



**SCREEN**

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**Roadmap and innovation pathways for technology development in CRMs value chains to unlock primary and secondary unexploited resources and introduce substitution solutions in industry**

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## Summary

Roadmap and innovation pathways for technology development in CRMs value chains to unlock primary and secondary unexploited resources and introduce substitution solutions in industry

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## DELIVERABLE 6.4

**Roadmap and innovation pathways for technology  
development in CRMs value chains**

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Michail Samouhos (NTUA)**

**Date of first submission: 16-12-2019**

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## INTRODUCTION

### FUTURE APPLICATIONS AND DEMAND TREND

Critical Raw Materials are essential for the production of a broad range of equipment and devices used in everyday life. They are also fundamental for future innovations and the development of sustainable and competitive technologies. Therefore, CRM are of high technical and economic importance to major European industry sectors.

Safeguarding the uninterrupted supply of CRM, as well as their resource efficient and responsible sourcing, are a high priority for the EU policy in the raw materials sector.

The foreseen growing consumption of CRM generates the need for the identification of new primary resources (ore deposits) and potential secondary (mineral-based and non-mineral-based wastes) sources.

Recycling from EoL could be part of the proposed solutions in terms of contributing to raw materials supply, providing better energy efficiency and less environmental impacts in the production of CRM. However, continuous reuse cannot provide alone the necessary quantities of CRM, due to recycling loss; the growing demand for CRM being higher than the rate of primary supply, recycled CRM production and finding new CRM sources and substitutions. Another main issue is the “metallurgical challenge” related to finding product and material groups with the highest potential for high-grade recovery of the

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CRM that are largely lost (e.g. indium, gallium, germanium, tantalum, rare earth elements). Therefore, it is unlikely to close the wide gap between future demand and supply by 2050, while in the long term, secondary supply from recycling is foreseen be able to meet almost 50 % of the demand, i.e. by 2100.

At the end of 2017, China remains the biggest producer of most CRM for the European market, with a strong monopoly for production of Antimony, Beryllium, Bismuth, LREE and HREE, Magnesium and Tungsten (>80% of the total production). Other important producers are for example Brazil, Russia, the Republic of South Africa and USA. The supply of CRM from EU sources has been zero or very limited in the recent years.

## PRIMARY RESOURCES

To fully meet future CRM needs, metals and mineral products from primary sources will still be needed in the future. Most of them will continue to be imported from sources outside Europe; but others can, for political and economic reasons, be produced domestically.

Development of new primary CRM production in Europe will decrease import dependence and make sure that exploitation takes place under sustainable conditions. This includes the necessity for exploration of deep-seated deposits in brownfield areas across the EU, where potential CRM resources may occur in genetic associations with common industrial and other high-tech metals.

The current mine production in the EU28 + Norway involves primary resources of the following CRM:

Calcined magnesite (ES, GR, NL, SL), Tungsten (AU, SP, PT, UK), Cobalt (FI), P, PGMs (FI), Baryte (BG, DE, IT, SK, UK), Fluorspar (DE, ES), Graphite (NO) and He (PL).

The mine production of CRM within the EU28 + Norway varies from 3% (for Helium) to 40% for (Tungsten) of the EU supply for those commodities that are mined in Europe. For some commodities, such as beryllium, gallium or rare earths, the import dependency is 100 %, so there is a need for new exploration activities and opening of new mines in the EU28.

SCRREEN insight reflects strong support for CRM exploration and extraction within the EU, as it shows the large potential for such raw materials to exist in potentially economic

concentrations within the European bedrock. However, opening of new mines in the EU is nowadays rare.

Refinery production is larger for some commodities (Boron chemicals, Cobalt, Gallium, Germanium, Hafnium, Indium and Silicon metal), but the raw materials are largely produced outside EU.

Occurrences and deposits of all non-biotic CRM are known in the EU28 countries, Norway and Greenland. However, most of them are currently considered as mined out, uneconomic, or not just explored at such detail that a feasibility study can be performed. New exploration activities are mainly taking place in the countries that still have active mines.

Finding a potential ore deposit and investigating it to the knowledge level that is required for the mining decision is a time and money-consuming process that may take even decades. In addition to the financial and technical obstacles, the establishment of new mines is hindered by prolonged permitting procedures, increasing environmental activism, and NIMBY attitudes in most EU28 countries.

The available amount of data related to CRM primary resources in EU28, Norway and Greenland varies immensely between the different countries. Reliable data for most commodities resources is generally very sparse and new data generated by exploration and mining companies is not collected in most member states, excluding the Nordic countries.

In this frame, the main issues to be addressed for the sustainable supply of primary CRM in Europe are:

- Enhancement of exploration activities towards the identification of raw materials resources with potentially economic concentrations in CRM within the European bedrock;
- Development of innovative technologies addressing exploration of CRM to discover new potential deposits;
- Inventory of CRM composition and volume characteristics in the mineral resources from primary ore deposits;
- Identification and data collection of known CRM occurrences and their evaluation in terms of current technical and economical constraints;
- Adapting mining technology to allow the exploitation of smaller and lower-grade deposits with increased complexity.

- Development of innovative technologies with reduced energy consumption and environmental impact to refine low grade ores and materials containing CRM;
- Development of innovative technologies to extract all valuable metals from currently-mined ores and recycled materials, including minor elements that are commonly now rejected;
- Development of the technologies adjusted to the properties of the processed CRM to increase extraction efficiency and metal recoveries.

## SECONDARY RESOURCES

From the secondary resources point of view, several CRM can be supplied from: (i) mineral-based resources (e.g. mining wastes, processing tailings); (ii) non-mineral based secondary resources, particularly industrial wastes and fabrication scraps (or new scrap), which are recycled at source; and (iii) EoL products (post-consumer scrap).

### MINERAL-BASED RESOURCES

The main challenges related to supply of secondary CRM from mineral-based wastes, e.g. mining waste, processing tailings, in Europe are:

- Inventory of CRM composition and volumes in mineral-based wastes, such as mining dumps and tailings;
- Inventory of CRM compositions and volumes in mineral processing and metallurgical wastes and slags;
- Innovations in the recovery of CRM as by-products from current primary resources processing;
- Innovations in the recovery of CRM from mine wastes, processing and metallurgical solid and liquid wastes; emphasis on the development of methods of extracting metals and other valuable products from heterogeneous secondary sources;
- Development on innovative technologies to decrease the high losses of CRM during pre-processing, beneficiation and the impurities in the residue that degrade its quality.

### NON MINERAL-BASED RESOURCES

A sustainable supply of mineral products and metals for European industry requires more efficient and rational consumption, enhanced substitution and improved recycling. Recycling is mandatory to secure the access to raw materials, now and in the future. Metals are in principle infinitely recyclable without a degradation of their pristine quality. However, recycling becomes much more difficult with increasing product complexity. Many metals are dissipated during product use, and contamination and dilution both lead to economic challenges during recycling.

In general, recycling of manufacturing wastes (e.g. new scrap) is in many cases less complicated than that of post-consumer wastes (e.g. EoL products). Nowadays, recycling is mainly managed by private companies and there are usually no requirements to publish detailed information on the quality and composition of recycled materials.

Based on the JRC background report on Critical raw materials and the circular economy, published by the EC DG Growth in December 2017, a good measure of the circular use of CRMs is the contribution of recycling to meeting the materials demand in the EU. For this, the end-of-life recycling input rate (EOL-RIR) measures how much of the total material input into the production system comes from recycling of 'old scrap' (i.e. post-consumer scrap).

Although several CRMs have high recycling potential, and despite the encouragement from governments to move towards a circular economy, the EOL-RIR of CRMs is generally low. A few CRMs, namely Antimony, Vanadium, Tungsten, Cobalt have a high recycling input rate as the collection rate at end-of-life is high. Some other CRMs have a good rate of recycling at end-of-life (e.g. recycling rates for PGMs reaches up to 95 % for industrial catalysts and 50-60 % for automotive catalysts) but this gives a contribution that is largely insufficient to meet the growing demand and thus the recycling input rate is low (e.g. 14 % for PGMs).

Particularly, the focus regarding CRM is on EoL products and components containing a high mass fraction of CRM, such as laptops and mobile phones. For many other applications, there are very few studies or other publications which include reliable data on concentrations. The results obtained by previous projects addressing CRM secondary sources, such as ProSUM and MSP-REFRAM, show that there are still significant gaps concerning the information on the CRM content in EoL products, and thus their potential recyclability. Currently, only one official, publicly available database containing information on CRM content in products has been identified, the Urban Mine Platform, which became available very recently (<http://www.urbanmineplatform.eu/homepage>).

Main technological challenges today are:

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- So called ‘metallurgical challenges’, that they are related to finding a product and material groups with the highest potential for high-grade recovery of the CRM that are largely lost today (e.g. indium, gallium, germanium, tantalum, rare earth elements).
- It is technically relatively easy to recycle base metals from simple products, but with increasing product complexity, metal heterogeneity, and recycling of trace components such as CRM, recycling becomes much more difficult. Innovative recycling technologies for CRM from complex products have to be developed in order to improve the recovery efficiency of materials.
- Development of innovative recycling technologies from complex products in order to improve the efficiency of material production and use throughout the whole supply chain up to the moment when waste becomes the resource needed by another process (product manufacturing; product distribution and use; end-of-life collection and logistics; end-of-life pre-processing) (e.g. redesign of manufacturing to facilitate recycling, collection and disassembly).

## CRM SUBSTITUTION

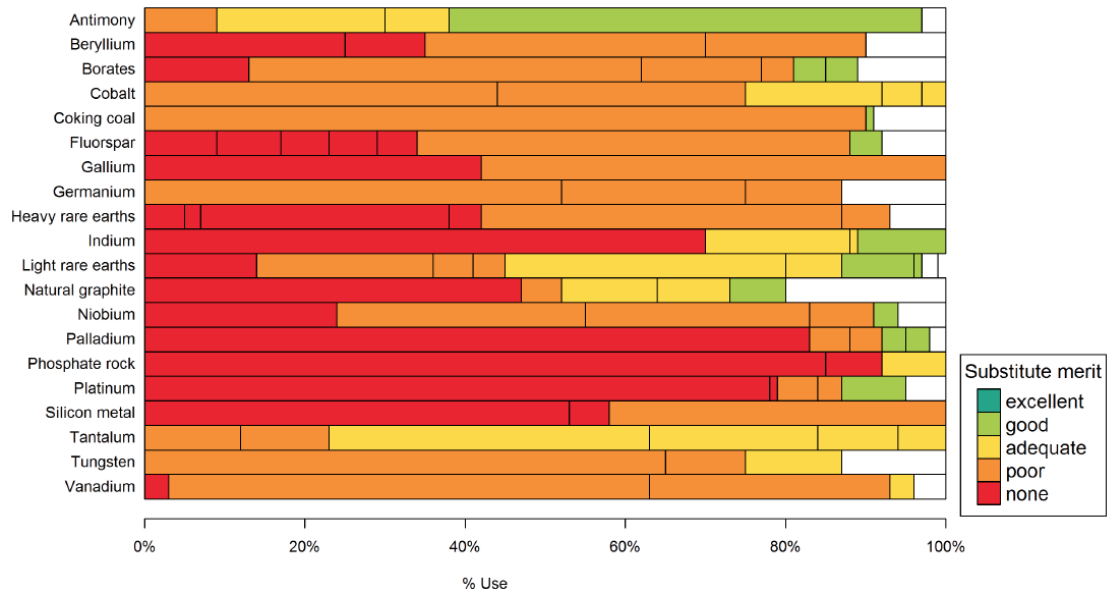
Substitution in the context of raw material criticality refers to the ability to achieve essentially the same function in a product or service by other means using alternative materials. In simple terms, the availability of suitable substitutes can be seen as a reasonable way to avoid a “no-build” situation, in which particular products (and services requiring these products) cannot be delivered because of a bottleneck in raw material supply.

These alternative materials can provide an equivalent function and although often the best option is discussed according to the application or sector, different ways of evaluating it arise. However, the importance of substitution in criticality seems unquestionable. For example, as already has been discussed throughout this project, and also during the evaluation of seminal criticality of the NRC (2008), the availability of substitutes is considered as a “key concept” to determine the importance of a raw material for a particular application. Moreover, the EC considers the lack of viable substitutes as a defining characteristic of criticality.

The diagram below illustrates the summary of 20 individual, detailed CRM substitution profiles completed within SCRREEN. A significant fraction of CRM demand is for

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applications where they play a key function not currently attainable by other means, or without being detrimental to competitiveness.



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## DELIVERABLE 6.4:

### ANNEX: ROADMAP AND INNOVATION PATHWAYS FOR TECHNOLOGY DEVELOPMENT IN CRMS

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## SUMMARY

The document presents the current situation of CRMs in respect of their demand and applications, their production by primary and secondary resources and the substitution perspectives. After the detailed description, the most exploitable CRMs in the European market are distinguished according to a number of indicators including;

- A forecast of demand trend and future applications that potentially commercialized in short and long term
- The existence of notable primary resources in EU-27 plus Norway
- The recovery yield, energy consumption and environmental impact in case of extraction by European primary resources and scraps
- The existence of innovative processes tested at laboratory, pilot or industrial scale

The technological and non-technological barriers which impede the commercialization of novel processing routes and the development of non-critical alternative materials, are stressed out and respective solutions are proposed.

## ROADMAP AND INNOVATION PATHWAYS FOR TECHNOLOGY DEVELOPEMNT IN CRMS

### ANTIMONY

#### **Main Uses**

The main applications for antimony are as a flame retardant and in the manufacture of lead-acid batteries. It has also minor uses in the production of plastics, glass and pigments.

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## Future Demand and trends

The demand for antimony is likely to increase in the coming years. Sb compounds are effective as flame retardant and their use in this application is likely to continue. The Sb demand for this application can be also driven by the adoption of more strict fire regulations. Moreover, Sb use in glass panes for solar cells is expected to grow. Possible decline in its use might be experienced in the long term, since it is often used together with halogenated hydrocarbons or lead.

## Primary production

### Primary resources

Antimony deposits are reported to exist in various EU countries including Austria, Bulgaria, Finland, Sweden, France, Greenland, Italy. However, antimony ores and concentrates are neither mined nor processed in Europe, therefore EU is 100% reliant on their import. Although some activity may take place in the EU mainly in Portugal, more information could not be found. However, EU does produce antimony trioxide (ATO) from unwrought metal, but the raw material must be mostly imported and partially comes from secondary resources (scrap lead-acid batteries).

### Primary Extraction Pathways

The mineral processing of mined ores is a rather tedious activity, comprising crushing, sorting (including sometimes hand sorting, e.g. in Chinese mining companies), grinding and physical separation techniques, such as gravity separation and flotation. This latter produces upgraded concentrates with Sb concentrations varying from above 5 to about 60 wt.%, leaving behind tailings with about 0.2 wt.% Sb, that should be landfilled according to local environmental law. Research on improving the flotation efficiency in different Sb deposits types has been carried out with promising results.

For further processing the upgraded antimony concentrates, either pyrometallurgical or hydrometallurgical methods are applied depending on the Sb content of the concentrates.

Generally, the concentrates of sulphidic type with 5-25% Sb content (lowest grade) are volatilized to raw  $Sb_2O_3$ ; the medium grade (25-40% Sb content) are smelted in blast furnace; and the high-grade concentrates (45-60% Sb content) are processed by liquation or reduction with iron (so called iron precipitation).

Hydrometallurgical methods are useful for processing all types of Sb concentrates. Generally, these methods comprise two-stage leaching followed by electrowinning. Only two lixiviant

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systems used for leaching of antimonial charges are currently available: alkaline sulphide and acid chloride, whereas the former predominates. Some innovative techniques are under development for the treatment of Au-Sb concentrates with good extraction yields for both metals.

## **Secondary Resources**

### Mine and Metallurgical Wastes

Mine and metallurgical wastes containing antimony arise from the production of lead, copper, gold and antimony. These wastes have different Sb concentrations and present a potential for recovery. However, most of this potential lies outside the EU as primary Sb production takes place outside the EU.

### Scraps

The most significant Sb containing scraps are: (1) flame retardant products containing Sb such as plastics, construction materials, electronics, textiles and coatings; (2) EoL materials such as ammunition, lead-acid batteries and other alloys; and (3) various types of glasses. A large share of primary Sb is used in flame retardant plastics, which are mainly used in electronic equipment. Sb is commercially recovered from electronic waste through pyrometallurgical techniques. Municipal solid waste ashes could be another possible source for Sb recovery, although more research is needed in respect to the chemical treatment of this kind of residue. In Sweden, a dedicated niche market has been set-up which includes the closed-loop recycling of metal oxide varistors for the recovery of zinc, antimony and other metals such as bismuth. In the case of lead-acid batteries, a large-scale close-loop recycling scheme already exists where secondary antimonial lead is fully recovered.

## **Substitution**

According to USGS Minerals Yearbook, selected organic compounds and hydrated aluminium oxide are substitutes as flame retardants. Chromium, tin, titanium, zinc, and zirconium compounds substitute for antimony chemicals in enamels, paint, and pigments. Combinations of calcium, copper, selenium, sulphur, and tin are substitutes for alloys in lead-acid batteries. The main technological barriers hindering the use of substitutes for antimony is the lower performance and higher cost of the new material. Another important, non-technological, barrier is the negative environmental, health and safety properties connected with substitutes. Solutions for those barriers are often difficult to find. It is suggested to search for a different substitute that does not compromise the performance and is not harmful to the

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environment. The incentive for antimony substitution in main applications is considered moderate from technical and economical perspective.

## BARYTE

### Main Uses

The mineral baryte, barium sulphate, is used as a filler additive in rubber, paint, ceramics, paper, plastics, glass and high-density concrete and as plaster weighting agent in oil and gas well drilling fluids. About 69-77% of the globally produced baryte is used as a weighting agent for drilling fluids in oil and gas exploration to suppress high formation pressures and prevent blowouts. Furthermore, it is also used for the synthesis of barium carbonate which is a component of LED glass for television and computer screens (in cathode ray tubes).

### Future Demand and trends

About 63% of the global baryte production is taking place in China and India. The production in China dropped by 25% in 2015 and is expected to further decrease the next years. The fluctuation of oil and gas production will determine the changes in the global baryte market. In EU the total of baryte amount is consumed as weighting agent (in paints, rubber and plastic products), for sound-deadening applications in the automotive sector, in medicine and in ceramic and glasses industries. Baryte demand can potentially be increased in the long term due to its use for the construction of electroceramic and dielectric materials. Despite the development of dielectrics and electroceramics industry, it is currently unclear how these technologies will project into the future the baryte demand.

### Primary production

#### Primary Resources

Baryte deposits are limited in EU member states (minor deposits still exist in Germany, Romania and Greece). Major deposits of the mineral occur in Brazil, Nigeria, Canada, Chile, China, India, Pakistan, Guatemala, Iran, Mexico, Morocco, Peru, Turkey, South Africa and US. In 2015, the production in the EU28 amounted to 178,811 tonnes from Bulgaria, Germany, Italy, Slovakia and the United Kingdom. This was, however, a significant decline compared to the production in the recent past, when production was also recorded in Belgium, France, Greece, Poland, Portugal, Romania and Spain.

#### Primary Extraction Pathways

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Conventional underground methods are used as appropriated to the shape and altitude of the deposit. After crushing and grinding further processing involves the removal of possible contaminants through beneficiation techniques (gravity separation and flotation). Research on the optimization of the flotation stage have been carried out, however, the environmental impact of the alternative processes has been hardly studied.

## **Secondary Resources**

### Mine and Metallurgical Wastes

The existence of significant amounts (28 Mt) of mining tailings containing baryte has been reported in Kremikovtzi mine in Bulgaria. Laboratory tests showed that the beneficiation of these tailing is possible through flotation process. Fluorite, quartz, galena and pyrite consist the main impurity phases. The production of a high quality baryte concentrate with BaSO<sub>4</sub> content over 95% and low Fe (0.82 – 1.52%) content was achieved. The flotation tests is necessary to be upscaled, while alternative enrichment methods (such as optical sorting) should be examined.

### Post-application residues

Baryte is barely re-used or recycled. In drilling projects, baryte is mostly dissipated and only its recovery at the drill site is possible. Recovering drilling muds is often practical and cost-effective and is an environmentally sustainable process. Recycling and reusing the muds can help companies save money on disposal costs and reduce truck traffic besides saving baryte consumption. The use of baryte mud wastes, after their drying, as an aggregate for alternative applications (e.g. roads construction) should be also examined. In most other applications, baryte is not recovered (fillers etc.) and cannot be recycled.

## **Substitution**

Economic deposits of baryte are relatively common and are found in many countries. Although prices have risen substantially in recent years, the commodity remains relatively inexpensive. Thus, it is unlikely that the oil and gas industry will have a need for substitutes in the short term. All the likely substitutes (celestite, hematite, ilmenite, and magnetite) present significant drawbacks. The principal strategic concern with respect to baryte is that adequate supplies are available at low cost in the geographic regions that are currently being explored for oil and gas resources and in geographic regions that will be explored in the future. Laboratory-scale studies have shown that hematite and ilmenite can be used as replacement of baryte in petroleum drilling fluids. Both mineral concentrates with particle size <25 µm present plastic viscosity comparable with the respective value of baryte. The high magnetic

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susceptibility of hematite and ilmenite, reaching the upper limit of acceptable paramagnetism, consists their main disadvantage as additives in drilling fluids. Additionally, a baryte-ilmenite mixture in ratio 1:1 has been successfully tested as an additive in drilling fluids.

## BERYLLIUM

### Main Uses

Lightweight structural components containing beryllium are used in the aerospace, computer, defence, medical, nuclear, and telecommunications industries. EU uses over 56 t/y of beryllium under various chemical compounds. In 2014 USA and Japan were the main Be processors, representing, 75% and 25%, respectively, of the world processing industry.

### Future Demand and trends

According to conservative estimations the beryllium consumption is forecasted to increase with an annual growth of about 2%. Its demand increase is driven by the utilization of beryllium alloys in various crucial applications including electrical and electronic equipment, aerospace and military sectors.

### Primary production

#### Primary Resources

Beryllium is primarily produced from two minerals: bertrandite, which contains about 15% wt, and beryl, which contains up to 5% wt. There is no mine production of beryllium in the EU and no known production of beryllium oxides, hydroxides, unwrought metal or powders. However, there are several beryllium occurrences in various EU countries, but scarce information about them is available. There are known unexploited resources (tonnage data exist) in Finland, France, Norway and Portugal and assumed unexploited resources (no tonnage data) in Denmark, Greenland, Germany and Sweden.

#### Primary Extraction Pathways

No active beryllium mining, beneficiation or metallurgy processes have been identified within the EU. There is an absence of available data concerning potential mining and processing routes for beryllium. Although quite a few of these have been in production at some time, most of them are currently considered as mined out, uneconomic, or not just explored at such detail that a feasibility study can be performed.

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At present the only country who is capable to host a fully integrated beryllium production, from mining to recycling, is USA.

## **Secondary Resources**

### Mine and Metallurgical Wastes

Metallurgical processing of mining and metallurgical wastes aiming to the recovery of beryllium have not been identified within the EU, so there is an absence of available data concerning such processes.

### Scraps

Beryllium-rich scrap is composed by EoL devices containing beryllium alloys. The European industry generates notable amounts of Be-containing scrap (around half of the beryllium input), which is partially sent back to producers outside Europe for reprocessing.

Beryllium-copper is a sustainable material that can be 100% recycled without altering its unique characteristics. NGK BerylCo is the main EU Be recycler, recycling new scrap (beryllium copper) with high recovery rates. Be recycling from EoL products reduces the production energy by 75% in comparison to the production by primary resources. CO<sub>2</sub> equivalent emissions, wastes and waste disposal cost are also decreased.

Be scrap (alloys from aerospace industry) is initially processed via pyrometallurgy in arc furnaces, while elemental Be is recovered after leaching.

Practically all of the waste products generated as furnace drosses, slag, manufacturing process scrap is recovered and recycled through the arc furnace as a valuable source of beryllium. It required less than half the energy to recycle beryllium compared to mining it from the earth and avoids the use of process chemicals such as sulfuric acid and ammonia.

Recycling of old scrap (post-consumer) is reported to be negligible, main barriers are the small size of the components, difficulty of separation, overall low beryllium content per device and the low beryllium content in the copper beryllium alloy (average 1.25 % beryllium).

## **Substitution**

Beryllium is used in numerous applications and in various sectors. Due to its high cost in comparison to other materials, it is used in applications in which its properties are crucial. Some possibilities do exist to substitute beryllium in alloys but this is accompanied by a downgrading of physicochemical properties. Substitution to alternative materials is generally not an option, since the functionality would be lost or the performance would be substantially

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impaired. The substitution of Be alloys seems more complex since almost pure Be is needed to provide unique properties.

## BISMUTH

### Main Uses

Bismuth is a metal mined as a by-product of lead, copper and tungsten. The metal is processed mainly in China, which holds 82% share of global supply. The remaining share of Bi refining belongs to Mexico and Japan, with 11% and 7% share respectively. Bismuth is considered as an “eco-friendly” material. Its main application is in the pharmaceutical and animal-feed industries (62% of total uses for Bi chemicals). Bismuth (III) is also used in nuclear medicine, anticancer, antitumor and antimicrobial studies. Fusible alloys represent the second most important use (28%). Bismuth is notably used as a replacement for more harmful metals (on top of which is lead) in solders. Other uses include metallurgical additives and a number of other industrial applications such as coatings, pigments, and electronics.

### Future Demand and trends

EU is 100% reliant on the import of refined bismuth. Europe’s largest producer of bismuth vanadate ( $\text{BiVO}_4$ ), a pigment used in paints and coatings, is BASF (Germany). However, bismuth is imported by non-EU countries. Geotech Internation B. V. from The Netherlands and Orrion Chemicals are other significant actors. According to market research prediction, global bismuth demand is expected to grow until 2024. This is driven by governments’ regulations to replace lead with bismuth in several applications (paints and coatings, alloys, and electronics). Automotive industry is expected to increase bismuth demand by using it in rust free coatings, clutch pads and brake linings. Moreover, increase in the production of tungsten, which is the main metal mined together with bismuth, is anticipated to impact the growth of Bi supply.

### Primary production

#### Primary Resources

In earth crust bismuth is twice as abundant as gold. The most important ores of bismuth are bismuthinite and bismite. Native bismuth is known from Australia, Bolivia and China. In China and Vietnam, bismuth is a by-product or co-product of tungsten and other metal ores processing. There is no mine production of bismuth within the EU. Several bismuth occurrences have been identified in the EU. However, it is a challenge of locating bismuth occurrences that their exploitation will be economic and competitive with other bismuth producing countries worldwide.

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## Primary Extraction Pathways

Bismuth is produced as a by-product during the metallurgical processing (pyrometallurgy) of other metals such as lead, copper, tin, molybdenum and tungsten, and therefore its production can be seriously affected by the main metals' extraction methods.

## **Secondary Resources**

### Mine and Metallurgical Wastes

Bismuth at various concentrations is contained in metallurgical residues generated in lead, copper and tungsten metallurgy plants. Bismuth has been found in several places in Europe associated with waste rock and mill tailings from the production of tungsten. Abandoned mine tailings across Europe may contain large amounts of bismuth, but it is hard to estimate the concentration. The fate of these hibernating stocks will be determined by whether bismuth extraction from these deposits in combination with other main elements is economically feasible or not.

Increased attention has been given to improving the bismuth recovery efficiency by refining residues or to developing novel techniques to reduce the use of reagents in hydrometallurgical processes i.e. leaching the copper smelter flue dusts using  $H_2SO_4$ -NaCl, recovery of bismuth from the leaching solution with Supported Liquid Membrane (SLM) or Emulsion liquid membrane (ELM).

### Scraps

Scrap sources in Europe are related to WEEE since the quantification of bismuth in steel alloy accumulated as stock in Europe needs further research and the chemical applications are mostly dissipative. Secondary bismuth is currently produced from WEEE by European large copper smelters through dedicated centralized routes. Few data exist on this process thereby leaving quantification to pure assumptions. Novel routes for bismuth recovery from scraps pertain mostly to the processing of WEEE either by pyrometallurgy or hydrometallurgy (pyrolysis under nitrogen atmosphere, vacuum metallurgy separation, separation through evaporation). PCBs are the main focus of current research aimed at extracting bismuth from these sources of WEEE given the replacement of lead by bismuth in PCB solders.

## **Substitution**

Bismuth has very similar properties to antimony and arsenic. Since it is not toxic, it is widely used in pharmaceuticals and cosmetics. Several substitutes were identified. However, there is little knowledge on bismuth substitutability. Bi can replace lead since it is not toxic, yet this

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does not improve its criticality performance. Studies have shown that substituting lead by bismuth-tin alloys is not the best solution to deal with this toxic element.

## BORATES

### Main Uses

Borate minerals (colemanite, kernite, tincal and ulexite) are the primary resource for the production of boric acid [B(OH)<sub>3</sub>] which is used in a wide number of crucial applications including fiberglass, glass in LCD flat panel displays, linings and ceramics for induction furnaces, welding flux by blacksmiths (as borax) etc.

### Future Demand and trends

Borates demand is expected to dramatically increase both in the short and the long term due to the growth of various sectors which are related with the utilization of boric acid or borax, including: frits/ceramics, TFT/LCD for various devices, borosilicate glasses, textile fiberglass, insulation fiberglass and oilfield chemicals.

### Primary production

#### Primary Resources

Borates deposits are associated with volcanic activity and arid, dry climates. The most important world deposits occur in USA and South America. The existence of notable deposits of borate mineral has not been reported in EU27. A significant sedimentary deposit containing jadarite (a complex borate mineral containing Li and Na) has been reported in Serbia (EU candidate country). It has been estimated that the deposit hosts 21 million tonnes of B<sub>2</sub>O<sub>3</sub>.

#### Primary Extraction Pathways

Production of boric acid by colemanite, kernite, tincal and ulexite is well established. Rio Tinto is developing innovative technologies for the extraction of lithium carbonate and boric acid from the Jadar deposit in Serbia. Innovative processes are being tested at small scale in Australia. However, no detailed information is available on these technologies.

### Secondary Resources

#### Scraps

The recycling of borosilicate glasses is problematic as they cannot be mixed with normal glass due to their higher heat resistance and higher melting point. Borosilicate glasses in LCDs are

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contaminated with various elements. The recycling of borosilicate glass is technically feasible in case of EoL PVs, however the operating cost is high.

### **Substitution**

There are no alternative materials that can substitute borates in the manufacture of borosilicate glass suitable for heat resistant cookware, heat resistant glass panels, laboratory ware, LCD screens and solar panels. Moreover, no alternatives have been reported as wool insulation products. The addition of alkali-components instead of boron cause the downgrading of glass physicochemical properties.

## **COBALT**

### **Main Uses**

Cobalt is used in a wide range of applications including; superalloys, electronics, permanent magnets, rechargeable batteries, pigments, catalysts and medical devices. The main producing country is the Democratic Republic of Congo, which accounts for about two-thirds of world production. China, Zambia and Australia follow, with 5, 4 and 4%, respectively. In the EU, 1.4 kt of cobalt concentrates are extracted per year in Finland. A total of around 15 kt/y of cobalt is refined in Finland, Belgium and France using imported cobalt concentrates.

### **Future Demand and trends**

The global Co consumption and demand is expected to significantly increase in the short term due to the expansion of the electric vehicles sector. Co is a crucial element for the construction of permanent magnets and rechargeable batteries for electric and hybrid vehicles. Over 40% of world Co production is consumed for batteries construction (mainly Li-ion and NiMH). This percentage is expected to be increased the next few years taking into account the electric vehicles market growth. The annual growth of cobalt use in rechargeable batteries was about 13% the last decade.

### **Primary production**

#### Primary Resources

The main primary Co reserves in the EU territory exist in Finland, where the metal is currently successfully recovered. Polymetallic nickel sulphides deposits in Scandinavia and nickeliferous laterites in Greece are the major unexploited primary Co reserves in EU.

#### Primary Extraction Pathways

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In Finland, Co is currently successfully recovered by polymetallic Ni-Co-Cu sulphides through various metallurgical routes including bioleaching (Freeport-McMoRan Company) and hydrometallurgy-pyrometallurgy combination (Outokumpu Company).

The effective beneficiation of Ni-Co rich sulphides is a major issue specifically in the case of the relatively medium-small deposits or large deposits with low Co grade in Scandinavia (Sweden and Norway). Flotation consist the most appropriate technique for the beneficiation of polymetallic cobalt rich sulphide ores. However, two major barriers have to be taken into consideration especially in the case of low grade ores: (i) a clean and satisfactory separation of pentlandite (which is the main Co-rich phase) from pyrrhotite and other sulphides is difficult in practice and (ii) talc and other naturally hydrophobic magnesia-bearing minerals present in the ore tend to aggregate with sulphides, resulting in a concentrate exceptionally high in magnesia thus leading to nickel and cobalt losses.

The metallurgical processing of polymetallic rich in Ni-Co-Cu sulphide deposits existing in Sweden and Norway is well established via different processing routes. The main technological barrier in the processing of these ores is mainly related with its beneficiation effectiveness. However, new improved flotation results have been reported in case of Ni-Co-Cu ores.

High-pressure acid leaching with sulphuric acid (HPAL) is the most efficient (yield>90%) method for Co recovery from laterites. Significant limonitic and serpentinitic nickeliferous laterite deposits exist in Greece. However, the major barrier for the recovery of Co from Greek nickeliferous laterites is mainly related with techno-economic data. The above described cobalt recovery process is well designed and successfully applied at laboratory scale. In the case of laterite bioleaching, the most important technological barrier that has to be overcome is the low yield of cobalt extraction (about 40%) during the heap leaching process.

## **Secondary Resources**

### Mine and Metallurgical Wastes

The exploitable Co-containing mining and metallurgical wastes are limited in the EU member states. Moreover, there is an absence of available data concerning their exact deposited amounts and the efforts that have been possibly performed for their processing at commercial scale. The generation of significant amounts (20 t/h) of slags with 0.5% w/w Co content has been reported in Harjavalta (Finland) metallurgy plant (Boliden Company), where nickel sulphides are processed through flash smelting. Unfortunately, there are no available data concerning the processing of this slag and further investigation should be necessary. Unexploited Co-containing copper slags have been deposited in IMI James Bridge secondary metal plant at Walsall, England. A study concerning the recovery of valuable metals from this

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type of slags has been performed. The simultaneous effective extraction of copper and cobalt is necessary for the commercialization of the slag treatment processes. Therefore, as a future investigation, the leaching of Co-containing copper slags with alternative gentle reagents is proposed, while in any case, a detailed identification of similar deposited slag material in EU territory should be performed.

### Scraps

There is a variety of Co-containing scrap materials which, more or less, are currently processed by large EU recycling companies (Umicore Company, Belgium, processes around 350,000 tonnes/y of more than 200 different types of scrap recovering a wide number of metals). Cobalt is mainly industrially recovered by cermets (tungsten carbide – cobalt tools) and catalysts. There is a lack of available data concerning specific gaps and barriers on this recycling process. The main unexploited or low-exploited Co containing scrap components in EU are: (a) the superalloys which mainly are recycled by a limited number of companies in UK; and (b) Li-ion batteries.

Several pyrometallurgical, hydrometallurgical and pyro/hydro metallurgical processes, mostly at laboratory scale, have been developed for the processing of superalloys. Pyrometallurgical processes and more specifically re-smelting and selective oxidation, have been proved problematic and hydrometallurgical processes present a number of disadvantages such as: difficulties in solid-liquid separation, high corrosive environments, elevated consumption of acids.

The recovery of Co, Ni and other critical metals from metal oxide varistors (MOVs) has been performed in lab scale but the recovery of these metals from the resulting cementation mixture needs to be further investigated.

The efficient and environmentally-friendly recycling of Co by spent Li-ion batteries will be possible in the short term due to the generation of large amount of EoL batteries. Cobalt is contained in the cathode of Li-ion batteries as  $\text{LiCoO}_2$ . The Co content in Li-ion batteries is ranged between 5 and 20 wt.%. Innovative processes for spent Li-ion batteries recycling have been tested at laboratory scale and they are based on the: (a) isolation of the cathode material through dismantling followed by its pyrolysis and leaching. Solvent extraction is used for Cu recovery and selective precipitation for Co and Li recovery. Pure metallic Co is finally received by calcination and electrowinning.

### **Substitution**

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Due to its extraordinary properties, cobalt generally has limited replacement options, as the suggested alternative materials present poorer physicochemical properties. More specifically:

Superalloys are developed to perform in extreme conditions. Alloys that have these requirements can be manufactured on a cobalt basis, but they can also be made from nickel and iron. However, to achieve reliability and efficiency in sectors like the aerospace industry, the use of superalloys containing cobalt is crucial.

Cobalt is used as a binder for tungsten carbide (WC) in the production of hard metals or aggregates of reinforcing materials. Although it may be replaced by nickel and iron, their use results in considerable loss of performance. Therefore, cobalt is practically irreplaceable for this application.

In the case of battery applications (portable, mobile), although  $\text{LiCoO}_2$  is the preferred material its replacement by  $\text{LiNiO}_2$  and  $\text{LiMn}_2\text{O}_4$  is potentially possible.

Cobalt is used as a catalyst for the removal of sulphur from petroleum products, in gases such as gasoline, diesel or kerosene. In this case the most suitable substitutes would be the use of ruthenium, molybdenum, nickel and tungsten.

## COKING COAL

### Main Uses

Coking coal is mainly used as raw material to produce metallurgical coke. Metallurgical coke is used in the production of hot metal in the blast furnace, but also in the production of other metals. When producing coke, part of the coking coal is directed to the gas phase. During the gas treatment, by-products as benzene, tar and sulphur is recovered and the gas is used for electricity production. Using the by-products, tap-hole clay and graphite electrodes are produced.

### Future Demand and trends

There are research activities aiming to reduce the dependence on fossil coal in general and coking coal specifically. However, according to World Steel Association, the production of iron via the blast furnace route is dominating the supply for steel production; moreover, it is this route that is expected to mostly increase. Additionally, gas based DRI production is increased, e.g. in India, and in this case the gas used for reduction is produced by coal gasification.

### Primary production

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## Primary Resources

The coking coal used in Europe mainly has its origin in Russia (32.5%), Colombia (23.2%), Australia (15.8%) and USA (14.3%). In Europe hard coals are mainly produced in Poland and Ukraine, but there is some minor production also in UK, Germany, Czech Republic, Spain and Turkey. However, in Europe many mines have been closed. Coking coal production in EU-28 is less than 4.2% of the world production, while the consumption is 8.7%.

## Primary Extraction Pathways

Coking coal is mainly mined and produced outside EU. Barriers exist in the metallurgical step related mainly with a. the optimisation of the coking procedure and b. development of functional additives to the coking coal blend. The innovation lies mainly in the development of the coking coal processing to coke. Moreover, the reduction of the coal ash amount is of importance. Further, licence to operate coking coal mines in Europe should increase the availability of coking coals in Europe.

## **Secondary Resources**

Secondary materials possible to use in the coking coal blend are mainly tailings, by-products generated in the coking plant, screened of coke fines, residues from petroleum industry and waste plastics. However, to increase the possible use of secondary materials there is need for development of methodologies that can enable the use of higher amounts of secondary materials including inert materials. Moreover, the development of alternative coking processes that enables higher pressure during coking should give a new opportunity to the use of secondary materials.

## **GALIUM**

### **Main Uses**

Gallium, an irreplaceable element in electronic applications under the form of gallium arsenide (GaAs), gallium nitride (GaN) or gallium antimony (GaSb), offers excellent electro-chemical properties as a semi-conductor with electron mobility six times higher than silicon. This and other features have pushed gallium use in integrated circuits (ICs) requiring high-performance such as military applications or communications. LED lighting also requires GaN as a semiconductor material to provide for example white light. Moreover, it is used as additive in the production of permanent magnets. Other uses of GaAs comprise integrated

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circuits (ICs), optoelectronic devices, including light emitting diodes (LEDs), laser diodes, photodetectors and copper-indium-gallium-selenium (CIGS) based on thin film solar cells.

### **Future Demand and trends**

It is forecasted that until 2020, the gallium demand will strongly increase by more than 8% annually, thereby showing the second largest demand growth rate in the EU of all classified critical raw materials after niobium, mainly driven by LEDs and solar applications.

### **Primary production**

#### Primary Resources

Gallium is a silvery-white, soft metal, which is one of the rarer elements in the earth crust. It is mainly found in enriched amounts suitable for economical use in ores of aluminum (bauxite) due to gallium's chemical similarity to aluminum, but also in ores of zinc (sphalerite) and in the fly ash of coal. There are no notable occurrences of Ga in EU.

#### Primary Extraction Pathways

Gallium is produced as a by-product through the aluminium metallurgy. At Bayer process, Ga accumulates in the sodium hydroxide liquor from which it can be extracted through a variety of methods. The most effective is the use of ion-exchange resin. The extraction efficiencies mainly depend on the original concentration in the feed bauxite. At a typical feed concentration of 50 ppm, only 15% of the contained Ga can be extracted. Ga is finally received and refined through electrolysis. Ga is also industrially produced as a by-product in zinc extractive metallurgy.

### **Secondary Resources**

#### Mine and Metallurgical Wastes

Ga presence has been reported in various metallurgical wastes such as in the slags of Zn refinery plants, Cu-Pb slags, coal fly ashes and brines of desalination systems. Nevertheless, Ga recovery by these resources is not economically sustainable according to the current data due to their low Ga concentration and the complexity of the required extraction processes.

#### Scraps

The recovery of gallium from Ga-based PVs is currently not economically sustainable. A detailed techno-economic analysis has shown that recycled gallium costs are still much higher

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than current Ga market costs. This situation will be potentially reversed in the long term due to the forecasted growth of the Ga-based PVs.

### **Substitution**

Due to its extraordinary electro-chemical properties, Ga is broadly used in a multitude of electronic applications. To date, no replacement exists for the large use of GaAs integrated circuits, although SiGe alternatives have been reported to be a potential replacement of GaAs ICs in some applications. Another important application is LED lighting, where Ga is widely used under the form of GaN and InGaN. OLED is an emerging technology with the capacity to replace, in the long-term, semiconductor-based LED. The uptake of OLED as a replacement technology for LED will reduce the demand for gallium, germanium and phosphorus elements given that OLED components are organic based. OLED still has a 5-10 year development curve to pair with LED in terms of price, performance and lifespan. Therefore, there are no concrete replacements for Ga for its major applications or the use of other CRMs as alternatives is required.

## **GERMANIUM**

### **Main Uses**

Germanium is applied in a wide range of electronics applications such as infrared optics, fibre optics, PV panels in space. It is also used as catalyst in the manufacturing of PET polymer. The unique optical properties of the element, mainly its excellent transparency to infra-red (IR), make it suitable for applications dependent of IR wavelength. Concisely, the major end uses for Ge worldwide are estimated to be fibre-optics (30%), infrared optics (25%), polymerisation catalysts (25%), electronics and solar electric applications (15%) and phosphors (5%).

### **Future Demand and trends**

Germanium demand is forecasted to increase until 2026 due to the growth of optical fibres and solar installations market. The use of Ge substrates in the production of solar energy has increased recently due to the advantages of germanium-containing semiconductors such as, low cost and increased efficiency. China, Russia, and the U.S.A. are the leading producers of germanium, therefore EU is exclusively depended on imports from non-EU countries.

### **Primary production**

#### Primary Resources

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Germanium is a silvery-white, hard, brittle n-type semiconductor. The primary Ge source is as by-product of zinc and copper ore mining where zinc is associated with sphalerite, as well as from coal and coal combustion fly ashes.

### Primary Extraction Pathways

Multiple stages are used for the production of various germanium compounds and metals that are needed for specific applications. Germanium sulphide (as an inclusion in sphalerite) is oxidised via oxidising roasting. Subsequently, germanium oxide is chlorinated with chlorine gas to germanium tetrachloride ( $\text{GeCl}_4$ ), which is a colourless liquid directly used as a raw material for the production of fibre-optic cable. Hydrolysis and drying of germanium tetrachloride produces germanium dioxide ( $\text{GeO}_2$ ), which is a white powder, used to manufacture certain types of optical lenses and as a catalyst in the production of plastic polyethylene terephthalate (PET) resins. Germanium dioxide is reduced with hydrogen to produce a germanium metal powder, which is subsequently melted and casted into bars. These bars, after refining, produce extremely pure germanium metal.

### **Secondary Resources**

#### Mine and Metallurgical Wastes

Ge is contained at various concentrations in slags of Zn refinery plants, Cu-Pb slags, coal fly ashes and brines of desalination systems. Conventional processes to recover Ge from coal fly ashes are difficult in regards to operating cost and environmental effect, while the recovery yield is low. Moreover, stabilisation of the residual sludge is required in order to prevent the release of toxic trace elements to the environment. No Ge production from Zn plant residues has been reported in EU.

#### Scraps

Around 30% of Ge is estimated to be globally supplied by recycling, mostly from scrap generated during the manufacture of fibre-optic cables and infrared optics. Recycling of Ge from EoL is a long term matter, as fibre-optic cables present a high lifetime. A limited number of companies, as for example Umicore (Belgium), Recylex (France) and Chemical and Technical developments Ltd (UK), recover Ge through the recycling of EoL products. Technical processes are confidential, and no data about the Ge production from recycling is available. The technical processes developed at lab scale to recover Ge are based on leaching with conventional reagents and extractants. To make the processes “greener and cheaper”, thus encouraging the implementation of such technologies for example by the coal and zinc EU industries, and to be able to extract the low concentrations of Ge existing in EoL products, new simple,

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selective and flexible methods must be developed. In general, studies for Ge recovery from secondary sources are limited and only performed (except for one case) at lab scale. High recovery rates have been obtained at lab scale, however no process upscaling nor testing in an industry environment has been performed. Moreover, there is a lack of products valorisation economic and market analyses.

### **Substitution**

Germanium offers excellent optic properties and can be used in many optic applications due to these properties. Replacement of germanium in some applications, such as in solar cells for satellites or as a catalyst for polymerisation, still requires further research. In IR optics, no other element and/or combination of elements offers a similar performance in a wide range of applications. Different combinations for different applications may be the answer for Ge replacement in the long term. Fibre optics based on doping silicon with phosphorous pentoxide can reach high performance in terms of very low attenuation, thus offering full replacement to germanosilicate fibres. Research and development activities must be coordinated to find different replacements for germanium in all fields of application.

## **HAFNIUM**

### **Main uses**

Hafnium is mainly used for the construction of control rods for nuclear reactors due to the ability of several hafnium isotopes nuclei to absorb multiple neutrons. It is also used as a component in superalloys with iron, titanium, niobium and tantalum. These specific superalloys are used in the aircraft industry.

### **Future demand and trends**

According to hafnium market estimations, Hf demand is expected to expand at a moderate growth rate by 2025. However, the demand could be finally higher than “moderate” due to (a) the difficulties in production of pure hafnium, and (b) the increase of hafnium consumption in the nuclear reactors in USA. The separation of the pair Zr-Hf is difficult due to the similarity of their chemical properties, such as atomic radius, ionic radius and electronegativity, yet the presence of zirconium impurities in hafnium impair its physical properties. The nuclear energy sector is not expected to grow in EU27, however the construction of new nuclear reactors in USA will possibly affect the price of hafnium.

### **Primary production**

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## Primary resources

There are no hafnium mines. Hafnium is found as a trace element in zirconium minerals, rutile and ilmenite. No significant exploitable Hf deposits have been reported in EU27.

## Primary extraction pathways

Heavy mineral sands consist the primary sources of Hf which are mined through simple open-pit methods. The production of hafnium-free zirconium is the main source for hafnium. About half of the hafnium metal quantity manufactured is produced as a by-product of zirconium refinement process for nuclear grade (similar chemical properties but almost opposite physical properties).

Several commercial techniques for the separation of zirconium and hafnium exist. Hafnium (IV) is extracted as chloride. The purified hafnium (IV) chloride is converted to its elemental form by metallothermic reduction according to the Kroll process. Studies to reduce extractive distillation and the use of the MIBK process are in progress. Apart from the fuel consumption, the radioelement concentration and the use of MIBK, there is no environmental impact specific to hafnium.

## **Secondary resources**

### Mine and metallurgical wastes

There are no Hf-containing mine and metallurgical wastes in EU, as the Hf production from primary resources is not taking place.

### Scraps

Recycling of hafnium is very low in Europe, the end-of-life recycling input rate being estimated by EU to 1% in 2017. This is most probably due to its contamination when used in the nuclear industry and to its low percentage content when used in superalloys. The recovery of Hf contained in scraps and wastes in EU cannot be accurately identified as it has not been implemented at commercial or research scale. Electron Beam Melting and Refining (EBMR) method, which is industrially applied for melting and metal purification, could be proposed as a possible method for recycling hafnium-containing scraps.

## **Substitution**

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Hafnium is used in cutting-edge applications due to its extraordinary physicochemical characteristics. Various raw materials have been identified as efficient substitutes in two major Hf applications; superalloys and nuclear reactor components. Concerning the physical metallurgy sector, it has been proved that niobium and tantalum and cobalt can replace Hf in superalloys. In nuclear applications, which require a high neutron absorption capability, boron carbide, BC<sub>4</sub>, and Ag-In-Cd alloys are the most important substitution candidates. Nevertheless, all the above mentioned elements consist critical raw materials. Thus, the barriers for substitution are non-technical and they are related with supply/demand dynamics of the substitute CRM.

## INDIUM

### Main Uses

Indium (III) oxide and indium tin oxide (ITO) are used as a transparent conductive coatings on glass substrates in electroluminescent panels. Indium tin oxide is also used as a light filter in low-pressure sodium-vapour lamps. The semiconductors InGaN and InGaP are used in light-emitting diodes (LEDs) and laser diodes. Indium wire is used as a vacuum seal and a thermal conductor in cryogenics.

### Future Demand and trends

Indium demand is expected to grow from 30 to 50% by 2020, together with ITO demand for LED technology, LCD panels and emerging displays technology using In-Ga-Zn Oxide. Demand for thin film solar cells has started declining against earlier estimations expecting growth. However, it is believed that there is enough supply to support the market growth. The supply could be further improved by recycling activities and higher recovery during ore processing. Indium is also used in multiple new technologies, such as OLED (Organic Light-Emitting Diode). In this technology CRMs, except for indium, are substituted by organic compounds. Indium is expected to penetrate the lighting market after 2025, which will lead to very limited use of phosphors and CRMs for lighting.

### Primary production

#### Primary Resources

Indium is produced as a by-product of zinc, mostly in China, South Korea and Japan. Production in Europe reaches 48t and takes place in Belgium, France and Germany from secondary resources. No notable primary indium resources have been reported in EU. Indium refined

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within the EU accounts for about 9% of the global production. Secondary resources play an important role in indium supply, since about 50-60% of the total production comes from recycling. More than half of indium production is used as Indium-Tin Oxide (ITO) for conductive layers of liquid-crystal displays.

### Primary Extraction Pathways

Indium is produced as a by-product mainly during the processing of zinc sulphide ores (sphalerite). Minor amounts are also extracted from sulphidic copper ores. During the roast-leach-electrowinning process of zinc smelting, indium accumulates in the iron-rich residues. From these, it can be extracted in different ways. It may also be recovered directly from the process solutions. Its purification is performed by electrolysis.

### **Secondary Resources**

#### Mine and Metallurgical Wastes

Secondary indium from mine and metallurgical wastes can be mainly recovered through hydrometallurgical processes (leaching of dusts, fumes and slags resulting from zinc and lead smelting processes). Since the production of primary indium is highly dependent on other major metals like zinc, lead and copper, the availability of secondary indium from this processing route depends largely on the demand of these major metals. One of the pointed sources for future availability of secondary indium are the current hibernating stocks resulting from the landfilling of mining/smelting/refining residues. Nystart in France has the capacity to produce 70 t/y, while in Belgium, Umicore produces indium from residues of the lead-copper smelting operation and has a capacity of 30 t/y. Nevertheless, the market price of indium seems to be an important factor for the recovery of indium from hibernating stocks rich in refining/mining residues.

#### Scraps

One of the main secondary indium resources are new scraps from the production of Indium-Tin Oxide (ITO) coating for flat-panel displays (FPD). However, since the production of these electronic displays takes place in Asia, most of secondary recovery of indium from ITO takes place there. During the production, a substantial part of sputtered indium cannot be fully imbedded into the semiconductor layer and it is directly recycled in-house. The same happens in the manufacture of thin-film solar PV cells.

Indium is largely available from EoL scraps and there is enough material in stock and in EoL materials to close the gap of primary demand. Nevertheless, the dispersion of the metal in a

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multitude of products combined with the lack of policies have as a result the loss of the metal in landfills or as tramp element in metals recycling.

New processing routes (vacuum pyrolysis followed by vacuum-chlorination and leaching of non-crushed ITO glass with sulphuric acid) have been tested at laboratory scale. These processing routes could be promising for indium supply from this WEEE source, but they have to be up scaled and tested at industrial conditions, while further analysis of the full life-cycle impacts is also required.

### **Substitution**

There are limited choices for indium replacement by alternative materials. Most of the substitutes are still under development and are not yet industrially available. Currently, materials used instead of indium present lower performances, in particular lower specific electric conductivity. Aluminium doped zinc oxide (AZO) and fluorine doped tin oxide have been proposed as replacements for indium-tin oxide. Carbon nanotubes have been proposed as indium replacement in electronics, field emission devices, electrochemical devices (supercapacitors). Nevertheless, all these materials have been tested only at laboratory scale.

## **MAGNESIUM**

### **Main uses**

Magnesium consists the third most commonly applied structural metal, following iron and aluminium. The importance of Mg is strictly related to its properties, in particular mechanical and low density, 1.78 g/cm<sup>3</sup>. It is largely used for the production of components in the following sectors: transport, steel industry and electronics, medical; moreover, it is used as reducing agent for obtaining pure elements as Be, Hf, Ur, Zr and Ti from their metal halides. In the case of the transport sector, it is largely used in aircrafts, trains and automobiles, while it is also used for the realization of chassis for notebook, tables and phones. In the steel production, which adsorbs about 15% of Mg consumption in the world, it is used as desulphurisation agent.

### **Future demand and trends**

Magnesium demand is expected to increase in the short term due to its globally increasing consumption in the automotive industry. According to data provided by Roskill the global growth in the magnesium market is expected to exceed 3% per year reaching 1.2 Mt by 2020. The growth of Mg market is difficult to be estimated in the long term as innovative

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magnesium-containing nanomaterials is possible to be applied at a commercial level (e.g. the magnesium infused silicon carbide nanoparticles). This concrete nanomaterial presents extraordinary mechanical properties and can potentially be used for the construction of lighter airplanes and vehicles.

## **Primary production**

### Primary resources

Significant magnesite deposits have been reported in three EU countries: a. Slovakia (Jelgava) where the largest deposit in EU occurs with 120 Mt reserves of magnesite; b. Greece, where 270 Mt of magnesite reserves exist in more than 10 magnesite deposits together with Mg ores related to lateritic deposits; c. Spain, with estimated magnesite reserved of about 35 Mt.

Metallic Mg is not produced in EU mainly due to the existing strict environmental policy framework. The world production of metallic Mg was approximately 1,100 kt in 2017, with the largest amount being produced in China (930 kt) and Russia (60 kt).

### Primary extraction pathways

Magnesium is extracted from calcined magnesite usually via the Pidgeon metallurgical process using ferrosilicon as a reducing agent. Alternative green metallurgical techniques have been proposed instead of the Pidgeon process and been tested at laboratory and pilot scale: (a) Carbothermal reduction of MgO under vacuum. Metallic magnesium is formed under gaseous form and subsequently it is received after condensation. Difficulties concerning the separation between the gaseous Mg and the produced CO have been reported; (b) The production of magnesium titanates via the sintering of magnesium and titanium oxides using a pilot scale solar furnace; (c) The production of nanostructured powders of magnesium and aluminum by carbothermal reduction of magnesia and alumina at 1000–1600 Pa using concentrated solar energy. The synthesis of 6061 type aluminum alloy containing magnesium and silicon has been also proposed through the use of solar energy.

The above efforts should be continued taking into consideration the existence of significant aluminum and magnesium primary resources in Europe.

## **Secondary resources**

### Mine and metallurgical wastes

The existence of significant amounts magnesite wastes (few million tonnes in Greece and Slovakia), produced after the beneficiation (mainly flotation tailings) step, have been reported. This particular wastes contains a number of impurities, such as: quartz, iron oxides,

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Al<sub>2</sub>O<sub>3</sub> and calcite with a total concentration around 10 wt.%. The enrichment/purification of the magnesite waste is technologically difficult due to its fine particle size (< 4 mm). The optical sorting separation methods has been tested at laboratory scale, for the beneficiation of the magnesite tailings, with promising results, however further research is needed for their optimisation and pilot scale testing.

During metallurgical smelting processes, as the production of steels, the removal of sulphur is necessary; this is achieved with the use of Mg, mainly deriving from primary resources. Mg containing slags are generally not recovered probably due to transport costs. About 41% of slags from desulphurisation processes are landfilled. These slags, after suitable treatment, can be used for other applications, as building materials.

Research on Mg recovery from coal fly ash and mine tailings is currently performed by non-European countries (e.g. Australia, Canada)

### Scraps

The Mg EoL-RIR (end-of-life recycling-input-rate, measuring the percentage of Mg coming from scrap in the total amount of Mg entering the EU) is only 7%, because of the dispersive nature of any magnesium applications, according to IMA, as well as of low efficient collection and recycling routes.

Suitable secondary Mg sources are first of all clean scrap from die-casting processes, while other classes of scraps could be sent to the steel industry for the desulphurisation process. In many cases after sorting the scrap requires a cleaning process. Some plants for magnesium die-casting processing own a recycling centre (Volkswagen). Shredded scrap from ELV belongs to class 8, which can be recycled with difficulty, but the expected increase of Mg use in transport sector and the directives on car recovery and recycling (target 85%) will probably facilitate the reduction of landfilled Mg containing wastes.

Magnesium contained in scrap composed by vehicle and aeroplane components is currently commercially recycled in EU by simple pyrometallurgical/refining processes. Significant amounts of Mg are recycled in Volkswagen Kassel plant in Germany.

### **Substitution**

Magnesium replacement in the short term can be attempted only in the case of non-metallic products. More specifically, magnesite used as additive in phosphate cements can be partially substituted by alumina and metakaolin. Furthermore, the possibility of magnesite substitution in refractories should be examined and documented in future studies.

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## NATURAL GRAPHITE

### Main uses

Natural graphite (NG) is mainly used for the construction of refractories, as electrodes in batteries, as a reducing agent in steelmaking industry, as brake linings and as a component in lubricants.

### Future demand and trends

At the moment, the higher percentage (about 30%) of globally produced NG is consumed in the refractories sector. The NG demand from this sector might be increased. In the near future, NG demand will be strongly related to the lithium-ion battery market as NG is used as an anode in this type of batteries. According to Roskill, the NG demand for battery applications is expected to grow by 17-23% per year until 2027.

### Primary production

#### Primary resources

Natural graphite is mainly mined and produced in China (61%), India (14%) and Brazil (7%). In EU, minor NG reserves occur in Norway, Finland, Sweden, Czech Republic and Slovakia. The NG production in EU is less than 1% of the total demand.

#### Primary extraction pathways

The mining and the beneficiation of the extracted natural graphite is well established and there is no significant room for further optimisation.

### Secondary resources

#### Mine and metallurgical wastes

NG at high concentrations remains in mining wastes and beneficiation residues, however it has been estimated that graphite recovery via further beneficiation (e.g. comminution) will downsize the graphite flake and thus decrease the economic value of the product.

#### Scraps

Graphite-containing refractory (especially the MgO-C refractory) and Li-ion batteries are identified as two sources of secondary graphite, which possess high recycling potential. With respect to graphite-containing refractory, technologies to recycle the graphite-containing refractory as slag former, as product and even as separated graphite exist. However, due to

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the difficulties of sorting and cleaning the spent refractory, the recycling rate of graphite at the moment is still very low. According to literature, remanufactured bricks containing up to 30% recycled spent refractory present almost identical properties as low-grade MgO-C bricks.

With respect to Li-ion batteries, different recycling technologies are being developed with focus mainly on the valuable materials (Co, Ni, Mn, Li, etc.); graphite can be recycled as well, however, there is no economic recycling/refining process or the economic incentive for recycling is low. However, emphasis should be given to graphite recovery from Li-ion spent batteries due to the rapid generation of this type of scrap. NG recovery from spent Li-ion batteries is possible in case of a hydrometallurgical recycling approach (multi-element extraction).

### **Substitution**

Synthetic graphite consists the only substitute of NG presenting more advanced physicochemical properties. Nevertheless, the entire substitution is problematic as the production of synthetic graphite presents a higher cost and a higher environmental impact.

## **NIOBIUM/TANTALUM**

### **Main uses**

Niobium and tantalum are transition metals. They have similar physical and chemical properties and are usually found as solid solutions in the same type of mineral deposits.

Niobium, a grain refiner and precipitation hardener, enhances the mechanical strength, toughness, high temperature strength, and corrosion resistance of steel. This makes Nb essential to the automotive, construction and energy industries.

Tantalum is used in different areas such as electronics, mechanical, aerospace, chemical machinery, process industry, vacuum techniques, optic and other applications. One of its main uses is in the production of electronic components, mainly tantalum capacitors. Alloyed with other metals, Ta is also used in making carbide cutting tools for metalworking and in the production of superalloys.

### **Future Demand and trends**

The Nb market is expected to increase with a rate approaching 6% during the period of 2019-2024. Major factors driving the demand are the increased consumption of the metal in structural steel and extensive utilization of Nb-based alloys in manufacturing aircraft engines.

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Niobium, is produced by a limited number of companies outside EU, therefore its supply is problematic. The market for tantalum is also expected to grow with a rate of around 6% during the same period. Major factors driving the Ta consumption are the growth of the electronic industry and the extensive usage of Ta alloys in aviation and gas turbines.

## **Primary production**

### Primary Resources

The main producers of Tantalum are Rwanda and Congo, while of Niobium are Brazil and Canada. The main reserves of Ta are in Australia (49%) and Brazil (26%) and of Nb are in Brazil (95%). The contribution of Europe in the world production of tantalum concentrate is very low. The most important EU deposits are located in Finland, Greenland, Bulgaria and France, but there is a lack of more detailed information.

### Primary Extraction Pathways

The extraction process of Ta/Nb from ores is simple and easy, although it generates a significant amount of residues. The process involves leaching with strong acids (such as hydrofluoric acid together with sulphuric or hydrochloric acid) followed by solvent extraction. The technological barriers are mainly related with: a. the effectiveness of beneficiation; b. the utilization of toxic reagents applied both in flotation and leaching techniques; and c. the low grade of Ta/Nb in deposits.

## **Secondary resources**

The secondary resources identified for Nb and Ta are: Tin slags; mine tailings; urban mines and manufacturing residues; super alloys; capacitors with a Ta anode; spent catalysts; cemented carbide and e-wastes.

There is a limited number of metallurgical residues containing Ta-Nb. The presence of these metals has been detected mainly in tin slags. There are no sufficient data concerning the presence of Ta-Nb-rich mining and metallurgical residues in EU.

There is a high potential for producing Ta and Nb in EU from secondary sources, for Ta mainly from electronic EOL devices, and for Nb from Nb-containing steels. Technology exists for Nb/Ta recover from tin slags and sludges, mine tailings, urban mines and manufacturing residues, cemented carbides, lump Ta wastes, Ta scraps, super alloys and capacitors, but research is needed to make the processes more environmentally friendly and cost-efficient. In this line, there are many new methods currently studied at lab scale. There is a need for upscaling and demonstration in an industry environment of these novel processes, and still

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the development of new specific and selective solvents replacing HF and fluorides, and novel extractants to make the processes greener and inexpensive.

### **Substitution**

Potential substitutes are titanium, vanadium, molybdenum, high nitrogen steels, ceramic composites and gallium alloys. While considering the substitution potential of Nb with other elements, it is important to take into consideration the global availability of those elements. Due to the physical and chemical similarities of Ni and Ta, the one metal can be substituted by the other in a large number of applications (e.g. in cemented carbides, corrosion resistant coatings, optics and hard disc drives). Though there are substitutes available for most applications of tantalum and its compounds, the use of these substitutes often sustains a cost or performance penalty or less versatility. The core use of Ta in capacitors has several possible substitutes (Al, ceramic or Nb-based capacitors) that are likely to answer most common needs. However, it is expected that Ta capacitors will remain the first-choice for applications requiring high reliability and resistance to elevated temperature where cost is not a primary consideration. Substitutes are also available in the case of mill products (e.g. glass, Ti, Nb) and high-temperature applications (e.g. Nb, W, Hf).

## **PLATINUM GROUP METALS**

### **Main Uses**

PGMs dispose a number of excellent properties such as high melting point, superior catalytic activity, and exceptional resistance to corrosive attack and high temperature oxidation, allowing these metals to be employed in a number of sectors including automotive (catalytic convertors, spark plugs, oxygen sensors), chemical and petroleum (catalysts and laboratory equipment), electrochemical (anode coatings), electrical and electronics (hard disk drives and multilayer ceramic capacitors), medical and dental (dental alloys, biomedical devices, and anti-cancer drugs), glass manufacturing equipment, as well as jewellery and investment areas.

### **Future Demand and trends**

The demand for PGMs continues to increase. PGMs use in automobile catalytic converters is expected to increase as more-stringent automobile emission standards are adopted worldwide. An emerging industrial use for platinum is in fuel cells that provide electricity for automobiles, homes, and businesses, while the demand for platinum jewelry is expected to grow significantly in major Asian economies, particularly in China.

### **Primary production**

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## Primary Resources

The mines of PGM are associated to basic or ultrabasic magmatic rocks and to placers resulting of their erosion. The mines producing PGMs are classified in two categories: a. oxidized deposits with Pt concentrations around 5 ppm and a lower Pd content (Bushveld, South Africa; Great Dyke, Zimbabwe; Stillwater, USA); b. sulphide Ni-Cu containing PGMs in specific mineral species (i.e. pentlandite), where, Pd concentration is higher than Pt (Norilsk-Talnakh and Pechenga, Russia; Sudbury, Canada; Jinchuan, China; Kambalda, Australia). The main producers both in terms of reserves and production are South Africa and Russia.

PGM production by primary resources in EU is mainly taking place in Finland. Kevitsa Ni-Cu mine consists the only currently active mine where PGMs are produced as by-products (production of 889 kg Pd and 1163 kg Pt in 2016). The Aguablanca Ni-Cu mine in Spain contained, in 2011, about 85 t Pd and 2 t Pt in the ore. However, there is no information regarding how much of the Pt and Pd is retained in the concentrates and whether it is actually recovered. Minor, currently non exploitable, deposits are reported in Norway, Sweden, Bulgaria and Greece.

## Primary Extraction Pathways

The extraction of PGM is mostly performed from underground mines.

Several flowsheets of PGMs recovery from ores are reported in literature. The beneficiation processes employed to concentrate PGM consists of crushing, grinding and flotation. As some PGMs are lost in the different stages of beneficiation, research is needed towards the optimization of the applied processes. Extractive metallurgy (pyro/hydrometallurgy) is mostly used to extraction PGM. The production of PGMs from Ni-Cu sulphide ores is well established following the Outokumpu process, which comprises; (a) the flash smelting of the enriched sulphide concentrate, (b) the leaching of the matte, (a) the Cu extraction with electrowinning and (d) the PGMs extraction as a mixture through solvent extraction.

## **Secondary Resources**

### Mine and Metallurgical Wastes

PGMs may be present in certain tailings, smelting slag, dusts from metal smelting furnaces and spent furnace refractory lining especially in Ni metallurgy plants in Finland, but there is a lack of relevant data (amounts and PGMs concentrations) in literature. Additionally, some steel slags contain oxide phases bearing PMs. These kind of slags are mainly landfilled as their valorisation/recycling is not economically feasible. The accumulation of their huge volumes create a serious environment problem and they are considered as a neglected source of RPMs.

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Several National and European projects focusing on PGM recovery from mining and metallurgical wastes are in progress.

### Scraps

PGMs can be mainly found in PCB scrap, mobile phone scrap. Their concentrations in WEEE are around 10 g/t - 10 kg/t, accounting for 40-70% of the total economic value of this waste. The automobile industry sector accounts for 35-60% Pt and Pd, and about 95% Rh consumption. These three precious metals are mostly used in automobile catalytic converters and can be found in the relevant scrap.

Extensive research has been performed and various techniques have been developed on RPMs recovery from urban mines. The pyrometallurgical methods are the most widely applied by the large companies (Boliden, Umicore, Aurubis) to recover PGMs from e-wastes. Hydrometallurgical methods present higher recovery yield however, they present several challenges from an environment point of view. The bio-metallurgy is the most promising technology for bioleaching of RPMs from e-wastes.

However, due of the complexity of urban mines, all the developed processes cannot achieve to completely recover the contained PGMs. The combination of the described methods is the best way to develop a process that will allow the full recovery of PGM from urban mines in the future. The most attractive process route is the flexible process capable of recovering PGM from different waste matrices.

Specific attention should be given to the optimisation of PGMs (platinum, palladium and ruthenium) recovery by spent automotive catalysts. Innovation is necessary towards (a) the optimisation of the scrap separation/classification step; (b) the increase of PGMs recovery yield; (c) the increase of selectivity during leaching; and (d) the utilisation of green technologies. Novel techniques, still applied at laboratory scale, have shown that the decrease of energy and acids consumption is feasible. However, more research is needed on these innovative processing routes, as the techno-economic analysis is often lacking, and it is difficult to compare the potential benefits of new processes with the current industrial processes.

### **Substitution**

The use of PGMs in a wide range of applications, some of which are considered as cutting edge, coupled with their relatively high prices has led to various attempts for their substitution with less expensive metals. PGMs substitution of by other less critical and more abundant metals is an ongoing concern. In most of the cases, PGMs can be effectively substituted only

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by other PGMs. The crucial applications of PGMs are related with their use as catalysts in diesel and gasoline vehicle converters and in petroleum and organic chemical industry. Numerous research studies have shown that the substitution of PGM catalysts is technologically feasible, however, various non-technological factors render the implementation of substitution impractical. The PGMs substitution, in case of catalytic converters, by Co, Ni and Au can lead to more intense environmental burdens. Apart from other PGMs, Ni, Co, and Au are the elements most likely to substitute PGMs in certain applications due to the chemical proximity between these metals and PGMs. Nanotechnology and fuel cells technology could potentially led to decreasing PGMs demand and supply risk, however this approach is going to take place in the long term.

## REE - LANTHANUM AND CERIUM

### Main uses

Lanthanum and cerium are used in various applications including optical glass manufacturing (La, Ce oxides), Ni metal hydride batteries, phosphors in TV screen and fluorescent lamps, catalysts in petroleum refining and high strength steel and aluminum alloys.

### Future demand and trends

La and Ce demand as percentages of the total REEs demand is expected to remain constant until 2025. However, a significant La demand increase will take place by 2030 in the sector of automotive industry due to the propulsion of the electric vehicles construction, as La is contained at significant concentrations in Ni metal hydride rechargeable batteries for hybrid and electric automobiles. La consumption is likely to further increase for the synthesis of Li-La titanate (LLTO), which is one of the most promising solid electrolytes for next generation batteries due to its high ionic conductivity at room temperature. Likewise, Ce demand is expected to increase also in the short term as it has been proposed to partially substitute Nd in permanent magnets. Concerning their potential applications in the long term, and subsequently their market growth, La and Ce can become crucial elements for fuel cells technology. Ceria can be potentially used for the construction of electrodes due to its unique properties. Additionally, La nickelate with the perovskite structure appears to have advanced electrochemical properties to be appropriately used as a cathode in hydrogen fuel cell applications.

### Primary production

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## Primary resources

The most significant La and Ce containing REE deposits are found in Scandinavia and Greenland. The Norra Kärr deposit, located in southern Sweden, with 41.6 Mt reserves (average concentration in REOs 0.57%) is the La and Ce major primary resource. In Greenland, the Kvanefjeld deposit has been characterized as a premium REE deposit with elevated concentrations of LREEs (La and Ce), while the Kringlerne deposit presents a total REEs content of about 0.65 wt.% and has the main advantage that it does not contain radionuclides. Olserum (Sweden) and Sokli (Finland) are also major La and Ce deposits.

## Primary extraction pathways

The feasibility study of La and Ce extraction in several European mining districts has been already completed. The exploitation of Norra Kärr (Sweden) and Kvanefjel/Kringlerne (Greenland) deposits is expected to begin during the next years. The processing of Olserum (Sweden) and Sokli (Finland) ores has also been tested. It should be stressed out that the beneficiation/enrichment processes of European REE containing ores can possibly be further optimised. Greenland ores are enriched in REEs through magnetic separation, however there are no sufficient published data concerning the chemistry and the mineralogy of the concentrate produced by the magnetic separation pilot tests. Olserum ore presents a complex mineralogy dominated by monazite-(Ce), xenotime-(Y), and fluorapatite hosted by veins that contain various silicate minerals. The beneficiation of the Olserum ore via flotation has been successfully tested at pilot scale. A complex magnetic separation-flotation process could be studied for the further enrichment of the ore, taking into account the presence of magnetite and ilmenite which dispose a high magnetic susceptibility value.

## **Secondary resources**

### Mine and metallurgical wastes

The recovery of La and Ce from metallurgical wastes including red mud and phosphogypsum has been studied using  $H_2SO_4$ ,  $HNO_3$  and HCl as leaching agents. The results indicate a poor recovery (<60%) in case of one step leaching of phosphogypsum, while about a 100% recovery of La was observed in red mud leaching with sulphuric acid. REEs are received via selective precipitation or solvent extraction. However, La and Ce recovery from phosphogypsum and red mud (despite the existence of significant deposited amounts in EU) is not economically sustainable at the moment taking into account the low La and Ce concentrations in these residues and their relatively low market prices. Furthermore, there is a lack of environmental life cycle analysis concerning their extraction from these metallurgical residues.

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## Scraps

Secondary industrial waste often contained a REE mix in which La and Ce are often the most abundant REE. However, the total content is 10 to 100 times lower than in primary ores. When looking more precisely at La and Ce, some scraps or EOL products are of higher interest due to a high La and/or Ce content, such as optical glasses, polishing powders, NiMH batteries or FCC catalysts. However, the amount to be treated annually is low.

Electrodes in spent NiMH batteries consist an important secondary resource for La recovery. La recovery from NiMH batteries has been developed in detail via various processing routes, at laboratory level, including the leaching with various acids and the recovery of La either through precipitation or solvent extraction. Concerning Ce extraction from scrap, the recycling of Ce containing LEDs has been attempted at pilot scale. The developed process comprises a combination of manual and mechanical processing steps aiming to the removal of non-metallic components and the enrichment of the recycling stream. The results of this research consists a useful tool for the further development of the dismantling and pretreatment processes in case of other electronic wastes.

However today, the market price of La and Ce is very low (6\$/kg for the pure metal, 2\$/kg for the pure oxide), limiting the potential development of a recycling market. In terms of environmental impact, if the recycling strategies rely on the same process used for the primary production, no significant difference is expected. Only a breakthrough in the selected processes could bring an added value for the development of a sustainable secondary production of La and Ce.

## **Substitution**

La and Ce substitution of by non-critical raw materials can be applied at a limited level. Specific importance should be given to the substitution of ceria abrasive by alternative ceramic materials. Ceria-based abrasives are widely used due to their high removal rate and high-quality surface finish. Zirconia-based ( $\text{SrZrO}_3/\text{ZrO}_2$ ) abrasives can partially substitute ceria as they present superior polishing properties such as creation of ultra-smooth glass surfaces. The cost analysis for the synthesis, via spray pyrolysis, of zirconia containing abrasives should be studied in detail.

## **REE – NEODYMIUM, PRASEODYMIUM, DYSPROSIUM, SAMARIUM**

According to 2015 data, about 82% of the global Nd-oxide production is consumed for the construction of NdFeB permanent magnets, which are used in a wide range of applications including wind turbines, hard drive discs and electric motors. Neodymium magnets contain

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also praseodymium and dysprosium, while their total REO content varies between 23 and 35 wt.%. Likewise, samarium global production is mainly used in Sm<sub>2</sub>Co<sub>17</sub> magnets (with Sm content of about 25 wt.%). Lower amounts of Nd, Pr, Dy and Sm are used for various other applications including the construction of NiMH batteries, fluorescent lighting sources, specific glasses and alloys for aerospace and catalysts.

### **Future demand and trends**

The future Nd, Pr, Dy and Sm demand will be driven by the wind turbines and electric vehicle motors sectors. The global offshore wind energy capacity is expected to significantly increase until 20130 even taking into account a conservative scenario. On the other hand, the growth of electric vehicles market is more difficult to be predicted as it is related by various factors. The production of EVs/HEVs is expected to be range between 3.2-9.2 million units by 2020. The development of EVs/HEVs industry will be directly related with the price of raw materials, especially REEs, and the applied government policies for the reinforcing of environmental friendly vehicles. Toyota and other large automotive industries are planning to install induction motors in EVs in case the price of Nd becomes unsustainable or supply is unreliable. In the long term, lower amounts of Nd, Pr, Dy and Sm will be potentially consumed for the construction of alternative REEs-doped phosphors and REEs containing catalysts in chemical industry. However, the properties of the above materials are currently under investigation.

### **Primary production**

#### Primary resources

The exploitation of multi-element deposits containing Nd, Pr, Dy and Sm in EU territory consist the most promising short term solution for decreasing the import dependency and supply risk for these REEs. Norra Kärr (Sweden) and Kvanefjeld-Kringlerne (Greenland) consists major world class deposits containing HREE, among them Nd, Pr, Dy and Sm. Pilot scale beneficiation, leaching and separation tests of Norra Kärr, Kvanefjeld and Kringlerne ores have been successfully performed. It has been estimated that the annual production of Nd and Dy in Greenland can reach 33.000 and 2.000 tonnes, respectively. This amount represents 5-8% of the global Nd supply and 10-16% of the global Dy supply.

#### Primary extraction pathways

The feasibility study for the exploitation of the Norra Kärr and Kvanefjel/Kringlerne deposits has been successfully performed following a classic metallurgical route including leaching, selective precipitation/solvent extraction, REEs separation and purification. The main challenges concerning the further optimisation of the metallurgical processes (i.e. problems

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during the REEs precipitation efficiency and creating of undesirable silica gel in the leachate) have been mentioned in the previous CRM paragraphs.

## **Secondary resources**

### Mine and metallurgical wastes

There are no available data concerning the existence and the potential recycling of mining and metallurgical residues containing notable concentrations of neodymium, praseodymium, dysprosium and samarium. The presence of Nd in Greek red mud has been reported in the literature, however at low amounts rendering the recovery of the metal economically non feasible.

### Scraps

Permanent magnets and metal hydride batteries consist and main secondary resources for the recovery of neodymium, praseodymium, dysprosium and samarium. The dismantling of permanent magnets from HDDs and air conditioners have been commercially developed by few non-European companies. The various forms of EoL devices containing permanent magnets consist the main barrier for the development of an automatic dismantler for general application.

Two different methodologies have been developed for the recycling of EoL permanent magnets containing REEs. The first, called direct recycling process, aims to the magnets reuse after their demagnetization, thermal treatment and re-alloying by the addition of extra amount of pure REEs in the EoL material. The low environmental impact consists the main advantage of the direct recycling process. Researchers at the University of Birmingham optimised the direct recycling of NdFeB magnets via hydrogen decrepitation technology. The second recycling methodology concerns the elemental recovery of Nd, Pr, Dy and Sm through classic hydro and pyro metallurgical techniques. Delft University developed a metallurgical route which is based on scrap leaching and REEs extraction through selective precipitation. Several technological barriers should be overcome prior to the commercialization of REEs extraction by EoL magnets. The most significant are: (a) the automation of magnets dismantling, (a) the reducing of leaching environmental impact and (c) the effective separation/purification of REEs in the leachate.

The recovery of metallic neodymium and praseodymium from metal hydride and Li-ion batteries has been commercially attempted by limited number of European companies. The recovery of Nd, Pr, Dy and Sm from EoL permanent magnets via numerous novel processes is described in literature. These processes have been successfully tested at laboratory or pilot

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scale, using shredded scrap that is pure and is composed by single devices. The investigation of Nd, Pr, Dy and Sm recovery at actual conditions using multi-composed scrap is necessary in order for the recycling sustainability to be proved.

### **Substitution**

The substitution of NdFeB and Sm-Co magnets by REEs-free magnets consist a technologically challenging issue. The main disadvantages of the REEs-free magnet alloys are the following: a. AlNiCo type alloys present low coercivity; b. ferrites present very low remanence; c. FeNi bulk material is very unstable and its synthesis and upscaling is problematic; and d. Fe<sub>3</sub>Sn presents a strong in-plane magneto-crystalline anisotropy. Therefore, the substitution of NdFeB and Co-Sm magnets by REEs-free magnets consists a low priority objective as the synthesis of operating REEs-free magnets should be further investigated.

## **REE - EUROPIUM, GADOLINIUM, TERBIUM**

### **Main Uses**

Europium (Eu), Gadolinium (Gd) and Terbium (Tb) represent 1.5% of the total produced amount of REEs. Eu and Gd are mainly used in phosphors, while Tb is added in NdFeB alloys of permanent magnets. Tb is also used in medicine diagnosis and treatment due to its unique fluorescence properties.

### **Future Demand and trends**

The Eu and Gd demand is directly related to the technological evolution of lighting materials. Substitution of fluorescent with more advanced light-emitting diode (LED) technology will significantly decrease the Eu demand in the short term. The development of organic light-emitting diode (OLED) is expected to reduce the Eu, Tb and Y demand, however the Gd and La demand will be potentially increased. Tb demand will be designed according to the development of wind-turbines market. This might be affected by the possible substitution of Tb with Dy in permanent magnets.

### **Primary production**

#### Primary Resources

The most important deposits of HREEs including Eu, Gd and Tb in EU are the Norra Kärr deposit in Sweden (41.6 Mt with an average 0.57% concentration in HREOs) and Kvanefjeld deposit in Greenland which is one of the largest HREEs-uranium deposits in the world containing 10.33 Mt of HREEs (ore amount > 1 billion tonnes, average HREEs concentration 1.10%).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

## Primary Extraction Pathways

No significant technological barriers have been reported for the exploitation (mining, beneficiation, mineral processing) for Norra Kärr and Kvanefjeld deposits. Technical issues like the removal of dissolved silica from the leachate solutions, the liquor purification and control of solvent extraction conditions can be appropriately addressed. Although, tests have been carried out at pilot scale, further optimisation of the leaching, precipitation and solvent extraction process should be performed. The most significant challenge concerning the exploitation of the Kvanefjeld deposit is related with the control of the workers exposure to radionuclides during mining and processing of the ore and to secure the compliance with the relative radioactivity regulations.

## **Secondary Resources**

### Mine and metallurgical wastes

There are not enough data concerning the existence and the potential recycling of mining and metallurgical residues containing notable concentrations of Eu, Gd and Tb in the EU. A possible source of Eu could be phosphogypsum disposals in EU countries and this possibility needs to be further investigated.

### Scraps

End of life fluorescent lamps consist the main secondary resource for the recovery of europium, gadolinium, and terbium contained in the phosphor materials. The extraction of Eu-Y from EoL lighting devices has been commercially performed in EU by Solvay (former Rhodia) company. The chemical separation plant installed in La Rochelle, France with a processing capacity of 3,000 tonnes of lamp waste/year, which corresponded to the forecasted European waste production for 2020 operated till 2016. The recycling activities were interrupted due to the decrease of REEs price. The main barrier concerning the sustainable recycling of fluorescent end-of-life lamps is not technological and it is related with the small supply amounts of scrap.

The main technological barriers that have been reported concern: (a) the physical separation of phosphors in case of compact fluorescent lamps (CFLs) in which the separation is manual and the concentrate is contaminated with the glass; and (b) the leaching efficiency of phosphors mixture due to their different acid resistivity behaviour. However specific technologies that have been recently developed and tested at laboratory scale, such as two-liquid flotation and fusion with molten salts, can potentially improve the recycling sustainability.

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## Substitution

Eu (phosphor applications) and Gd (MRI imaging) present unique physicochemical properties; as a result no substitutes are currently available. The required Eu and Tb amount in LEDs, which progressively replace fluorescents, is progressively reduced. The use of Eu in lighting is expected to be significantly reduced due to the OLEDs spreading, while the use of Gd might be increased.

## REE - HOLMIUM, ERBIUM, THULIUM, YTTERBIUM AND LUTETIUM

### Main uses

Holmium (Ho) is a component in high magnetic strength alloys and holmium-doped yttrium iron garnets (YIG). Erbium (Er) is used as photographic filter and as additive in alloys for workability. Thulium (Tm) doped yttrium aluminum garnet is applied in lasers. Ytterbium (Yb) is applied as gamma ray source and also in atomic clocks and as steel additive. Ce-doped lutetium oxyorthosilicate (LSO) detectors are applied in PET.

### Future demand and trends

The Ho, Tm, Yb and Lu demand is expected to increase in the next years due to the expansion of cutting-edge applications in developing countries. On the other hand, end-of-life recycling rates for Ho, Tm, Yb and Lu are all below 1%, therefore the production is exclusively related to the production from primary resources. The demand is possible to further increase due to the commercialisation of novel materials in short the term, like  $\text{CoFe}_{2-x}\text{Ho}_x\text{O}_4$  which consists a promising material in the long term for applications in high density magnetic recording media, ferro fluid technology, magnetic resonance imaging enhancement, biosensors and gas sensors; Thulium:YAG laser, tested as an alternative to yttrium aluminum garnet (YAG) laser for lithotripsy; Nd/Er:YAG material, suitable for diode laser (LD) pumping applications.

### Primary production

#### Primary resources

Significant exploitable deposits of Ho, Tm, Yb and Lu exist in Scandinavia and Greenland, as previously described.

#### Primary extraction pathways

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Ho, Tm, Yb and Lu are expected to be extracted by Scandinavian and Greenland ores through a conventional hydrometallurgical process as it was previously described.

## Secondary resources

### Scraps

Ho, Tm, Yb and Lu recovery from scrap has not been attempted even at laboratory scale due to the limited number of EoL devices containing these REEs and their low concentrations. Specific attention should be given to the collection, classification and dismantling of EoL scraps containing Ho, Tm, Yb and Lu as a first recycling-action.

### Substitution

The efficient substitution of Ho, Tm, Yb and Lu, according to the current data, is practically impossible. Gd, Nd, Tb and Er have been examined as substitutes of Ho, Tm, Yb and Lu in super alloys and optical fibres, however these REEs consist also CRMs.

## YTTRIUM

### Main uses

The construction of yttria-containing lattice doped europium (III) red phosphors consists the main current application of yttrium (Y). The metal is also used for the synthesis of synthetic garnets as microwave filters (and generally various ceramic materials), in synthetic jewels, as an additive in high strength aluminium and magnesium alloys and as yttrium lithium fluoride for lasers.

### Future demand and trends

According to a study on the fluorescents and LEDs lighting market in USA, yttria demand will peak between 2019 and 2022 and then decline off. This trend is due to the commercialisation of OLEDs, which are expected to replace the currently used fluorescents and LEDs. Yttria will be substituted by lanthanum and gadolinium based materials. On the other hand, various novel technologies involving the use of Y, is possible to be commercialised in the long term. Yttrium-doped barium zirconate (BZY) has been proposed as an advanced ceramic electrolyte in protonic devices, such as gas sensors, steam electrolyzers, and protonic-ceramic fuel cells (PCFCs). BZY presents excellent chemical stability, which consists the most crucial factor in protonic-ceramic fuel cells. Yttrium-containing W-Cr-Y alloys are suggested as an alternative

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(instead of tungsten) wall material of future fusion reactors. Despite the indications of Y utilisation in cutting edge future applications, its growth demand is difficult to be forecasted after 2030.

## **Primary production**

### Primary resources

Y production by primary EU resources is expected during the next years. Norra Kärr (Sweden), Kvanefjeld (Greenland, Denmark) and Lamujärvi (Finland) REEs deposits contain elevated Y concentrations. Feasibility studies, as well as, beneficiation and metallurgical tests have been already performed for the above mentioned REEs deposits. High radionuclides content in the case of the Kvanefjeld ore consists the main technological barrier for the exploitation of this deposit.

### Primary extraction pathways

In the case of the European REE ores, Y is distributed in nepheline syenites or contained in eudyalite phase. Therefore, it will be extracted simultaneously with the REEs. As it has been already stressed out, the most important technological barriers which should be eliminated are related to (a) the further optimisation of the leaching and selective precipitation steps; and (b) securing the health and safety standards in the case of the Kvanefjeld ore mining due to the elevated concentration of radionuclides.

## **Secondary resources**

### Mine and metallurgical wastes

Yttrium can be extracted from ores like bastnäsite ores, monazite ores, xenotime ores and gadolinite, which can be found in some places in Europe. Xenotime ore can be found in some places of Norway (Flekkefjord, Arendal and Tvedestrand, Ytterby), in Sweden (Resarö Island, near Vaxholm) and in Switzerland (Binntal, Valais). Bastnäsite ore exists in: karst bauxite deposits in Hungary, Greece and the Balkans region; carbonatites (Fen Complex, Norway); and in the unusual granites of the Langesundsfjord area, Norway. Gadolinite is found in Ytterby, Resarö, Vaxholm, Uppland, Sweden.

### Scraps

Phosphors originated from EoL LCDs, computers, X-ray tubes, light bulbs and TV-sets is a significant secondary resource of yttrium. Yttrium is currently industrially extracted from various electric and electronic scrap materials in EU (Rhodia Company, Narva Light Sources GmbH, Eco Recycling in Northern Italy).

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The automation of the EoL LEDs and LCDs dismantling consists a key-action for the commercialisation of multiple element's extraction (various REEs + Y) by this type of scrap. A number of patents in the literature describe the development of dismantling machines for the automated mechanical treatment of EoL fluorescent lamps.

Some current strategies for Y recycling are acid/basic leaching or solvent extraction. In the last years, several European projects were carried out to improve and develop novel strategies for recycling Yttrium. For example, in the SepSELSA project a successful new approach called solid-state chlorination was developed, which could provide various advantages in terms of costs and disposal.

### **Substitution**

For the majority of applications, Y is irreplaceable, as substitutes are generally much less effective. Especially in electronics, lasers, and phosphors, Y cannot be replaced efficiently by other elements. Yttria is possible to be substituted by CaO or MgO as stabiliser in zirconia ceramics, however lower toughness properties have to be accepted at that case. Concerning the potential development of OLEDs, Y will be probably replaced by lanthanum and gadolinium, which are also considered as CRMs.

## **SCANDIUM**

### **Main uses - Future Demand and trends**

The annual global Sc supply and consumption is estimated to be about 10 to 15 tons. The principal current applications of Sc is in aluminum alloys for military aircraft components and sporting equipment. The Sc demand by the aviation industry is expected to increase in the short term due to the use of Al-Sc alloys in civil aircrafts. Additionally, Sc demand will be further increase in the long term as new uses are expected like: use of powder aluminium-scandium alloys for the construction of high-strength components through 3D printing; Sn use as an electrolyte material (scandia stabilised zirconia-ScSZ) in solid oxide fuel cells. ,

### **Primary production**

#### Primary production

Currently, only three mines worldwide produce Sc: the uranium and iron mines in Zhovti Vody, Ukraine, the REE mines in Bayan Obo, China, and the apatite mines in the Kola Peninsula, Russia. The primary Sc deposits in EU territory (plus Norway) are limited and mainly exist in

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Eastern Finland, Kiviniemi Scandium deposit (162.7 ppm Sc); in Norway Biggejavri REE-Sc-U deposit (130.0 ppm Sc); and in Greece, the nickeliferous laterite ores ( $\leq 100$  ppm Sc).

### Primary Extraction Pathways

Sc extraction necessitates the application of both beneficiation and metallurgical processes with the exception of nickeliferous laterites which cannot be submitted to enrichment. For the first two deposits preliminary beneficiation and hydrometallurgical testing has been performed at lab scale, while in the case of nickeliferous laterites leaching via the Neomet process has been tested at pilot scale. The up to now research results have shown the need for the development of: a. more efficient beneficiation techniques and b. new hydrometallurgical processes with emphasis on the reduction of acid consumption and the optimisation of the Sc recovery. In the case of Greek laterites a detailed investigation and a quantification of the lateritic beds which contain Sc at relatively high concentrations (i.e.  $>80$  ppm) is required.

### **Secondary resources**

#### Mine and Metallurgical Wastes

Red mud, the aluminum industry residue, consists the most significant secondary resource for Sc extraction. It is estimated that about 5-6 million tonnes of red mud are annually generated in EU, with a Sc concentration of about 70 to 100 ppm. Greece and Hungary are the main red mud producers in EU. Sc extraction from the aluminum industry residue (red mud) has been studied at lab and pilot scale, however it has not been applied commercially. Three processing routes have been studied (Orbite Company process, Kamensk Uralsky Alumina Refinery process and the SCALE project process). The main technological issues to be addressed are the increase of the Sc recovery and the minimization of acid consumption.

#### Scraps

Future Sc secondary resources will become available from Sc-Al alloys and  $Sc_2O_3$  in solid oxide fuel cells and electronic devices. Sc recovery from Sc-Al alloys and  $Sc_2O_3$  consists a complex issue as: (a) there is lack of information on the amount of Sc-containing electronic wastes and whether this materials are collected and processed by the recycling companies, (b) the number of specific cutting-edge devices containing Sc is small and therefore the potential recovery amounts are limited.

### **Substitution**

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The main Sc substitutes are related with elements which can be alternatively added in aluminum. Some rare earth elements such as ytterbium, dysprosium, gadolinium etc., as well as titanium and zirconium, can be successfully partially substitute scandium presenting similar or advanced properties. However, most of the substitutes consist also CRMs.

## SILICON

### Main uses

About 80% of the elemental silicon produced remains as a ferrosilicon alloy, while approximately 20% is refined to metallurgical grade purity (a total of 1.3–1.5 million metric tons/y). An estimated 15% of the world production of metallurgical grade silicon is further refined to semiconductor purity ("nine-9" or 99.9999999% purity), while the rest 5% is used mainly for the construction of Al-Si alloys. Elemental silicon is also used for the production of the  $(\text{CH}_3)_2\text{SiCl}_2$  monomer, which is used for the synthesis of silicones. Silica is used as raw material for the production of various complex materials (glasses, optical fibres, ceramics, etc.).

### Future demand and trends

There are no sufficient published data concerning the demand and price forecast of elemental silicon and ferrosilicon. The price trend is strongly related to the productivity of ferrosilicon in China and the photovoltaics market development. Currently, Chinese ferrosilicon production has been subject to increasingly stringent government controls on overcapacity and emissions and the Pidgeon process, in which vast amounts of FeSi are consumed, will be replaced by technologies with a lower environmental impact. On the contrary, the silicon use for the construction of PV panels will constantly increase in the short term. By 2022, electricity generation capacity will correspond to double the capacity produced by nuclear energy. The exact Si amount demand by the PVs industry is difficult to be forecasted, as due to new technologies the wafers thickness is progressively reduced. The Si consumption for cutting edge technologies such as silicon fibres for various applications (such as in integrated systems, medicine, alloy and compound fibres in lasers) is expected to increase.

### Primary production

#### Primary resources

Quartz mines exist in several EU countries, while silicon, ferrosilicon and microsilica is produced in Norway by Elkem Silicon Materials Company. The annual silicon production is around 215.000 tonnes, while Elkem is world's leading supplier of microsilica with an amount

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of 300,000 tonnes. Elkem Silicon Materials operates three quartz mines, two in Norway and one in Spain.

There are good perspectives for the exploration of new pure-quartz deposits in Scandinavia, especially in granitic bedrocks. Various advanced methodologies, such as the use of unmanned aerial vehicles equipped with appropriate sensors or the utilization of satellite data, can be suggested as exploration tools.

### Primary extraction pathways

Silicon of 96-99% purity is produced by reducing quartzite or sand with highly pure coke. The reduction is carried out in electric arc furnaces, with an excess of  $\text{SiO}_2$  in order to prevent silicon carbide formation. Ferrosilicon is produced by the reduction of a mixture of silicon dioxide and iron scrap with low amounts of phosphorus and sulphur.

### **Secondary resources**

#### Mine and metallurgical wastes

No mine and metallurgical wastes have been reported from which Si can be extracted by a sustainable way.

#### Scraps

Silicon is not currently recovered from post-consumer wastes, moreover most chemical applications are dispersive, thus not allowing for any recovery. The recovery of silicon contained in metallic scrap such as aluminium alloys, cast iron and steel is incidental to that of the primary metal; some silicon is recycled internally in smelters when fines or off-grade material are remelted. In the case of silicon wafers, there is research on their recycling, however it has not yet materialised in marketable solutions; during the production process only 45-50% of the silicon feedstock reaches the end, all other is lost as waste in the processes like sawing and block cutting. A large part of the current production of silicon wafers is used in the production of photovoltaic solar panels.

Emphasis is given on the recycling of silicon for PV industry and from end-of-life panel, as the management of EoL silicon-based photovoltaic solar panels will be a major environmental problem the next few decades. It has been estimated that about 60 million tons of PV panels waste will be lying in landfills by the year 2050. Germany, France, Italy and Denmark is expected to be the major EU producers of PV panel wastes. EoL solar PVs are classified as e-wastes, while they consist the most significant secondary resource for elemental silicon. A “total recycling” methodology for the simultaneous extraction of Si, Cu, Al and glass by the

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EoL PVs has been developed. The most significant barrier for the elemental extraction of Si by EoL PVs is non-technological and it is related with the high recycling operating cost. It has been estimated that the “total recycling” method will be economically sustainable in case that the operating cost is reduced by 30%.

### **Substitution**

The substitution perspectives are negative as silicon can be efficiently replaced, in the case of its main applications in electronics and photovoltaic systems, only by a number of critical and expensive metalloids such as germanium, gallium and indium. Nevertheless, silicon consumption in EU is possible to decrease as a result of ferrosilicon consumption decrease in steel and magnesium industries. Ferrosilicon is currently the most widely used deoxidising agent in the steel industry, however due to novel electric arc furnaces its consumption has been decreased in Western Europe over the last 25 years, from around 7.5 kg/t of steel to approximately 3.5 kg/t of steel. Similar actions should be taken in the case of magnesium metallurgy and the substitution of FeSi-consuming Pidgeon process by alternative technologies.

## **TUNGSTEN**

### **Main Uses**

Tungsten (W) is widely used in cemented carbides (for mining petroleum construction, metal-working industries purposes), steel alloys, superalloys (corrosion resistance turbines blades, marine vehicles), mill products (lighting filaments, audio-visual projectors, fibre-optical systems) and chemical compounds (paints, dyes, enamels, painted glass, catalysts). About 54 to 72% of tungsten in the world are used for hard metals.

### **Future Demand and trends**

The W consumption continues to increase as the amount of carbide tool production increases with the expansion of markets in developing countries.

### **Primary production**

#### Primary Resources

There are W reserves in EU countries UK (1.6%), Spain (1%), Austria (0.3%), and Portugal (0.1%). 81% of world W production Tungsten comes from China, which is estimated to have about 69% of the international reserves. Twelve tungsten mines were exploited during the 20<sup>th</sup> century in France, and three deposits still have recognized resources of more than 10,000

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t of  $WO_3$  each. Tungsten oxide concentrate is produced in Portugal by Almonty Company. The produced  $WO_3$  amount was 926 tonnes in 2016.

### Primary Extraction Pathways

The majority of W deposits contain less than 1.5% of  $WO_3$ , while the metallurgy uses concentrates containing 60-75% of  $WO_3$ . Therefore, a large amount of gangue should be separated and removed near the mine, to avoid transportation costs. Industrially, W is extracted by the reduction of  $WO_3$  using hydrogen or solid carbon as reducing agents. Alternatively, tungsten can also be extracted by hydrogen reduction of  $WF_6$ . Several research projects have been carried out and innovations have been proposed to improve the beneficiation process, focusing on the separation of the finer ore fractions and the yield increase despite the existence, in several cases, of complex ore mineralogies. Concerning W metallurgical processing, research should focus on decreasing the W losses in precipitation and purification, reducing chemical consumption and improving the efficiency of the ion exchange and solvent extraction methods. In the case of pyrometallurgical methods, achievement of carburisation as a one-step process will result in improving the economical and energy consumption conditions.

### **Secondary Resources**

#### Mine and Metallurgical Wastes

Large amounts of waste rock that contain tungsten come from surface mining, mostly from open-pit mines of copper, uranium, phosphate, iron and taconite. Significant amounts of wastes in the form of mine tailings exist in Portugal and Spain. The main technological barrier in their exploitation is the fine particle size of the material and in this direction research and tests to improve tungsten recovery have been made.

To increase tungsten recycling rates, a reliable identification and estimation of available secondary resources is required. Although large tungsten-bearing tailings in Europe have been identified, various other potential feed streams remain undiscovered, especially various kinds of industrial waste (mill tailings, grinding sludge, dust, sweepings) which are withdrawn from the value chain of recycling.

#### Scraps

Tungsten scrap is a very valuable raw material due to its high tungsten content in comparison to ore.

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In hard metal applications, W included in monocarbides can be relatively easily recycled with established technologies. In turn, in steels and in other applications, where W is diluted in the material, its recycling is problematic, and W cannot be really recovered.

More complex hydrometallurgical routes are being developed that can treat a wider variety of scrap. One of the biggest challenges is making the process profitable as these methods are very energy and reagents intensive. A proper solution might be to develop processing plants that can recover multiple metals and can turn them into high quality end-products. Another issue is that these plants produce a lot of effluents and waste. New technologies might also be needed to reduce the environmental impact of these type of recycling plants.

Besides methods for the recycling of scrap, new technologies are also being developed to recycling tungsten from other sources such as drill bits, roller collars, catalysts and e-waste. Recycling technologies for these types of waste are still in an early stage of development.

Main barriers to post-consumer recycling are: the dispersion or dilution in the material/structure (low-grade material); the lack of appropriate post-consumer collection systems for open-loop recycling; and the poor economic viability.

### **Substitution**

For tungsten's main application, WC-based cemented carbides, substitution appears technically possible but implies higher cost and, in some cases, a decrease in performance. Tungsten can also be substituted in cemented carbides and alloys but at high cost and/or loss of performance. Titanium carbides (TiC) and nitride (TiN) are potential substitute, but the technology is not competitive at the moment. Tungsten can be replaced by other refractory metals such as niobium (CRM) or molybdenum in steel products. In other application areas, possible substitution of tungsten is affordable, as super-alloys for gas turbine engines substituted by Ceramic Matrix Composites (CMCs) made of a silicon carbide/nitride matrix. Also, substitution with nanostructured n-alloys such as FeTa could be possible in 10 years, since the current TRL are very low (TRL 3-4). Substitution in the lighting sector is well underway.

## **VANADIUM**

### **Main Uses**

Vanadium (V) is mainly used as additive in HSLA (high-strength-low-alloyed) steel and special alloys to improve their strength and resistance to corrosion; vanadium oxide is also used as

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catalyst and as pigment for ceramics and glass. V is currently produced in China (53%), South Africa (25%) and Russia (20%) with a total annual production of 71,000 tons.

### **Future Demand and trends**

The future demand on vanadium is driven by the market need of lighter and higher strength steels. The addition of just 0.2% V to steel increases steel strength by up to 100% and reduces the weight in relevant applications by up to 30%. Future demand for vanadium in the EU is expected to increase in all the above sectors especially due to increase in steel production and the increase of V consumption per ton of steel. The demand is also expected to be influenced by innovations in the manufacturing of battery products mainly with the development of Vanadium Redox battery for stationary energy storage (close to 2,000 tons of V world demand in 2016).

### **Primary production**

#### Primary Resources

There is no primary production of Vanadium in Europe. V occurs in deposits of phosphate rock, titaniferous magnetite, and uraniferous sandstone and siltstone, in which it constitutes less than 2% of the host rock. Significant quantities are also present in bauxite and carboniferous materials, such as coal, crude oil, oil shale, and tar sands. Vanadium is typically recovered as a by-product or co-product from the vanadium-containing slag generated from the metal production. Titanomagnetites represent a valuable raw material for the production of vanadium and titanium. Minerals4EU website reports resources data for Sweden, with 24.6 million tonnes vanadium, or 140 million tonnes at 0.2% of V of inferred resources. The EU import reliance on vanadium is 84%. A possible new resource in EU could be the blackshale layer covering phosphorite materials in Estonia. Huge amounts of blackshale have already been stockpiled to give access to the exploitation of this material.

#### Primary Extraction Pathways

Vanadium is mainly produced from titaniferous magnetite, which is a type of iron ore. Therefore, the methods applied for mining iron ore in general apply for mining of titaniferous magnetite. Nowadays, the mining and mineral processing methods for iron ore have been well developed, and there is a little space for innovation. Nevertheless, titanomagnetite ore processing is a sophisticated large-scale process, during which a large volume of wastes or residual materials are generated.

The main barriers for mining and mineral processing of titaniferous magnetite lies in the various environmental problems than can potentially arise due to the creation of

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secondary/waste materials during processing. The main barrier for the vanadium extraction in the pyrometallurgical process lies in the presence of titanium in the titaniferous magnetite, which could on one hand affect the iron making process in the blast furnace and on the other hand deteriorate the steel quality due to the involvement of titanium in the steel. The main barrier for the vanadium extraction in the hydrometallurgical process lies in the low vanadium content and low recovery of vanadium from the materials, which decrease the economic value of the extraction process. In the future, the development of a comprehensive process to concentrate the iron, vanadium and titanium in the ore in different fractions by either mineral processing and/or metallurgical processing is the challenge, as this will improve the raw materials efficiency and the economic value of the production process.

## **Secondary Resources**

### Mine and Metallurgical Wastes

V-containing resources generated through the mining and metallurgical activity include: (1) tailings, mainly from the mineral processing of titaniferous magnetite ore; (2) residual materials from the roast-leach processing; (3) low-grade slag generated during the various smelting processes, (4) other industrial residual materials, such as fly ash. There are no current processes to obtain vanadium from mining tails or metallurgical wastes. Currently various processes are applied for V recovery from oil fly ashes and spent catalysts coming from the fuel industry. According to literature, V extraction from the fly ash can be implemented either by hydrometallurgical or pyrometallurgical processing. Mintek has developed a complete pyrometallurgical process.

### Scraps

The recycling of vanadium from HSLA steels is very rare due to the low vanadium content and the oxidation of vanadium during the scrap re-melting. V recycling from spent catalysts is common and is performed at commercial scale due to the toxicity of vanadium as well as the existence of other valuable elements in the spent catalyst. Vanadium in the special steel scrap and vanadium alloy scrap are possible to be recycled, if these scraps are processed under reducing condition (such as in the Electric arc furnace with addition of strong reducing agent) or recycled by melting under vacuum conditions. Vanadium used in low-vanadium-alloyed steels is almost entirely dissipative and this means that the recycling rate of vanadium from old steel scrap is almost zero. The main target, nowadays, is its recovery from HSLA steels.

## **Substitution**

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Due to the market demand of lighter and higher strength steels, vanadium has become indispensable in HSLA steels. Vanadium as an alloying component in steels can be replaced by several other elements to some extent; however, sometimes the higher price of the substitute elements makes the substitution less economic. Steels containing various combinations of other alloying elements can substitute steels containing vanadium. Certain metals, such as manganese, molybdenum, niobium (columbium), titanium, and tungsten, are to some degree interchangeable with vanadium as alloying elements in steel. Platinum and nickel can replace vanadium compounds as catalysts in some chemical processes. Currently, no acceptable substitute for vanadium is available for use in aerospace titanium alloys.

## CRM: EXPLOITATION BY PRIMARY AND SECONDARY RESOURCES/SUBSTITUTION

Table 1 summaries the information that were assessed during the implementation of WP6 concerning the technology gaps/barriers and innovation pathways in CRMs exploitation by primary and secondary resources and, as well as, their substitution by non-CRMs. According to Table 1, the most promising exploitable CRMs in EU, and the respective innovation paths that should be followed for the processing unlocking, are the following (alphabetically):

### **Baryte**

The existence of significant amounts (28 Mt) of mining tailings containing baryte has been reported in Kremikovtzi mine in Bulgaria. Laboratory tests showed that the beneficiation of these tailings is possible through flotation process. The flotation tests is necessary to be

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upscaled, while alternative enrichment methodologies (such as optical sorting) should be examined.

Laboratory scale studies have shown that hematite and ilmenite can be used as replacement of baryte in petroleum drilling fluids. The high magnetic susceptibility of hematite and ilmenite, reaching the upper limit of acceptable paramagnetism, consists their main disadvantage. Complex mixtures containing hematite can be tested.

### **Cobalt**

Cobalt is currently recycled from various EoL. However, there are no available data concerning the followed industrial techniques in case of Co recovery from spent Li-ion batteries. Pyrometallurgy presents relatively low Co recovery yield and a high energy consumption. Laboratory scale investigations revealed that Co, Li and Cu extraction is technologically feasible using a combination of pyrolysis, leaching, selective precipitation of Co and Li and Cu electrowinning. Graphite, also a CRM, can be recovered at the dismantling step. The methodology deserves to be upscaled.

### **Coking coal**

Coking coal use and demand can be potentially limited by the use of biocoal, while, at the same time, NO<sub>x</sub> and SO<sub>x</sub> emissions will be decreased. Steel-making industry consists a major consumer of coking coal in EU. Recently, the Swedish steel-producer company SSAB tested the replacement of coking coal by biocoal at industrial scale using small blast furnaces. The preliminary results are encouraging, while the project is expected to be completed in 2019.

### **Magnesium and magnesite**

The production of metallic magnesium in EU, through conventional metallurgy (Pidgeon process) is not techno-economically feasible due to the EU environmental policy framework. Alternative, high temperature carbothermal reduction processes using solar furnaces have been tested at laboratory and pilot scale and their development should be further supported.

Magnesite production is currently taking place in few EU countries (Slovakia, Greece, Spain). The production can be increased by the processing of old mining wastes and flotation tailings. The small particle size of these secondary residues consists the main obstacle. The use of innovative beneficiation techniques (i.e. advanced optical sorters combining the raw material magnetization) could be proposed.

### **Natural rubber**

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The production of natural rubber in EU can be achieved by alternative primary resources and methodologies. More specifically, natural rubber is possible to be produced by Guayule instead to Hevea, which is cultivated in tropical environment. Additionally, a product similar to natural rubber can be synthesised via the polymerisation of oligomeric allylic pyrophosphates (biosynthesis).

### **REEs and yttrium**

The production of RRE from primary European deposits consists a high-priority action of the CRMs sector taking into account the high supply risk and the import dependency of Europe on these elements. World-class REE deposits have been identified in Scandinavian countries (including Greenland) and Finland. The most significant deposits are: a. Kvanefjeld in Greenland which is characterised as the 2<sup>nd</sup> largest REE deposit worldwide (about 108 Mt) containing terbium, dysprosium, neodymium and praseodymium, as well as LREEs (lanthanum and cerium), at an average concentration of 1.4 wt.%; b. Kringlerne in Greenland (4300 Mt) consists of polymetallic ore with 0.65% TREO, 0.2% Nb<sub>2</sub>O<sub>5</sub> and 1.8% Zr<sub>2</sub>O<sub>3</sub>; c. Norra Kärr in Sweden containing 41.6 Mt of ore with an average 0.57 wt.% in REOs mainly LREEs, Nd, Dy, Pr and Y.

The feasibility study for the mining, ore enrichment and metallurgical treatment has been performed for Norra Kärr and Greenland REE deposits. The optimisation of the REEs extraction route from these deposits is suggested to be focused on the (a) efficient separation of REE-containing eudyalite-aegirine by the gangue in the case of Norra Kärr, (b) semi-industrial scale testing of precipitation after the leaching; and (c) establishment of proper health and safety procedures in the case of U-containing Kvanefjeld deposit exploitation.

The recovery of specific REEs from secondary resources is necessary to be accelerated in the short term. Currently, only 7% of the LREEs and 6% of the HREEs are produced through recycling from secondary sources. The implementation of large EU research projects revealed that the recovery of Ce, La, Eu, Gd, Tb and Y by LCDs and LEDs (TVs, PC monitors, smartphones, notebooks, fluorescent lamps, lasers etc.) is technically feasible. The efficient collection of the scrap material and the automation of the phosphors separation are the main barriers that should be overcome. The recovery of Nd, Pr, Sm, Dy and Tb from spent permanent magnets (wind turbines, HDDs, electric vehicle motors) is suggested to be tested at pilot or semi-industrial scale.

### **Silicon**

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EoL PV panels consist the most significant secondary resource for elemental silicon. The amount of available PVs scrap is expected to dramatically increase during the next decade due to the end of the working life of currently operating panels.

A “total recycling” methodology has been proposed and tested at laboratory scale for the simultaneous recovery of Si, Al, Cu and glass. The method consists of the following main steps: automated dismantling and separation of Al frame, cables, panels (glass+Si) and polymers; separation of Si-glass in PV sandwich by melting at controlled inert atmosphere; optical separation and refinement of glass; plastic removal by calcination; Si recovery from calcination ash by leaching with HNO<sub>3</sub> and filtration; recovery of other metals via electrolysis.

The main technological barriers are related to the necessity for further optimisation in the dismantling step and the reduction of the generated wastes. LCA studies have shown that “total recycling” can become economically feasible in case that the operating cost decreases by 30%.

Table 1. Current situation of CRMs concerning their production by primary and secondary resources and substitution possibilities.

CRM	Forecast for consumption	Existence of resources in EU		Recovery from primary resources				Recovery from secondary resources				Substitution potential
		Primary resources	Secondary resources	Practice scale	Energy efficiency	Recovery efficiency	Environmental impact	Practice scale	Energy efficiency	Recovery efficiency	Environmental impact	
Antimony	increase	not significant	significant	not taking place				industrial		high		moderate
Baryte	might increase	not significant	low	industrial	high	high	moderate	Laboratory scale	High	moderate	low	moderate
Beryllium	might increase	moderate	moderate	not available				industrial				low
Bismuth	increase	low	moderate	not taking place				industrial		moderate	moderate	low
Borates	might increase	not significant	moderate	not available				laboratory	low	moderate	low	low
Cobalt	increase	moderate	low (from mining/metallurgical wastes)	industrial (Ni-Co-Cu sulphides in Scandinavia); lab scale (laterites)		moderate	moderate	Industrial scale by superalloys, laboratory scale by Li-ion batteries	moderate	high	moderate	low
Coking coal	might increase	not significant	not possible	industrially at small scale	low	high	low	not possible				moderate
Fluorspar	might increase	not significant	not possible	industrially but limited reserves				not possible				low
Ga-Ge-In	increase	not significant	extensive	not taking place				-industrially via pyrometallurgy	moderate	moderate	moderate	low
Hafnium	might increase	not significant	low	not taking place				not available				low
Helium	might increase	not significant (natural gas)		not taking place				not possible				low
Magnesium	increase	moderate	moderate	- Magnesite industrially - Metallic Mg not taking place	low	high	high	- industrially in case of magnesite (flotation tailings)	- High (magnesite)	High (magnesite)	Moderate (solar furnace)	low
Natural graphite	might increase	not significant	moderate	industrial at limited extent				industrial at small scale by spent refractories	moderate	moderate	moderate	low

CRM	Forecast for consumption	Existence of resources in EU		Recovery from primary resources				Recovery from secondary resources				Substitution potential
		Primary resources	Secondary resources	Practice scale	Energy efficiency	Recovery efficiency	Environmental impact	Practice scale	Energy efficiency	Recovery efficiency	Environmental impact	
Natural rubber	increase	not available		possible recovery by non-tropical plants (pilot scale)		high		not possible				low
Nb-Ta	increase	not significant	moderate	industrial at very limited extent	moderate	high	high	Industrially by tin metallurgy slags. Lab-scale by EoL	low	low	high	low
PGMs	increase	low	significant	industrial	moderate	high	high	industrially via conventional metallurgy, lab-scale green technologies	moderate	moderate	high	low
P and phosphates	might increase	moderate	significant	industrial at limited extent	high	high	low	industrial at limited extent	low	low	high	low
REE (Eu-Gd-Tb)	might increase	significant	low	pilot scale	moderate	high	satisfactory	laboratory/pilot scale concerning the dismantling	moderate	moderate	moderate	low
REE (Hm-Er-Th-Yb-Lu)	might increase	significant	low	pilot scale	moderate	high	satisfactory	laboratory	moderate	moderate	moderate	low
REE (Nd-Pr-Sm-Dy)	increase	significant	significant	pilot scale	moderate	high	satisfactory	laboratory/semi-industrial scale for dismantling	moderate	high	moderate	low
Lanthanum	increase	significant	moderate	pilot scale	moderate	high	satisfactory	laboratory	moderate	high	moderate	low
Cerium	might increase	significant	moderate	pilot scale	moderate	high	satisfactory	laboratory	moderate	moderate	moderate	low
Yttrium	increase	significant	significant	pilot scale	moderate	high	satisfactory	laboratory/pilot scale concerning the dismantling	moderate	moderate	moderate	low
Scandium	increase	not significant	significant	not taking place				pilot	moderate	moderate	high	low
Silicon	increase	not significant	extensive	not taking place				laboratory	low	high	moderate	low
Tungsten	might increase	moderate	moderate	industrial at very limited extent				industrial	moderate	high	moderate	low
Vanadium	might increase	not significant	moderate	not taking place				no available data				low