxidized forms of Rhenium during the processing of copper concentrates in pyrometallurgical processes, it accumulates in dusts and gases. When traditional shaft furnace technology is used, Rhenium partially distillates and accumulates in the sludge in a sulphide form. The rest remains in copper matte from which, after being subjected to the Bessemer process, Rhenium as a Rhenium (VII) oxide is transferred to the gas phase, at which point it is washed in the washing and cooling section of a sulphuric acid plant (FKS). In the case of fluidized-bed furnaces, Rhenium distillates as an oxide and along with other gases proceeds to sulphuric acid plant, and in the washing and cooling installation of this plant it passes to the weak acidic waste effluent. Dusts from shaft furnaces, sludge from scrubbing and dusts from converters and fluidized-bed furnaces are conveyed to the lead smelter. During the smelting of lead in an oscillating-rotary furnace, Rhenium contained in processed gases passes partially to the gas phase, where it is recovered in secondary dusts. In the lead recovery production cycle, an Fe-As alloy by-product is formed [81]. Molybdenum roasters equipped to recover Rhenium are one of the main commercial sources for this metal.

### EXTRACTIVE METALLURGY

#### Hydrometallurgy

Rhenium can be recovered by liquid and solid ion exchange as presented in the figure below:



Flowsheet for Rhenium production

Extractants commonly used for Rhenium are: trioctylamine, di-isododecylamine and tributyl phosphate [11]. Re may be recycled from W-Re scrap via an oxidative pyrometallurgical roasting technique. Initially, the scrap is roasted at 1000°C in an oxidizing atmosphere to produce Rhenium heptoxide, which is then condensed in the cooling chamber of the tube furnace. This material is then sent for digestion in water. The aqueous Rhenium is subsequently precipitated as potassium perrhenate by adding potassium chloride. The potassium perrhenate is filtered and further purified via continued dissolution and recrystallization. After purification, the salt is dried and sent for reduction in a hydrogen atmosphere at approximately 350°C. Experimental results show that 93.1% of the Rhenium was recovered to produce a 99.98% pure Re product [82] [83].

# TECHNICAL ANNEX B: REFRACTORY METALS MAIN SUBSTITUTES

## TUNGSTEN SUBSTITUTES

Application	Potential Substitute	Advantages	Drawbacks
Cemented carbides	<p>Tool Steel</p> <p>Ceramics</p> <p>Ceramic-metallic composites</p> <p>Mo carbide</p> <p>Nb carbide</p> <p>Ti carbide</p> <p>Ti carbonitride in the metallic binder phase</p>	<p>A TiC microstructure that contains a complex carbide phase forming a frame around each carbonitride particle core and providing a strong bond between these hard phase particles and ductile binder metal. Ti supply risk is lower.</p>	<p>Higher cost</p> <p>Loss in product performance</p> <p>Mo (RM)</p> <p>Nb(CRM)</p>
Tool/high speed Steels	<p>Mo combined with alloying with Cr, Va, Ni.</p> <p>ASS (Alumina, silicon nitride, sialon)</p> <p>AZS (Alumina, zirconia, silicon carbide)</p>	<p>Better performance (Addition of 5-10% of Mo increases hardness and toughness).</p> <p>Cost-effective</p> <p>Mo combined with V prevents softening and embrittlement of steels at high T.</p> <p>[ASS] can increase productivity and</p> <p>[AZS] can improve wear and corrosion resistance.</p>	<p>Molybdenum (RM)</p> <p>ASS (Overcoming inadequate fracture toughness)</p>
Super-alloys (corrosion resistance turbines blades, marine vehicles)	<p>Molybdenum</p> <p>Ceramic Matrix Composites made from a silicon carbide/nitride matrix toughened with a coating of silicon</p> <p>Tantalum fiber-reinforced super-alloys</p>	<p>Lower weight, strong, tough and can be mass- produced.</p> <p>CMC durability has been validated through significant testing in customer gas turbine engines accumulating almost 30,000 hours of operation</p>	---
Mill products	<p>Carbon nanotube filaments</p> <p>Induction technology</p> <p>Light-emitting diodes</p>	---	<p>W replacement appears extremely difficult at the moment</p>

## TANTALUM SUBSTITUTES

Application	Potential Substitute	Advantages	Drawbacks
Capacitors	Nb-oxide	Lower cost possible	Usually larger and have a shorter life-span, Nb is CRM
	Aluminium	Lower cost, higher availability, shorter production lead times, low leakage current, higher voltage range	More sensitive to harsh and hot operating conditions
	Ceramic	Lower cost, smaller size, and/or reliability	---
Cemented carbides	Nb,W	---	CRM
	TiC and TiN	Lower cost	---
Steel super-alloy applications where strength is required at high T	Va or Mo	---	---
Super-alloys for high-temperature applications	Hafnium, Iridium, Molybdenum, Niobium, Rhenium and Tungsten	---	Iridium, Niobium and Tungsten CRM
Process equipment, resistance to corrosion and high-temperature environments	Niobium	Similar crystallographic properties	Nb CRM
Process equipment, corrosion resistant	Glass, Platinum, Ti, Zirconium	---	Platinum CRM
SAW filters and SAW resonators in electronic applications in cell phones, TV sets, video recording, etc.	Lanthanum gallium silicate	---	La and Ga both CRM
Surgical equipment	Cr/Ni steel alloys	---	Lower durability of the oxide coating layer and a lower malleability
Orthopaedic applications	Titanium and ceramics in some cases	---	---
Hard disk drives	Niobium	---	Niobium CRM
Optics/lenses	Niobium in some cases	---	Niobium CRM

## MOLYBDENUM SUBSTITUTES

Application	Potential Substitute	Advantages	Drawbacks
Stainless steel grade 316	Grade 445M2 (higher Cr content)	No Ni addition, smaller, Mo content reduced from 2.2% to 1.2%, better pitting corrosion resistance.	Higher use of Cr
Alloy steels	B, Cr, Nb, V	---	---
Tool steels	W	---	---
Refractory materials in high T electric furnaces	Graphite, Ta, W	---	W (CRM)
Refractory properties	Nb	---	Nb (CRM)
Material strengthening	Nb	---	Lower and more stable prices, Nb is the lightest of the refractory metals, Nb is unique in that it can be worked through an annealing process to achieve a wide range of strength and elasticity
Super-alloys	W-alloyed Ni-and Co-based super-alloys	HT strength and creep strength, high thermal fatigue resistance, good oxidation resistance, excellent hot corrosion resistance, air melting capability, air or argon re-melting capability and good welding properties	W (like Mo) can form detrimental carbides and tcp phases, density increase

# ANNEX C: MAIN EUROPEAN STAKEHOLDERS IN REFRACTORY METALS VALUE CHAINS

## TUNGSTEN

The following tables present a mapping of European companies which are likely to use Tungsten in their activities, whether as intermediate product manufacturers or end-users.

*List of companies that are end-users of Tungsten-based products*

Company	Country	Activity
ABSCO Materials	UK	Chemical industry
Acerinox	SPAIN	Stainless steel
Althammer	GERMANY	Stainless steel/ Steel Alloys
Ampere Alloys	FRANCE	Steel Alloys
Aperam Sourcing SCA	LUXEMBOURG	Stainless steel
Arcelor Mittal	LUXEMBOURG	Steelmaker
Boehler Edelstahl GmbH & Co KG	AUSTRIA	Steel Alloys
Bollinghaus GmbH & Co KG	GERMANY	Stainless steel/ Steel Alloys
CM Chemiemetall GmbH	GERMANY	Steel alloys
Core Alloys UK Ltd	UK	Stainless steel/ Steel Alloys
Cogne Acciai Speciali Spa	ITALY	Steel alloys/Stainless steel
Cronimet Suisse	SWITZERLAND	Stainless steel scrap/ Steel Alloys
Delachaux	FRANCE	Steel alloys
Deutsche Edelstahlwerke GmbH	GERMANY	Stainless steel/steel alloys
ELG Haniel Trading GmbH	GERMANY	Stainless steel/steel alloys
Elektrowerk Weisweiler GmbH	GERMANY	Steel alloys
Eurecat France	FRANCE	Chemical
Europa Tool Co. LTd	UK	Tool steels
GFE Metalle Und Materialien	GERMANY	Steel alloys/Chemicals
Haldor Topsoe	DENMARK	Chemicals
HC Starck GmbH	GERMANY	Steel alloys
Ireland Alloys	IRELAND	Stainless steel/steel alloys
JSC Dneprospetsstal	UKRAINE	Steelmaker
Outokumpu Stainless AB	SWEDEN	Stainless steel
Plansee	AUSTRIA	Steel alloys
Sandvik	SWEDEN	engineering group, mining, construction
Savinox	ITALY	Steel alloys
SIJ - Slovenska Industrija Jekla	SLOVENIA	Stainless steel/Steel alloys/tool steels
SSAB Oxelosund	SWEDEN	Steelmaker
Thyssenkrupp Acciai Speciali Terni Spa	ITALY	Stainless steel

Company	Country	Activity
Torrecid Group	SPAIN	Chemicals
Treibacher Industrie	AUSTRIA	Stainless steel/ Steel Alloys
Ugitech SA	FRANCE	Stainless steel/ Steel Alloys
Royal Dutch Shell	NETHERLANDS & UK	Oil & gas
Total	FRANCE	Oil & gas
Volkswagen	GERMANY	Automotive
Eni	ITALY	Oil & gas
Daimler	GERMANY	Automotive
Statoil	NORWAY	Oil and gas
Fiat	ITALY	Automotive
BMW	GERMANY	Automotive
ArcelorMittal	LUXEMBOURD	Steel
EADS	NETHERLANDS	Aeronautics and defence
Airbus	FRANCE	Aeronautics and defence
Vallourec & Mannesmann Tubes	FRANCE	End user oil&gas, power generation, construction, automotive
Akzonobel	NETHERLANDS	Chemical/Petrochemical
BASF	GERMANY	Chemical/Petrochemical
British Gas	UK	Oil & gas
Sandvik	SWEDEN	Mechanical engineering
Outokumpu	SWEDEN	Mechanical engineering
Vacuumschmelze	GERMANY	Materials manufacture
Ceratizit Group	LUXEMBOURG	Mechanical engineering
BIC	FRANCE	Pen's manufacturer
3M - WINTERTHUR	EUROPE	Abrasive tools - cutting tools
PHILIPS	EUROPE	Lamps

## NIOBIUM

The following tables present a mapping of European companies which are likely to use Niobium in their activities, whether as product manufacturers (steelmakers or alloy producers) or end-users. Trading companies are also mentioned, as they can play an important role in the value chain (most of them are members of either the Nb-Ta International Study Center Association (Tanb) or the Minor Metals Trade Association (MMTA)).

### *List of European companies manufacturing Nb products*

Company	Country	Sector/Activity	Reference
ArcelorMittal	Luxembourg	Steelmaker	[84]
Thyssen Krupp	Germany	Steelmaker	[85]
Aperam	Luxembourg	Steelmaker	[86]
Outokumpu	Finland	Steelmaker	[87]
SSAB	Sweden	Steelmaker	[88]
Vallourec	France	Steelmaker	[89]

Company	Country	Sector/Activity	Reference
Voestalpine	Austria	Steelmaker	[90]
Tata Steel	UK	Steelmaker	[91]
Acerinox	Spain	Steelmaker	[92]
Rautaruukki	Finland	Steelmaker	[93]
Salzgitter AG	Germany	Steelmaker	[94]
Commexim Group A.S	Czech Republic	FeNb alloy producer (also recycler and trader)	MMTA
Fondel Metals BV	UK	FeNb alloy producer (also trader)	MMTA
Treibacher Industrie AG	Austria	Carbides	TANB
Villares Metal	Netherlands,Finland	Carbides	[95]
Böhler	Spain	Carbides	[95]
Syigma Aldrich	International	Nb chemicals	[96]
Cabot	Latvia	Nb chemicals	[97]
American Elements	UK,France,Germany	Nb chemicals	[98]
NEC	International	Producer of Niobium containing ceramic condensers and actuators	[95]
Corning	France	Optical. Producer of optical lenses containing Niobium	[95]
Shott	Germany	Optical. Producer of optical lenses containing Niobium	[95]
Bayer	Germany	Catalyst systems	[95]

*List of Nb traders and recyclers in EU*

Company	Country	Sector/Activity	Reference
A&M Minerals and Metals Ltd	UK	Trading	TANB
Cronimet Central Africa AG	Switzerland	Trading	TANB
DM Chemi-met Ltd	UK	Trading	TANB
Krome Commodities Limited	UK	Trading	TANB
Scandmetal International S.A	Belgium	Trading	TANB
Stapleford Trading Limited	UK	Trading	TANB
Traxys	Luxembourg	Trading	TANB
CellMark Metals/Sonaco	Sweden	Trading	MMTA
Delta Products UK Ltd	UK	Trading	MMTA
FerroMet AB	Sweden	Trading	MMTA
Grondment gmbh &Co Kg	Germany	Trading	MMTA
Lipmann Walton&Co Ltd	UK	Trading	MMTA
London Chemical&Resources	UK	Trading	MMTA
RJH Trading Ltd	UK	Trading	MMTA

Company	Country	Sector/Activity	Reference
Stapleford Minerals&Metals	UK	Trading	MMTA
William Rowland Ltd	UK	Trading	MMTA
Wogen Resources Ltd	UK	Trading	MMTA
Euroinvest commodities	Romania	Trading	MMTA
Womet Gmbh	UK	Trading	MMTA
F.W. Hempel Metallurgical Gmbh	Germany	Trading	MMTA
Firth Rixson Metals	UK	Trading	MMTA
Maritime House	UK	Trading	MMTA
ATI Specialty Alloys &Components	UK, Poland	Secondary Processing	TANB
Elite Material Solutions	UK	Secondary Processing	TANB
Heraeus Deutschland GmbH&Co	Germany	Secondary Processing	TANB
Plansee SE	Austria	Secondary Processing	TANB
H.C. Starck GmbH	Germany	Processing	TANB
Buss&Buss Spezialmetalle GmbH	Germany	Recycling	TANB
Innova Recycling GmbH	Germany	Recycler, trading	MMTA
Jean Goldschmidt International SA	Belgium	Recycler, trading	MMTA
Metherma KG	Germany	Trading and recycling	MMTA, TANB
ELG Utica Alloys Ltd	UK	Processing, recycling, alloys	TANB
Metallum Metal Trading AG	Switzerland	Recycler, Trading	MMTA

*Non-exhaustive list of companies using Nb as end-users*

Company	Country	Activity	Reference
Mercedes Benz	International	Incorporate Nb steels in the design of automotive pieces	[95]
Toyota	International	Incorporate Nb steels in the design of automotive pieces	[99]
Ford	International	Incorporate Nb steels in the design of automotive pieces	[99]
Jaguar	International	Incorporate Nb steels in the design of automotive pieces	[99]
Europipe	Germany	Linepipe producers	[95]
Norwegian Statoil	Norway	Linepipe consumer	[95]

Company	Country	Activity	Reference
Exxon	International	Linepipe consumer	[99]
British Gas	UK	Linepipe consumer	[95]
Alstom	International	Cable manufacturer. Buy Niobium alloy products in such finished forms as billets, rods and sheets	[95]
Outokumpu	Finland	Cable manufacturer. Buy Niobium alloy products in such finished forms as billets, rods and sheets	[95]
Vacuumschmelze	Germany	Cable manufacturer. Buy Niobium alloy products in such finished forms as billets, rods and sheets	[95]

## TANTALUM

As is the case with most minor metals, the EU is host to many companies active in the Tantalum market. The list shown in the table below is probably not complete but should contain the main players. Swiss companies have been included as they are part of the EU supply chain. The list is split into traders, processors/recyclers and companies involved in mining. (Note: Primary processors can use Tantalum concentrates, synthetic concentrates or scrap. Secondary processors rely on intermediate products, such as K-salt and Tantalum ingot).

<u>Company</u>	<u>Country</u>	<u>Activity</u>	<u>Notes</u>
<b>Trading</b>			
A&M Metals and Minerals	UK	Trading	Ta minerals.
Cronimet Central Africa	Switzerland	Trading	Ta minerals. Major trader of Central African tantalum minerals.
Delta Products	UK	Trading	
DM Chemi-Met	UK	Trading	Minerals, compounds, metallurgical products.
E & C Trading	Switzerland	Trading	
Engelhart Commodities	UK	Trading	
Krome Commodities	UK	Trading	
Lipmann Walton	UK	Trading	Various minor metals.
Maritime House	UK	Trading	Authorised distributor for a Chinese processor.
Metallum Metal Trading	Switzerland	Trading	
RJH Trading	UK	Trading	Covers most metals.
Scandmetal International	Belgium	Trading	
Specialty Metals Resources	Belgium	Trading	
Stapleford Trading	UK	Trading	Mostly Ta minerals.
Tradium	Germany	Trader	Various minor metals.
Traxys	Luxembourg	Trading	Mostly minerals, compounds and scrap.

<u>Company</u>	<u>Country</u>	<u>Activity</u>	<u>Notes</u>
<b>Processing and recycling</b>			
Avon Specialty Metals	UK	Recycling	Mainly in aluminium but involved in other metals.
Buss & Buss	Germany	Recycling	Production approximately 40tpy Ta.
ELG Utica Alloys	UK	Processing, recycling	Various Ta products, mostly from recycling.
Elite Material Solutions	UK	Secondary processing	Mainly Ta metal products.
Freiberger NE-Metall	Germany	Processing (probably secondary).	Various alloys.
GfE (AMG)	Germany	Processing (probably secondary).	Various alloys. AMG is also a major tantalum miner (in Brazil – output goes to the USA).
GMH Stachow-Metall	Germany	Recycling, trading	
H.C. Starck	Germany	Processing	Various refractory metals.
Heraeus Deutschland	Germany	Secondary processing	Alloy additives and finished products.
Honeywell Specialty Chemicals	Germany	Processing Chemicals	
Innova Recycling	Germany	Recycling, trading	Various metals from scrap and residues.
Metalysis	UK	Secondary processing	New process, not yet fully commercialised.
Metherma	Germany	Recycling, trading	
Nordmet	Estonia	Recycling, trading	Appears to be mainly focussed on rhenium.
NPM Silmet	Estonia	Processing	Mainly a Nb producer. Raw materials imported mainly from Brazil and Nigeria.
Plansee	Austria	Secondary processing	Approximately 50% of sales are in Europe.
Treibacher Industrie	Austria	Carbides	Ta, Nb and mixed.
<b>Mining</b>			
Imerys Ceramics	France	Mining (France)	Produces a small amount of tantalum as a by-product of kaolin mining. All output believed to be exported from the EU.
Minerals Resources International	Switzerland	Mining (DRC)	
Strategic Minerals	Spain	Mining (Spain)	Mainly a tin project but will supply tantalum in slags. Expected to come into production in Q1 2017.

## MOLYBDENUM

The following tables present a mapping of European companies which are likely to use Molybdenum in their activities, whether as product manufacturers (steelmakers or alloy producers) or as end-users. Trading companies are also mentioned, as they can play an important role in the value chain (most of them are members of IMOA).

### *Non-exhaustive list of companies using Nb as end-users*

<b>Company</b>	<b>Country</b>	<b>Activity/Description</b>	<b>Reference</b>
Treibacher Industrie AG	AUSTRIA	Produces FeMo	[2]
Plansee SE	AUSTRIA	Development and manufacture of Mo mill products and finished products for applications in lighting and electronics industries, high-temperature furnace construction as well as medical and coating technologies	[2]

Company	Country	Activity/Description	Reference
Jean Goldschmidt International SA	BELGIUM	Processing and Recycling	[6]
Sadaci NV	BELGIUM	Produces roasted Mo concentrates, FeMo and sodium molybdate	[2]
Haldor Topsoe A/S	DENMARK	Conversion based suppliers of Mo products	
Ampere Alloys	FRANCE	Part of a distribution network in Europe for ferroalloys and non-ferrous metals for foundries. Traders of Mo products	[2]
CM Chemiemetall GmbH Bitterfeld	GERMANY	Producer of Mo metal powders	[2]
AB Ferrolegeringar	SWEDEN	Producer's agent, and supplier of ferroalloys. Trading	[2]
Alfred H Knight International Ltd	UK	Samplers and Assayers of Mo products (Mo concentrates, Mo oxides, FeMo, Mo metal and Mo products)	[2]
ALS Inspection UK Ltd	UK	Samplers and Assayers of Mo products (Mo concentrates, Mo oxides, FeMo, Mo metal and Mo products)	[2]
S.J.M Alloys and Metals	UK	Suppliers of Pure Mo/ Mo airmelt/Super alloys containing Mo	[7]
Climax Molybdenum	Netherlands	Molybdenum chemicals producer	[8]
Luma Metal	SWEDEN	Wire Mo products	[9]
ABSCO Materials	UK	Chemical industry	[13]
Acerinox	SPAIN	Stainless steel	[6]
Althammer	GERMANY	Stainless steel/ Steel Alloys	[14]
Ampere Alloys	FRANCE	Steel Alloys	[6]
Aperam Sourcing SCA	LUXEMBOURG	Stainless steel	[2]
Arcelor Mittal	LUXEMBOURG	Steelmaker	[6]
Boehler Edelstahl GmbH & Co KG	AUSTRIA	Steel Alloys	[6]
Bollinghaus GmbH & Co KG	GERMANY	Stainless steel/ Steel Alloys	[6]
CM Chemiemetall GmbH	GERMANY	Steel alloys	[6]
Core Alloys UK Ltd	UK	Stainless steel/ Steel Alloys	[14]
Cogne Acciai Speciali Spa	ITALY	Steel alloys/Stainless steel	[6]
Cronimet Suisse	SWITZERLAND	Stainless steel scrap/ Steel Alloys	[6]
Delachaux	FRANCE	Steel alloys	[6]
Deutsche Edelstahlwerke GmbH	GERMANY	Stainless steel/steel alloys	[6]
ELG Haniel Trading GmbH	GERMANY	Stainless steel/steel alloys	[6]
Elektrowerk Weisweiler GmbH	GERMANY	Steel alloys	[6]
Eurecat France	FRANCE	Chemical	[6]
Europa Tool Co. Ltd	UK	Tool steels	[15]

Company	Country	Activity/Description	Reference
GFE Metalle Und Materialien	GERMANY	Steel alloys/Chemicals	[6]
Haldor Topsoe	DENMARK	Chemicals	[6]
HC Starck GmbH	GERMANY	Steel alloys	[6]
Ireland Alloys	IRELAND	Stainless steel/steel alloys	[6]
JSC Dneprospetsstal	UKRAINIAN	Steelmaker	[6]
Outokumpu Stainless AB	SWEDEN	Stainless steel	[2]
Plansee	AUSTRIA	Steel alloys	[6]
Sandvik	SWEDEN	Engineering group in tooling, materials technology, mining and construction	[6]
Savinox	ITALY	Steel alloys	[14]
SIJ - Slovenska Industrija Jekla	Slovenia	Stainless steel/Steel alloys/tool steels	[6]
SSAB Oxelosund	SWEDEN	Steelmaker	[6]
Thyssenkrupp Acciai Speciali Terni Spa	ITALY	Stainless steel	[6]
Torreacid Group	SPAIN	Chemicals	[6]
Treibacher Industrie	AUSTRIA	Stainless steel/ Steel Alloys	[6]
Ugitech SA	FRANCE	Stainless steel/ Steel Alloys	[6]

#### Traders of Mo products in EU

Company	Country	Activity/Description	Reference
Metherma KG	GERMANY	Trading (MoO <sub>3</sub> , FeMo, ADM, pure MoO <sub>3</sub> , metal powder, scraps and residues)	[2]
Groundmet Metall-und Rohstoffvertriebs GmbH	GERMANY	Trading and FeMo conversion	[2]
Traxys Europe S.A.	LUXEMBOURG	Trading (Suppliers of Mo oxide and FeMo)	[2]
Scandinavian Steel AB	SWEDEN	Trading (Mo concentrates, oxide, FeMo metal)	[2]
FW Hempel Intermetaux Sa	SWITZERLAND	Trades of Mo concentrates, Mo oxide/ ammonium molybdate/ Mo semis such as bar trading	[2]
Cronimet Metal Trading AG	SWITZERLAND	Purchase and sale of Mo concentrates and ferro Molybdenum. Trading	[2]
Derek Raphael & Co Ltd	UK	Trading (Mo concentrates, oxides, FeMo and metal)	[2]
Moxba BV	NETHERLANDS	Trading Mo oxide, Mo concentrate	[6]
SADACI	NETHERLANDS	Trading Mo products (FeMo, Roasted Mo concentrate)	[9]
Lipmann Walton & Co Ltd	UK	Trading of Mo products	[9]
London Metal Exchange	UK	Trading of Mo products	[9]

*Main end-user European companies*

Company	Country	Activity
Royal Dutch Shell	NETHERLANDS & UK	Oil & gas
Total	FRANCE	Oil & gas
Volkswagen	GERMANY	Automotive
Eni	ITALY	Oil & gas
Daimler	GERMANY	Automotive
Statoil	NORWAY	Oil and gas
Fiat	ITALY	Automotive
BMW	GERMANY	Automotive
ArcelorMittal	LUXEMBOURD	Steel
EADS	NETHERLANDS	Aeronautics and defence
Airbus	FRANCE	Aeronautics and defence
Vallourec & Mannesmann Tubes	FRANCE	End user oil&gas, power generation, construction, automotive
Akzonobel	NETHERLANDS	Chemical/Petrochemical
BASF	GERMANY	Chemical/Petrochemical
British Gas	UK	Oil & gas
Sandvik	SWEDEN	Mechanical engineering
Outokumpu	SWEDEN	Mechanical engineering
Vacuumschmelze	GERMANY	Materials manufacture
Ceratizit Group	LUXEMBOURG	Mechanical engineering

## RHENIUM

The European Chemicals Agency (ECHA) provides information on registered substances in compliance with REACH. Thus, some data is publicly available concerning quantity ranges of Re and Re compounds manufactured and/or imported by registered companies in the European Economic Area. They are the following:

*Main processors and end-user European companies*

Company	Country	Activity
Heraeus Deutschland GmbH & Co. KG	GERMANY	Manufacture of intermediate products, alloys, computer, electronic and optical products, electronic equipment
Metraco S.A. Sw.	POLAND	Manufacture of intermediate products, alloys, computer, electronic and optical products, electronic equipment
Climax Molybdenum	THE NETHERLANDS	Chemicals/Use as intermediate product

Company	Country	Activity
Lipmann Walton & Co	UNITED KINGDOM	Chemicals/
Airbus	FRANCE	Aerospace
Rolls Royce	UNITED KINGDOM	Aerospace/Engines manufacturing

Big end-users of Rhenium in the EU are found in the aerospace and defence industries. Aircraft manufacturers such as AIRBUS are directly concerned.

The manufacture of aircraft engines is dominated by only four players: Cannon-Muskegon (USA), General Electric (USA), Pratt & Whitney (USA) and Rolls Royce (UK). They are important users of nickel super-alloys containing Rhenium, and represent up to 55% of the total consumption.



The European MSP-REFRAM (Multi-Stakeholder Platform for a Secure Supply of Refractory Metals in Europe) project aims to establish a durable multi-stakeholder network that will carry out a comprehensive study of the entire value chain of key refractory metals including mining, processing, recycling and final applications (and potential substitution opportunities), and taking account of crosscutting aspects: policy/society, technology and market.

The consortium stems from the PROMETIA Association and includes 5 partners from industry/SMEs, 8 research and technology centres, 6 academics, 1 public authority and PROMETIA.

**MORE INFORMATION**

<http://prometia.eu/msp-refram>

[contact@prometia.eu](mailto:contact@prometia.eu)



9 782919 313105